This is to certify that the

thesis entitled

ENERGY BALANCE ANALYSIS FOR
FUEL ETHANOL PRODUCTION

presented by

Robert Yemoh Ofoli

has been accepted towards fulfillment
of the requirements for

MS degree in Agric. Eng.

B A Stout
Major professor

Date____________________

ENERGY BALANCE ANALYSIS FOR FUEL ETHANOL PRODUCTION

By

Robert Yemoh Ofoli

A THESIS

submitted to
Michigan State University
In partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1980

ABSTRACT

ENERGY BALANCE ANALYSIS FOR FUEL ETHANOL PRODUCTION

By

Robert Yemoh Ofoli

The energetics of conventional industrial ethanol production are examined. Energy inputs for corn production, off-farm transportation, and the alcohol plant processes are accounted for. A net energy analysis model is used, and the energy value of distillers grains for ruminant feed is determined.

A total energy input of 6,800 Kcal/l (102,100 Btu/gal) was required to produce dry land corn and convert it to ethanol. Irrigated corn required 7,320 Kcal/l (110,000 Btu/gal). Ethanol and by-product output was determined to be 7,900 Kcal/l (118,700 Btu/gal). Thus, 16% and 8% more total energy is produced than is required for dry land corn and irrigated corn, respectively.

If premium fuels are used to produce and convert corn to ethanol, 21% and 30% more premium energy is used than is produced, respectively, on the same basis. If coal is used to fuel the alcohol plant, 200% and 150% more premium fuel, respectively, is produced than is required.

Approved: B A Stout
Major Professor

Approved:
Department Chairman

To
Jonathan, for making this possible

and
Sherry, for being there whenever needed

ACKNOWLEDGEMENTS

The author wishes to thank Dr. B. A. Stout (Agricultural Engineering) for his encouragement, guidance, assistance and constructive criticisms and suggestions; and for being his major professor.

Appreciation is also expressed to the faculty and staff of this department for their uplifting friendliness and friendships.

Gratitude is expressed to Dr. Roy Black (Agricultural Economics), Dr. Martin Hawley (Chemical Engineering), and Dr. Alan Rotz (Agricultural Engineering) for being on the committee.

The author will also like to extend his gratitude to all the graduate students of this department for helping to make MSU such a happy place to be.

The financial support provided by the Michigan Farm Bureau for this study is gratefully acknowledged.

Last, but certainly not the least, a warm thank you to the McKallips of Winslow, Maine, for being a true family to him.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

A	acre
atm	atmospheres (pressure)
bbl	barrels
Btu	British thermal units
bu	bushels
C	Carbon (the element)
CBM	constant boiling mixture
cs	control surface
cv	control volume
cwt	hundredweight (100 lb)
D	distribution coefficient in liquid-liquid extraction
dA	elemental area
dV	elemental volume
g	acceleration of gravity
gal	gallon(s)
gm	gram(s)
H	Hydrogen (the element)
ha	hectare(s)
hr	hour(s)
Kcal	kilocalories
kg	kilogram(s)
km	kilometer(s)

l	liter(s)
lb	pound(s)
m	meter(s)
m.c.	moisture content
mi	mile(s)
N	extensive property of a system, e.g. mass or energy
$\hat{n}$	unit vector, positive outward
O	Oxygen (the element)
ODT	oven dry tonne(s)
u	internal energy per unit mass
U	total internal energy of the system at a given instance
V_b	velocity of the system boundary at the control surface
V_i	velocity of the system relative to an inertial reference frame
V_r	velocity of the system at the boundary
W	work done by the system on the surroundings
z	height relative to a fixed datum
^oC	degree(s) Celcius
^oF	degree(s) Fahrenheit
α	separation factor in liquid-liquid extraction
η	intensive property of the system, property/mass
ρ	material density
ΔU	change in total internal energy

1.0 INTRODUCTION

Prescott and Dunn (1949) wrote that "the subject of ethyl alcohol production by fermentation has assumed new interest on account of attempts to find substitutes for gasoline. ... Present day demands for motor fuels are great but the sources of petroleum are limited." This statement, made 31 years ago, is as true today as it was then.

In 1976, the United States consumed about 74 quads of energy. Diehn (1979) estimated that the United States would consume about 454.0×10^9 l (120.0×10^9 gal) of gasoline in 1979. It appears that no single foreseeable technology will meet the energy demand of the United States in the year 2000 (Bliss and Blake, 1977).

Imports account for about 45% of the liquid fuels currently consumed in the United States. According to the 1979 Department of Energy report on alcohol fuels (DOE, 1979), more than half the liquid fuels consumed is used in transportation -- about three quarters of that amount is in the form of gasoline for automobiles. Therefore, the manufacture and widespread use of alcohol fuels can provide a significant potential for reducing United States oil imports.

1.1 Current and potential outcomes of the energy crisis

Recent international events and their effects on the United States domestic fuels market are well documented. The high dependence of the United States on foreign oil imports has led (or can lead to) the following problems (Stone, 1979; Stout, 1979):

1. a substantial economic cost;
2. economic instability and vulnerability;
3. uncertainty about energy supplies;
4. continued collapse of the United States dollar abroad;
5. inflation at home;
6. a threat to the national security;
7. serious trade deficits;
8. increasing unemployment; and
9. a possible decline in the standard of living.

While everyone of these problems may not be a direct result of the energy crisis, they have combined to direct attention to alternative fuels and sources of energy.

1.2 Extent of this study

This study includes a brief discussion of biomass as an energy feedstock, production of ethanol, and a comprehensive energy balance analysis on industrial scale alcohol production. Some methods of improving the energy balance are also presented. The study does not include an economic analysis.

2.0 OBJECTIVES

The study objectives are:

1. To establish an energy accounting method to comprehensively portray the input and output energy relationships of industrial scale fuel ethanol and its by-products.

2. To derive (as a result of objective 1) the energy balance of ethanol production on an industrial scale.

3. To discuss some methods of improving the total energetics of ethanol production.

4. To provide an up-to-date reference on fuel ethanol.

3.0 LITERATURE REVIEW

3.1 History of alcohol development

The word "alcohol" most likely derived from the Arabic word, "al-koh'l" (Simmonds, 1919).

Fermented liquors were known to the ancients. Distillation was known to the Chinese in the remote past, but it is usually accepted that Arabian chemists discovered alcohol from wine (Simmonds, 1919). Arrack, distilled from toddy (a fermented liquor obtained from rice and palms), has existed in India since 800 B.C. and in Ceylon (Sri Lanka) from time immemorial (Simmonds, 1919).

In 1659, Willis described a ferment as "a body in a state of decomposition, with energetic motion in its particles; this motion it can impart to another body which is capable of fermentation" (Simmonds, 1919). Stahl, in 1697, described fermentation as a "matter of the decomposition of a fermentable body into its components, which then recombine in a different manner to form new substances" (Simmonds, 1919).

In 1648, Van Helmont stated that during fermentation, a gas as well as alcohol was produced. He also stated that a ferment was needed to start the process (Simmonds, 1919). This was a major contribution toward the understanding of fermentation.

In 1680, Leeuwenhoek laid the foundation of research on fermentation when he studied yeast using a homemade microscope of 150 magnifying power (Simmonds, 1919).

In the 18th century, Black stated that ethyl alcohol and carbon dioxide were the only end products of ethanol fermentation (Prescott and Dunn, 1949).

MacBride, in 1764, identified Van Helmont's gas as Black's fixed air or carbon dioxide (Simmonds, 1919). Cavendish, in 1766, determined that the proportion yielded by fermentation of the "fixed air" was 57% (Simmonds, 1919).

In 1789, Lavoisier discovered a third product which he called acetic acid. From 95.9 parts sugar, he obtained 57.7 parts ethanol, 33.3 parts carbon dioxide, and 2.57 parts acetic acid (Prescott and Dunn, 1949).

In 1793, Lavoisier showed by various experiments that alcohol and carbon dioxide were the quantitative results of sugar decomposition (Simmonds, 1919).

Gay-Lussac studied Lavoisier's results and formulated the following equation (Prescott and Dunn, 1949)

$$C_6H_{12}O_6 \xrightarrow{\text{yeast}} 2C_2H_5OH + 2CO_2 \qquad (1)$$

which states that one glucose molecule yields two ethyl alcohol molecules and two carbon dioxide molecules. From 45 parts glucose, he obtained 23 parts alcohol and 22 parts carbon dioxide.

During the 19th century, a controversy arose between Pasteur and Liebig on the cause of fermentation. Until the question was settled in the 1830's, fermentation was considered a chemical rather than a a biological process, and yeast a chemical reagent rather than a living organism. In 1830, Gay-Lussac proposed that yeast was needed in the fermentation process (Simmonds, 1919).

In 1836, using a microscope, Cagniard-Latour recognized yeast as a living organism. Within 2 years, three researchers -- Kützing of Nordhausen, Schwann and Turpin -- had come to similar conclusions. Even though the two very distinguished chemists of the time -- Buzelius and von Liebig -- presented opposing views, Pasteur confirmed the Cagniard-Latour theory. Pasteur also established that in addition to alcohol and carbon dioxide, succinic acid and glycerol were produced. He further showed that each kind of fermentation (alcoholic, lactic, etc.) required a special microorganism (Simmonds, 1919).

In an 1897 publication, Buchner discussed the role of enzymes in the fermentation process. Hansen, beginning in 1879, investigated the life-history of alcohol producing yeasts and also developed a method of cultivating a pure yeast from a single mother cell (Simmonds, 1919).

3.2 Historical use of alcohol

Al-koh'l was an indigenous Easter antimony sulfide which women used to darken their eyebrows and eyelashes. In time, the name was applied to fine powders. Wine may have been given the name "alcohol" because the process of sublimation to produce fine powders resembles that of distillation for wine (Simmonds, 1919).

The Arabs and Romans used alcohol in the industrial preparation of perfumes, cosmetics and medicines (Miller, 1979).

Around 1830, alcohol replaced whale oil in lamps because it was clean and odorless (Bossong, 1978).

The Otto cycle, developed in 1876, could burn either alcohol or gasoline (Bossong, 1978; DOE, 1979; Teague, 1978). Both Alexander Graham Bell (in 1922) and Henry Ford (from 1935 to 1947) supported the use of ethanol as a fuel (Mitre Corp., 1978). The carburetor in Henry Ford's Model T was designed to enable the engine to run on pure alcohol, pure gasoline or any blends of the two (DOE, 1979; Teague, 1978).

In spite of the high production costs, alcohol has been used in times of petroleum shortages, agricultural surpluses, and during efforts to gain national independence from oil imports (David, et al., 1978; Teague, 1978).

Use of straight alcohol and alcohol-gasoline blends in Brazil dates back to 1923. Alcohol-gasoline blends have been in general use since 1967 not to save petroleum, but to use up excess sugar from the sugar mills (Carvalho, et al., undated; Pischinger and Pinto, 1979, Yang, et al., undated). Alcohol content in blends ranged from 0 to 30%. Currently, Brazil is promoting alcohol use to save petroleum imports.

In 1931, a blend of alcohol, ethyl ether and ordinary motor fuel called "gasonol" was introduced in the Phillipines (Willkie and Kolachov, 1942).

Alcohol was used as a fuel extender in Europe during both World Wars (Klosterman, et al., 1977). Between the wars (World War I and II), several European countries sponsored costly programs, through subsidies, to develop an ethanol production industry. Gasoline at that time cost \$0.09 per gallon, while ethanol cost \$0.44 per gallon. The high cost of the subsidies was justified to: 1) achieve automobile fuel autonomy in the event of war; 2) establish a secure source of ethanol for a munition industry; 3) stimulate agriculture, labor and industry during the depression; and 4) reduce national trade deficits (Mitre Corp., 1978).

In the 1930's, Chrysler Motor Corporation modified cars to run on straight alcohol for shipment to New Zealand, then poor in oil reserves (Bossong, 1978; Mitre Corp., 1978). International Harvester also designed tractors for the Phillipines to run on straight alcohol. To make this possible, International Harvester equipped the tractors with high compression pistons and changed the carburetor floats from cork to metal (Mitre Corp., 1978; Willkie and Kolachov, 1942).

In the late 1930's (circa 1939), various countries in Europe made it compulsory for motorists to use alcohol in certain proportions (Bossong, 1978; Willkie and Kolachov, 1942). For example, Italian motorists were forced to use motor fuels containing 12% alcohol. In other countries, the percentage of alcohol in fuel blends was higher: Czechoslovakia and Hungary, 20%; Lithuania and Latvia, 25%; and Germany, 13% (one-third methanol and two-thirds ethanol, except in motor fuel containing benzol).

During World War II, German vehicles ran on potato-derived alcohol while the United States Army obtained ethanol from a plant in Omaha (DOE, 1979; Mitre Corp., 1973; Teague, 1978). During the same period, service stations in Kansas, Nebraska and Illinois sold Agrol, a gasoline-ethanol blend similar to our present-day Gasohol (Mitre Corp., 1978; Teague, 1978).

The end of World War II restored cheap petroleum fuels and most alcohol programs ceased (Mitre Corp., 1978).

3.3 Historical production of ethanol

Beer brewing processes were depicted by the Mesopotamians and the Egyptians as far back as 2500 B.C.; however, modern methods have developed only since the mid-19th century (Mitre Corp., 1978). During that period, F. T. Kützing, a German botanist and Louis Pasteur, a French chemist, demonstrated the function of yeast in fermentation.

Boswell, Steinbauer, Babb, Burlison, Alderman and Schoth published a detailed report in 1936 on their study of the Jerusalem artichoke (Prescott and Dunn, 1949). Brown, in 1941, and again in 1947 (in collaboration with Regosa and Whittier) successfully produced ethyl alcohol from whey (Prescott and Durnn, 1949).

Boruff and Van Lanen reported that 2.65 x 10^9 l (0.70 x 10^9 gal) of alcohol were made from wheat and wheat products from late 1942 to July 1945 (Prescott and Dunn, 1949).

The Balls-Tucker process in 1943 used enzymes normally occuring in yeasts for saccharification. This was a move intended to save malt (Prescott and Dunn, 1949).

In 1944, Jump, Zarow and Stark studied ethanol production from dehydrated sweet potatoes. Foth, Sankey and Rosten in 1944, and Joseph and Ericson in 1947 (along with other investigators) described the process of making ethanol from sulfite liquor (Prescott and Dunn, 1949).

To use wood sugars to produce ethyl alcohol, toxic substances must be removed and nutrients added. Leonard and Hajny, in 1944, developed several reducing agents, and also used sulphite waste liquor, reduced iron filings and several other substances to remove toxins

(Prescott and Dunn, 1949).

In 1945, Dunning and Lathrop reported on the laboratory saccharification of cellulosic agricultural residues -- corncobs, cottonseed, cane bagasse (Prescott and Dunn, 1949). The method they used resembles the Tsao-Purdue process currently under investigation at Purdue University. Dunning and Lathrop used a 2-stage hydrolysis method. Dilute sulfuric acid was used to hydrolyze pentosans at the first stage and concentrated sulfuric acid was used to hydrolyze cellulose during the second stage.

In 1947, Altsheler and his colleagues designed a continuous alcohol unit capable of producing 19 l (5 gal) of 190 proof alcohol per day from 2 bu of grain.

Since then, and until recently, cheap fossil fuels have stifled alcohol research.

3.3.1 Fermentation

Humphrey (1977) wrote: "Fermentation is one of man's oldest technologies. An Assyrian tablet of 2000 B.C. lists beer among the commodities Noah took aboard the ark. Egyptian documents dating back to the Fourth Dynasty describe the malting of barley and the fermentation of beer. Kui, a Chinese rice beer, has been traced back to 2300 B.C. When Columbus landed in America, he found that the Indians drank a beer made from corn."

In 1942, Bilford and his colleagues described a laboratory process of rapid continuous fermentation using molasses as feedstock (Prescott and Dunn, 1949). Their process required much less equipment than the conventional process in use at that time.

3.3.2 Distillation

Distillation dates back to the 10th century. As early as the 13th century, people knew about repeated distillation to produce a brandy of a higher alcohol content (Silver Eng. Co., undated).

3.3.3 Alcohol Synthesis

Berthelot has generally been credited with the first synthesis of alcohol. In 1854, he obtained alcohol from olefiant gas, absorbed the gas in sulfuric acid, diluted the product and distilled it (Simmonds, 1919). Meldola showed, however, that the Englishman, Henry Henell, had succeeded at synthesis 26 years before Berthelot (Simmonds, 1919).

3.4 Energy balance

Reilly (1978) reported that from 7,300 Kcal/l (109,600 Btu/gal) to 8,000 Kcal/l (120,200 Btu/gal) is needed to process corn from the cooking stage through distillation to 190 proof. Anhydrous alcohol production requires between 8,300 Kcal/l (124,700 Btu/gal) and 9,100 Kcal/l (136,700 Btu/gal) more. Reilly calculated the overall efficiency (defined in Table 3.1) of alcohol production to be 45.1% to 48.7%, and the efficiency of using normally combusted fuels to be 55.3% to 64.3%. Another 3,200 Kcal/l (48,100 Btu/gal) to 4,000 Kcal/l (60,100 Btu/gal) was assigned to the production of fertilizers, herbicides and pesticides

Table 3.1 Energy balance inputs, Reilly (1978)

INPUTS:

	Low Kcal/l (Btu/gal)	High Kcal/l (Btu/gal)
Processing to anhydrous	8,300 (124,700)	9,100 (136,700)
Electricity	700 (10,500)	1,400 (21,000)
Total fossil fuels	9,000 (135,200)	10,500 (157,700)
Corn combustion energy	10,000 (150,200)	10,000 (150,200)
Total	19,000 (285,400)	20,500 (307,900)
Farm energy	3,200 (48,100)	4,000 (60,100)
TOTAL ENERGY INPUT	22,200 (333,500)	24,500 (368,000)

OUTPUTS:

	Kcal/l (Btu/gal)
Ethanol	5,800 (87,100)
Distillers grains	3,500 (52,600)
TOTAL	9,300 (139,700)

Definitions:

$$\text{Overall efficiency} = \frac{\text{sum of combustion energy of products}}{\text{sum of combustion energy of reactants}}$$

$$\text{Efficiency of normally combusted fuels} = \frac{\text{ethanol output energy}}{\text{fossil fuel energy}}$$

and to till, plant, harvest and dry the corn feedstock. This reduces the overall efficiency of ethanol production to 37.7% to 41.7% and that of normally combusted fuels to 40.0 to 47.7%. Based on these results, Reilly concluded that ethanol requires more energy for production than it releases. Table 3.1 summarizes his data.

Kendrick and Murray (1978) used two procedures for an energy balance analysis on ethanol production from corn. One method regarded corn as a flow resource while the other considered it a stock resource. Under the flow resource evaluation, an energy input of 14,300 Kcal/l (214,800 Btu/gal) was calculated against an energy output of 5,900 Kcal/l (88,600 Btu/gal), leading to a thermal efficiency (defined in Table 3.2) of 59%. Under the stock resource evaluation, input energy was determined to be 19,300 Kcal/l (289,900 Btu/gal) against an output of 9,400 Kcal/l (141,200 Btu/gal), providing a thermal efficiency of 52%. Complete input and output quantities are presented in Table 3.2.

Park, et al. (1978) determined that there is an energy input of 8.32×10^5 Kcal (3.30×10^6 Btu) for every 909 kg (2000 lb) of sugarcane processed, with an output on the same basis of 1.411×10^6 Kcal (5.600×10^6 Btu). The resulting net energy gain is 5.79×10^5 Kcal (2.30×10^6 Btu). Of the energy input, 3.78×10^5 Kcal (1.20×10^6 Btu) was from coal. This led to a net petroleum gain (defined in Table 3.3) of 9.57×10^5 Kcal (3.80×10^6 Btu). Comparable analysis for corn grain and residues yielded an input of 1.83×10^6 Kcal (7.25×10^6 Btu) and an energy output of 1.03×10^6 Kcal (4.10×10^6 Btu), a net energy loss of 7.94×10^5 Kcal (3.10×10^6 Btu). Of the input energy, 1.29×10^6 Kcal (5.10×10^6 Btu) came from coal; therefore, the net petroleum gain was 4.91×10^5 Kcal (1.95×10^6 Btu).

Table 3.2 Energy balance inputs, Kendrick and Murray (1978)

Corn as a flow resource

	Kcal/l (Btu/gal)
INPUTS:	
Energy investment in corn production	5,000 (75,100)
Fermentation and distillation (including drying of DDG)	9,300 (139,700)
TOTAL	14,300 (214,800)
OUTPUT:	
Ethanol	5,900 (88,600)

Corn as a stock resource

INPUTS:	
Corn combustion energy	10,000 (150,000)
Fermentation and distillation (including drying of DDG)	9,300 (139,700)
TOTAL	19,300 (289,700)
OUTPUTS:	
Ethanol	5,900 (88,600)
DDG	3,500 (52,600)
TOTAL	9,400 (141,200)

Definition:

$$\text{Thermal efficiency} = \frac{\text{energy input} - \text{energy output}}{\text{energy input}}$$

Table 3.3 Energy balance inputs, Park, et al. (1978)
(All figures based on 909 kg (1 ton) of feedstock)

	Feedstock	
	Sugar	Corn
	Kcal x 10^6 (Btu x 10^6)	
INPUTS:		
Petroleum fuels	0.351 (1.394)	0.330 (1.310)
Electricity	0.007 (0.027)	0.005 (0.020)
Fertilizer & pesticides	0.096 (0.379)	0.207 (0.820)
Total petroleum derived fuels	0.454 (1.800)	0.542 (2.150)
Coal	0.378 (1.500)	1.285 (5.100)
TOTAL	0.832 (3.300)	1.827 (7.250)
OUTPUT:		
Ethanol	1.411 (5.600)	1.033 (4.100)
ENERGY GAIN	+0.579 (+2.300)	-0.794 (-3.150)

Definitions:

Net petroleum gain = ethanol output - net petroleum input

Net energy gain = total energy output - total energy input

Silva and Serra (1978) analyzed the Brazilian alcohol program. Based on energy return, sugarcane was the most efficient crop, followed by sweet sorghum (milo) and cassava (mandioc).

Stroup and Miller (1978) identified the energy value of ethanol as 5,030 Kcal/l (75,600 Btu/gal) and that of its by-products as 70 Kcal/l (1,100 Btu/gal) while using a plant energy requirement figure of 7,200 Kcal/l (108,100 Btu/gal) in fossil fuel input. From these values, they concluded that the resources that are needed to produce ethyl alcohol "are more valuable in other uses."

David, et al. (1978) reported that there are no generally accepted energy accounting procedures, and described three accounting methods and their resultant energy efficiencies for corn. An accounting of all raw material inputs and and all energy inputs and outputs (calory accounting method) yielded and efficiency of 49% (see Table 3.4 for the definition of efficiency).

A second method (the production energy investment method) obtained an efficiency of 78% by accounting for the production and harvesting energy input of raw materials, and all plant energy inputs and outputs.

The third method (the allocation method) assumes that: 1) distillers grains resulting from a bushel of processed corn have a feeding value equivalent to 0.41 bu of corn; and 2) certain process energy inputs can be assigned either to ethanol or to distillers grains. From these assumptions, 59% of the farm input energy for corn was allocated to ethanol, yielding an efficiency of 86%; while the accounting for distillers grains yielded an efficiency of 68%.

Energy values used for the three procedures were: calorific content of corn, 10,000 Kcal/l (150,200 Btu/gal); ethanol, 5,590 Kcal/l

Table 3.4 Energy balance inputs, David, et al. (1978)

	Calory accounting method	Production energy investment method	Allocation method
		Kcal/l (Btu/gal)	
INPUTS:			
Corn	9,650 (145,000)	2,730 (41,000)	1,600 (24,000)
Process energy	8,720 (131,000)	8,720 (131,000)	4,930 (74,000)
TOTAL	18,370 (276,000)	11,450 (172,000)	6.530 (98,000)
OUTPUTS:			
Ethanol	5,590 (84,000)	5,590 (84,000)	5,590 (84,000)
Distillers dried grains	3,330 (50,000)	3,330 (50,000)	- -
TOTAL	8,920 (134,000)	8,930 (134,000)	5,590 (84,000)
EFFICIENCY	49%	78%	86%

Definition:

$$\text{Efficiency} = \frac{\text{Total energy output}}{\text{Total energy input}}$$

(84,000 Btu/gal); distillers grains, 3,330 Kcal/l (50,000 Btu/gal) of ethanol. The average energy required to produce and harvest a bushel of corn was calculated to be 26,700 Kcal (106,000 Btu). This included fertilizers and chemicals but not farm machinery and equipment.

Thimsen, et al. (1979) studied the production of fuel ethanol from corn and wheat. They arrived at a total energy input of 15,700 Kcal/l (235,800 Btu/gal) to 21,300 Kcal/l (138,200 Btu/gal) for corn. The output energy reported was 9,200 Kcal/l (138,200 Btu/gal) from ethanol and 3,600 Kcal/l (54,100 Btu/gal) representing the feeding value of the distillers grains and solubles. They claimed that the figures used were representative of a well-designed plant processing 1 million bushels of corn per year. From their energy analysis, they concluded that ethanol-gasoline blends in internal-combustion engines offer no engineering advantages, that the production of ethanol is not energy-efficient and that the process is not economically feasible.

Using the heat content of corn, Hofman (1979) determined the overall energy input into alcohol production to be 18,400 Kcal/l (276,000 Btu/gal), the overall output (ethyl alcohol and distillers dried grains) as 8,920 Kcal/l (134,000 Btu/gal) and arrived at an energy efficiency of 49%, from which he concluded that fuel alcohol will have the effect of depleting fossil fuel reserves. The Hofman (1979) energy analysis inputs and outputs are listed in Table 3.5.

Bergland (1979) concluded that while present ethanol distillation methods dissipate more petroleum resources than they produce, and use of renewable resources or optimization of energy use only lead to minimal or questionable reduction in petroleum imports, the use of coal for distillation energy could provide a net reduction of 8.50×10^8 bbl of

Table 3.5 Energy balance inputs, Hofman (1979)

INPUTS:	Kcal/l	(Btu/gal)
Heat content of corn	9,650	(145,000)
Process energy needed for:		
cooking	600	(9,000)
fermentation	0	(0)
distillation	3,460	(52,000)
feed recovery and drying	2,800	(42,000)
misc. (grinding, handling, etc.)	1,530	(23,000)
electricity	330	(5,000)
TOTAL	18,370	(276,000)
OUTPUTS:		
Ethanol	5,590	(84,000)
Distillers dried grains	3,330	(50,000)
TOTAL	8,920	(134,000)

Definition:

$$\text{Production efficiency} = \frac{\text{output energy}}{\text{input energy}}$$

petroleum per year. His analysis was based on a 3.79×10^9 l (1.00×10^9 gal) per year ethanol program nationwide. His analysis assumes that distillers dried grains would replace soybean meal and credits alcohol with the energy that would otherwise have gone into producing soybean meal.

Krochta (1979) did an energy analysis for various crops and arrived at the following energy efficiencies (defined in Table 3.6): corn, 80-110%; sorghum, 80-120%; wheat, 90-110%; potatoes, 70-110%; sugar beets, 100-120%; sugarcane, 90-110%; molasses, 90%; and residues, 160-180%. No crop production energy input was attributed to the cellulosic residues.

Table 3.7 shows a summary of the inputs, outputs, and energy balance of the researchers presented here. All the plant energy requirement figures for these previous studies are rather high, except for Stroup and Miller (1978). In many cases, even the energy loss shown is enough to produce at least a gallon of fuel ethanol.

It appears that the energy requirements for fuel alcohol production used in these analysis are really those of beverage alcohol. Because of the greater purity of ethanol required, beverage alcohol processes are energy-intensive. On the other hand, fuel alcohol can contain fusel oils, corn oil, and other components (usually separated in beverage alcohol manufacture) without impinging on the fuel value of the product.

Table 3.6 Energy balance inputs, Krochta (1979)
(All figures are Kcal/l, with Btu/gal in brackets.)

	Corn	Sorghum	Wheat	Potatoes
		(Thousands)		
INPUTS:				
Corn production	2.2- 4.3 (33- 65)	2.5- 5.1 (38- 76)	1.9- 4.3 (29- 64)	1.3-4.6 (19- 69)
Feedstock preparation	0.6 (9)	0.6 (9)	0.6 (9)	0.6 (9)
Fermentation	0	0	0	0
Distillation	2.0 (30)	2.0 (3)	2.0 (30)	2.0 (30)
By-product recovery and drying	2.0 (30)	2.0 (30)	2.5 (37)	0.8 (12)
Miscellaneous	1.0 (15)	1.0 (15)	1.0 (15)	1.0 (15)
Electricity	0.7 (10)	0.7 (10)	0.7 (10)	0.7 (10)
TOTAL	8.5-10.6 (127-159)	8/8-11.4 (132-170)	8.7-11.1 (130-165)	6.4-9.7 (95-145)
OUTPUTS:				
Ethanol	5.6 (84)	5.6 (84)	5.6 (84)	5.6 (84)
By-products	3.3 (50)	3.3 (50)	4.1 (62)	1.3 (20)
TOTAL	8.9 (134)	8.9 (134)	9.7 (146)	6.9 (104)

Definition: Efficiency $= \frac{\text{outputs}}{\text{inputs}}$

Table 3.6 (cont'd)

(Thousands)

	Sugar beets	Sugarcane	Molasses	Residue
INPUTS:				
Crop production	1.4-2.7 (21- 41)	0.7-2.1 (11-31)	2.7 (41)	0
Feedstock preparation	0.6 (9)	0.6 (9)	0	1.2- 2.4 (18- 36)
Fermentation	0	0	0	0
Distillation	2.0 (30)	2.0 (30)	2.0 (30)	4.0 (60)[a]
By-product recovery and drying	2.6 (39)	0	0	1.0 (15)
Miscellaneous	1.0 (15)	1.0 (15)	1.0 (15)	2.0 (30)
Electricity	0.7 (10)	0.7 (10)	0.7 (10)	1.3 (20)
TOTAL	8.3-9.6 (124-144)	5.0-6.4 (75-95	6.4 (96)	9.5-10.7 (143-161)
OUTPUTS:				
Ethanol	5.6 (84)	5.6 (84)	5.6 (84)	5.6 (84)
By-products	4.3 (65)	0	0	11.2 (168)[b]
TOTAL	9.9 (149)	5.6 (84)	5.6 (84)	16.8 (252)

a. includes pentose conversion.
b. includes products of lignin and pentose conversion.

Table 3.7 Summary of energy balance results of previous researchers (All figures are Kcal/l with Btu/gal in parentheses)

Researcher	Total Inputs	Total outputs	Energy balance
Reilly (1978)			
Low	22,200 (333,500)	9,300 (139,700)	-12,900 (-193,800)
High	24,500 (368,000)	9,300 (139,700)	-15,200 (-228,300)
Kendrick and Murray (1978)			
Corn as flow res.	14,300 (214,800)	5,900 (88,600)	- 8,400 (-126,200)
Corn as stock res.	19,300 (289,900)	9,400 (141,200)	- 9,900 (-148,700)
Stroup and Miller (1978)	7,200 (108,100)	5,100 (76,600)	- 2,100 (- 31,500)
David, *et al*. (1978)			
a. Calory accounting method	18,400 (276,400)	8,900 (133,700)	- 9,500 (-142,300)
b. Production energy investment meth.	11,500 (172,700)	8,900 (133,700)	- 2,600 (- 39,000)
c. Allocation meth.	6,500 (97,600)	5,600 (84,100)	- 900 (- 13,500)
Thimsen, *et al*. (1978)	15,700 (235,800)	9,200 (138,200)	- 6,500 (- 97,600)
Hofman (1979)	18,400 (276,000)	8,900 (133,700)	- 9,500 (-142,300)
Krochta (1979)			
Corn	9,600 (143,000)	8,900 (134,000)	- 700 (- 9,000)
Sorghum	10,100 (151,000)	8,900 (134,000)	- 1,200 (- 17,000)
Wheat	9,900 (149,000)	9,700 (146,000)	- 200 (- 3,000)
Potatoes	8,100 (120,000)	6,900 (104,000)	- 1,200 (- 16,000)
Sugar beets	9,000 (134,000)	9,900 (149,000)	+ 900 (+ 15,000)
Sugarcane	5,700 (85,000)	5,600 (84,000)	- 100 (- 1,000)
Molasses	6,400 (96,000)	5,600 (84,000)	- 800 (- 12,000)

4.0 BIOMASS AS FUEL

Biomass, simply defined, is stored solar energy. It includes all grown organic matter, i.e., agricultural crops, forests, and aquatic plants. It is a storage mechanism that results from the photosynthetic process.

Biomass falls in three broad categories:

1. saccchariferous or natural sugar-containing materials;
2. amylaceous or starchy materials; and
3. cellulosic materials, the main feedstock of most biomass conversion processes.

Biomass is food, fiber, feed, fuel (energy), fertilizer and feedstock. It is renewable and also flexible in the ways in which it can be used as an alternative to petroleum fuels (Cervinka and Mason, 1979).

Because of their potential to be relatively non-polluting, and since they derive from free sunlight, biomass fuels are very attractive (Nathan, 1978). Use of biomass for fuels on a widespread, commercial basis can lead to a secure domestic supply of fuel, mostly favorable environmental impacts, decreased dependence on foreign oil, and will enable a transfer of the scarce non-renewable resources from one generation to another (Kohan, et al., 1979). Biomass is low in sulfur and averages about 4,440 Kcal/kg (8,000 Btu/lb) of dry material (Alich and Inman, 1974).

To use biomass for fuel on a large scale, such issues as growth, collection, densification, transportation and utilization need resolution (Stout, 1979).

Cervinka and Mason (1979) report that the United States is importing progressively less oil for the export of agricultural commodities because the increase in oil costs exceeds that of food costs. This fact is represented in Table 4.1. The figures represent how many barrels of oil an acre of a given crop could purchase over the years 1965-1967 and 1975-1977. The number of barrels has gone down considerably since 1967. It would, therefore, be more logical to produce energy crops than to export food to pay for petroleum imports.

The United States potential for recoverable residue from biomass is about 4.5×10^{11} kg (1.0×10^{12} lb) per year (Diehn, 1979). This includes 2.7×10^{11} kg (6.0×10^{11} lb) of agricultural residue, 9.1×10^{10} kg (2.0×10^{11} lb) of forest residues, 4.5×10^{10} kg (1.0×10^{11} lb) of livestock manure, and 2.7×10^{10} kg (6.0×10^{10} lb) of municipal waste. This represents a tremendous energy resource.

From their illustrative evaluation of energy from agricultural biomass, Carlson, et al. (1979) concluded that 8 quads of energy is feasible from biomass utilization.

From their base case assumptions, Ernest, et al. (1979) project that most biomass until the year 2020 will derive from by-products of animal, food and fiber production, and that only a small contribution is expected from energy crops.

According to Alich and Inman (1974), sugarcane, sorghum, sunflower and certain forage crops have the best potential for biomass.

Table 4.1 Imported crude oil, selected years

Crop	1965	1966	1967	1975	1976	1977
		(bbl per crop-acre equivalent)				
Wheat	14.42	17.50	14.94	9.35	6.70	5.42
Rice	84.58	87.32	93.95	32.67	26.51	32.58
Corn	34.66	37.00	34.38	18.78	15.30	14.13
Cotton	62.41	42.61	49.73	19.93	24.14	20.61
Soybeans	25.09	28.51	25.42	12.15	14.39	13.14

EXAMPLE:

The value of corn produced from 1 A and exported provided revenue for the import of 34.66 bbl of crude oil in 1965, but only 14.13 bbl of crude oil in 1977.

Source: Cervinka and Mason, 1979.

4.1 Photosynthesis

It is believed that Joseph Priestly, in 1773, initiated photosynthesis studies when he found that green plants reverse the effect of breathing (Robertson, 1977). Thirty years later, Jan Ingenhousz recognized that photosynthesis depends on light (Robertson, 1977).

Through the sun's energy together with the photosynthesis process, elements of air, water and soil are transformed by the plant into complex organic compounds that make up the plant (Merva, 1975; Sladek, 1979).

Photosynthesis results in the storage of energy in the biomass material. This energy may be in the form of starches, sugars, cellulose or lignin, among others.

The chemical photosynthetic process is often represented mathematically as

$$6CO_2 + 6H_2O \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6O_2. \qquad (2)$$

The process converts 6 moles each of carbon dioxide and water to a mole of glucose and 6 moles of oxygen. This occurs during a series of oxidation-reduction reactions (Merva, 1975).

The sun, through photosynthesis, is agriculture's most important energy source.

4.2 Basic biomass conversions

There are two major conversion categories for biomass -- thermochemical conversions and biochemical conversions.

4.2.1 Thermochemical conversions

Thermochemical conversion technologies use high temperatures to transform biomass materials, basically cellulose, into more useful forms. Direct combustion, pyrolysis, gasification and hydrogenation are thermochemical conversion processes. The best feedstock for these processes are woody plants, low-moisture plants and mischellaneous collected residues.

4.2.1.1 Direct combustion

Traditionally, burning wood has been the most common way of extracting energy through direct combustion. Through the process, heat, steam, electricity, or any combination of these, can be produced.

Direct combustion involves several processes that lead to various products. Two of these are briefly described:

a) burning in excess air to produce heat, and

b) burning in a controlled atmosphere with a limited supply of oxygen to produce carbon monoxide (a combustible gas), hydrogen and methane (Stout and Loudon, 1976).

4.2.1.2 Pyrolysis

This is the decomposition of organic matter by the use of heat in the absence of oxygen. The reaction produces gases (low- to intermediate-Btu), liquid (tar and oils), chars and chemicals (ERDA, 1977; Kohan, et al., 1979; Love and Overend, 1978; Stout, 1979).

Destructive distillation, a process used to produce wood alcohol, is a form of pyrolysis. This process also produces charcoal, chemicals and acetone.

4.2.1.3 Gasification

Gasification is a partial oxidation process carried on under pressure in the absence of oxygen to produce gaseous fuels from biomass. The products are usually low- to intermediate-Btu gas. From the intermediate-Btu gas (IBG), synthetic natural gas (SNG), ammonia, methanol or Fischer-Tropsch hydrocarbons can be manufactured (Kohan, 1979; Love and Overend, 1978).

Hydrogasification is a dual process involving first the degradation of higher organic compounds and then their saturation with hydrogen. The process is carried on under high pressures and temperatures to produce a methane-rich gas which can be upgraded to SNG (ERDA, 1977; Love and Overend, 1978).

4.2.1.4 Hydrogenation

Hydrogenation is a reduction reaction whereby carbon monoxide reacts with biomass to form a liquid fuel oil (Love and Overend, 1978). The process is carried on under high temperatures (250-350°C) and pressures (70-350 atm) and in the presence of catalysts (ERDA, 1977; Love and Overend, 1978). The process was developed by the United States Bureau of Mines and is also known as liquefaction or carboxylolysis (Love and Overend, 1978). The heavy fuel oil produced by hydrogenation can be upgraded to distillates, light fuel oils, and gasoline.

4.2.2 Biochemical conversions

Biochemical conversion processes use microorganisms to convert biomass to fuels. Enzymes provide catalysts for the chemical reactions. Two major processes, anerobic digestion and anaerobic fermentation, will be briefly discussed.

4.2.2.1 Anaerobic digestion

This is so named here to differentiate it from anaerobic fermentation. It is the conversion of complex organisms by bacterial action to methane and carbon dioxide. As the name implies, the process is performed in the absence of oxygen. It is, basically, a fermentation process but, unlike anaerobic fermentation, the feed material need not be sterile and may actually be highly contaminated by anaerobic organisms (Jones, *et al.*, 1978).

4.2.2.2 Anaerobic fermentation

Anaerobic fermentation results in the production of ethanol and carbon dioxide if both the feed material and the process are kept sanitary. It will be discussed in more detail in Chapter 5.

4.2.3 Summation

Table 4.2 summarizes some products of biomass conversion and some processes that lead to them.

4.3 The alcohol fuels

The Department of Energy estimates that through 1985, alcohol could replace 40,000 bbl of oil per day, nationally. A much greater impact is expected locally in agricultural states (DOE, 1979).

The major potential for alcohol fuels is their use in spark-ignition engines, gas turbines, Diesel engines, boilers, utility fuel cells and in petrochemical applications (API, 1976; DOE, 1979).

4.3.1 Ethanol

Ethyl alcohol is present in some plants as ethyl esters (Simmonds, 1919). Also called grain alcohol, it is a two-carbon member of the generic family of alcohols (David, et al., 1978). It will be treated more fully in subsequent chapters.

Table 4.2 Selected products and processes of biomass conversion

Product	Process(es)
Electricity	direct combustion
Heat	direct combustion
Steam	direct combustion
SNG	gasification/methanation carboxylolysis in the vapor phase anaerobic bacterial digestion
Medium-Btu fuel gas	gasification
Fuel oil	pyrolysis carboxylolysis in the liquid phase
Charcoal	pyrolysis
Ammonia	gasification hydrogenation
Methanol	gasification destructive distillation
Ethanol	anaerobic fermentation
Methane	anaerobic digestion

4.3.2 Methanol

Also called methyl or wood alcohol, methanol has a molecular weight of 32.0 grams -- the lightest of the alcohol chemical compounds (Segal, 1979). Its chemical formula is CH_3OH.

Dumas and Peligot were first to study methanol in 1834 (Simmonds, 1919). They called it "methyl alcohol". In nature, methanol is found as methyl esters in many plants that are constituents of various essential oils. Examples are salicylate, anthranilate and cinnamate (Simmonds, 1919).

It is produced synthetically through destructive distillation.

Because of its favorable emissions, methanol's use in gas turbines is expected in the late 1980's (DOE, 1979).

It is poisonous (Hofman, 1979) and will corrode lead, zinc, magnesium, plastic and rubber components of automobile engines (DOE, 1979).

4.3.3 Ethanol is favored over methanol in this study

Even though methanol appears to be less expensive to produce than ethanol, when the primary, secondary and tertiary benefits of alcohols are analyzed, ethanol becomes cheaper than methanol. In addition, ethanol has the potential to help agricultural production. Ethanol can be produced from agricultural commodities, including surpluses. Also, gasoline-ethanol blends are often considered better than gasoline-methanol blends in terms of their fuel properties

(Mitre Corp., 1978).

4.3.4 Alcohol blends

"Gasohol" is a trademark registered in Nebraska by the Agricultural Products Industrial Utilization Committee (APIUC) of the State of Nebraska. Gasohol was approved by the Environmental Protection Agency (EPA) on December 16, 1978, under Section 211(f)(3) of the Clean Air Act. It is a mixture of 10% (by volume) anhydrous ethanol and 90% (by volume) unleaded gasoline.

Gasohol can be (and is being) satisfactorily used without changes in current internal-combustion engines. The presence of water in the blend can lead to phase separation. Phase separation, in a layman's definition, is the phenomenon where water (mixed with some alcohol) settles to the bottom of the gas tank while gasoline (mixed with the rest of the alcohol) forms a layer on top.

After testing ethanol/gasoline blends, Allsup and Eccleston (1979) concluded:

a) the volumetric fuel economy (miles per gallon, as it is better known) was slightly decreased;

b) energy economy (miles per Kcal or Btu) was slightly increased;

c) regulated emissions — carbon monoxide, hydrocarbons, nitrogen oxides — were reduced at $-6.7^{o}C$ ($20^{o}F$), $7.2^{o}C$ ($45^{o}F$) and $23.9^{o}C$ ($75^{o}F$) but increased at $37.8^{o}C$($100^{o}F$);

d) Gasohol produced about 25% more aldehydes than the base fuel at all temperatures except $7.2^{o}C$ ($45^{o}F$) where they were equal; and

e) Gasohol increased the road octane number (RON) by 4.5 on an

81 RON base fuel and by 3 on a 91 RON base fuel.

The amount of octane enhancement achieved by alcohol depends on the octane rating of the base fuel.

The EPA in Ann Arbor, Michigan, published these results after testing Gasohol (Lawrence, 1979):

a) evaporative emissions increased by about 50% over the base fuel;

b) exhaust hydrocarbons were decreased by about 9%;

c) nitrogen oxide emissions were increased by about 7%;

d) carbon monoxide emissions were decreased by 35%; and

e) fuel economy or miles per gallon (using the carbon balance method) was decreased by about 2%.

The Department of Energy, in a recent report on alcohol fuels (DOE, 1979), stated that even though evaporative emissions increase with Gasohol, the problem can be reduced or eliminated by modifying the base gasoline.

5.0 PRODUCTION OF ETHANOL

Introduction: The alcohol production processes described in this chapter assume that corn is the feedstock. Other feedstocks, and any departures they lead to from what is described will be treated in the subsection on raw materials.

5.1 Overview of ethanol production

Unger (1941) presented a four-step treatment of the alcohol production process in terms of chemical equations. These mathematical relationships are reproduced here:

$$\text{Starch cell} \xrightarrow{\text{water + heat}} \text{solubilized starch } (C_6H_{10}O_5) \quad (3)$$

$$2(C_6H_{10}O_5) + H_2O \xrightarrow{\text{diastase}} C_{12}H_{22}O_{11} \quad (4)$$

$$C_{12}H_{22}O_{11} + H_2O \xrightarrow{\text{maltase}} 2(C_6H_{12}O_6) \quad (5)$$

$$C_6H_{12}O_6 \xrightarrow{\text{yeast}} 2(C_2H_5OH) + 2CO_2 \quad (6)$$

Equation (3) is a starch preparation phase; equation (4) shows the conversion of starch to sucrose; equation (5) presents the conversion of sucrose to glucose; while equation (6) shows the fermentation reaction -- the conversion of sugar to ethanol and carbon dioxide.

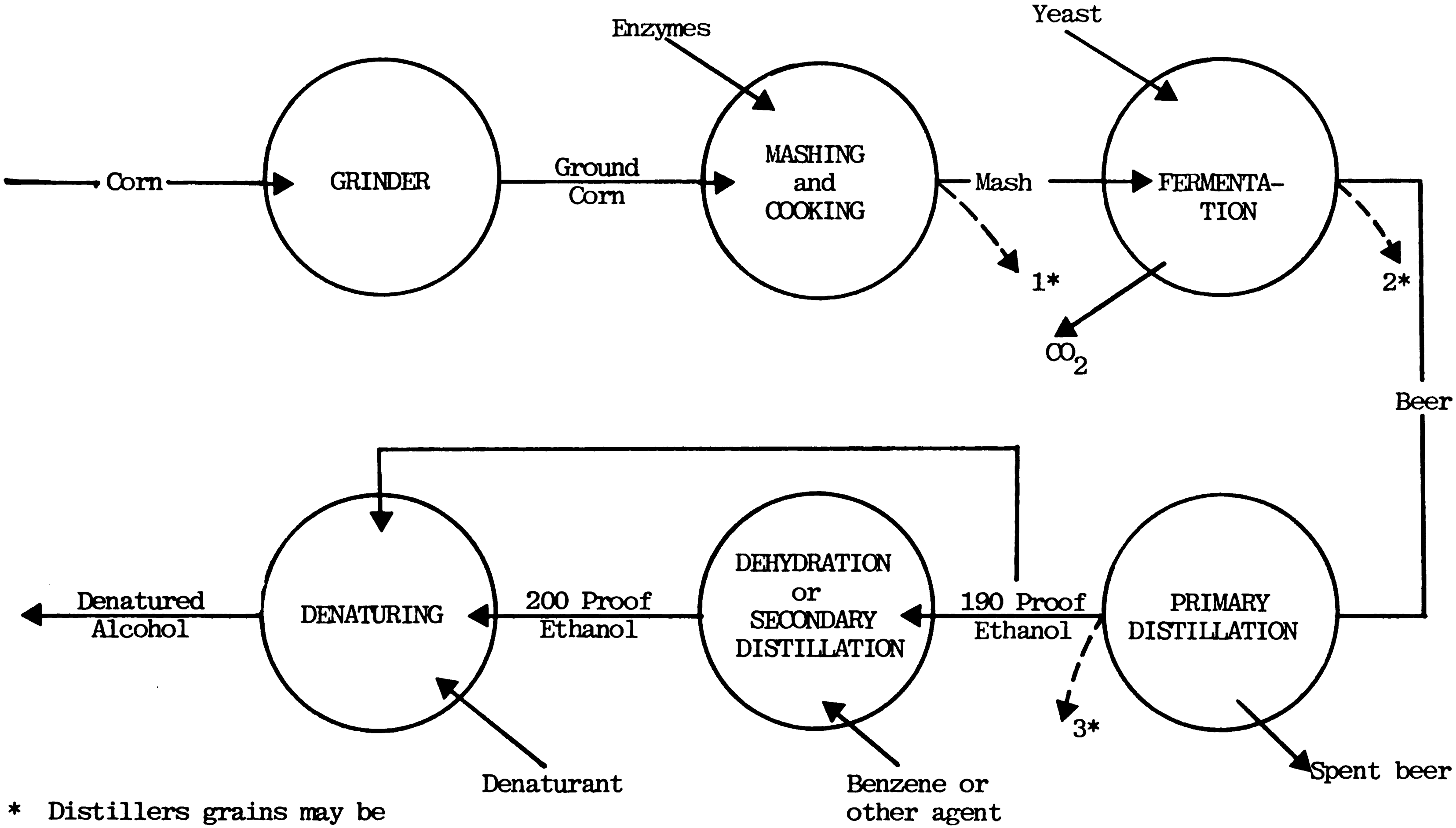
The process of alcohol production from corn feedstock is shown in Figure 5.1. First the grain is ground, mashed and cooked. Enzymes are added during the mashing stage to convert starch to sugar. Yeasts, during fermentation, convert the sugar to alcohol. The process yields a beer (usually 8 to 12% alcohol), carbon dioxide, and heat, since it is an exothermic reaction.

The beer is then distilled to 190 or 191 proof alcohol. A dehydration process will yield essentially 200 proof ethanol if anhydrous alcohol is required. The alcohol, at this stage or the previous stage, is then denatured (made unfit to drink as a beverage) by adding a suitable denaturing agent.

Distillers grains, a major by-product of alcohol production can be extracted at three different points — just before fermentation if saccharification is complete, just before distillation or after distillation. Where this by-product is withdrawn before distillation, the corn grind need only be fine enough to allow effective hydrolysis. However, when the distillers grains are removed after distillation, the corn must be finely ground so the distillation column will not be become plugged.

The three major products of the alcohol process — ethanol, distillers grains and carbon dioxide — are produced in nearly equal quantities, on a weight basis.

Factors affecting alcohol yields the most are grain mash preparation methods, how adequately pH and temperature are monitored and controlled during the process, and the time allowed for and the efficiency and completeness of saccharification.



* Distillers grains may be taken out at 1, 2, or 3.

Figure 5.1 A flow diagram for ethanol production.

The ratio of alcohol yield to available fermentable sugars is 0.5 under optimum methods. This means 1 kg (2.2 lb) of fermentable sugars will yield 0.5 kg (1.1 lb) of ethanol.

5.2 Specific processes

A discussion of the specific processes of ethanol production follows.

5.2.1 Grinding, mashing and cooking

Unger (1941) determined that while grains should be ground well enough to enable proper cooking and saccharification, grinding is not crucial for efficient ethanol production.

Mashing the grains solubilizes the starchy material and prepares the starch content for conversion to sugar. Mashing is a hydrolysis reaction during which enzymes convert starch to sugar.

Cooking the grain helps burst the starch cells, making them more accessible to enzymes. Either batch or continuous cooking will prepare the grain for saccharification to sugars by gelatinizing the starches.

Batch cooking can be done at atmospheric pressure or under imposed pressure. The continuous process usually requires very high temperatures and pressures and the grains are exposed to that atmosphere for only a short time. It was developed by Unger and was the most modern method in 1949 (Prescott and Dunn, 1949). Unger also determined that cooking temperature and duration directly affect production efficiency.

Cooking units are equipped with inlets and outlets for water, grains, and the broth resulting from saccharification. They also need agitators or stirrers since the mash should be stirred continuously during the cooking process to keep the solids in the mash in suspension.

Figure 5.2 presents a mashing and cooking scheme. This scheme was satisfactory in a laboratory situation during a training workshop organized by the National Alcohol Fuels Producers Association at Colby Community College, Colby, Kansas. However, ethanol can be made in several different ways. Figure 5.2 illustrates only one way to produce it. Enzymes used for this scheme were brandnames obtained from Miles Laboratory in Elkhart, Indiana, and are suited to operation at the temperatures shown in the figure. (Enzymes from other manufacturers may require different operation temperatures.) "Taka-Therm" is an alpha-amylase which breaks down the α-D-1,4-glucosidic linkages of starch. Take-Therm converts starch, amylose and amylo-pectin to soluble dextrins and small quantities of glucose and maltose (Miles Laboratory, undated). 'Diazyme" is a liquid gluco-amylase capable of hydrolyzing both the α-D-1,6-glucosidic branchpoints and the premominating α-D-1,4-glucosidic linkages of starch (Miles Laboratory, undated).

5.2.2 Saccharification

Saccharification is the process of converting starch (a polysaccharide) to sugar (a monosaccharide) by enzymatic action. pH is an important factor in the process as is evident from Figure 5.2.

The saccharification process is presented mathematically as:

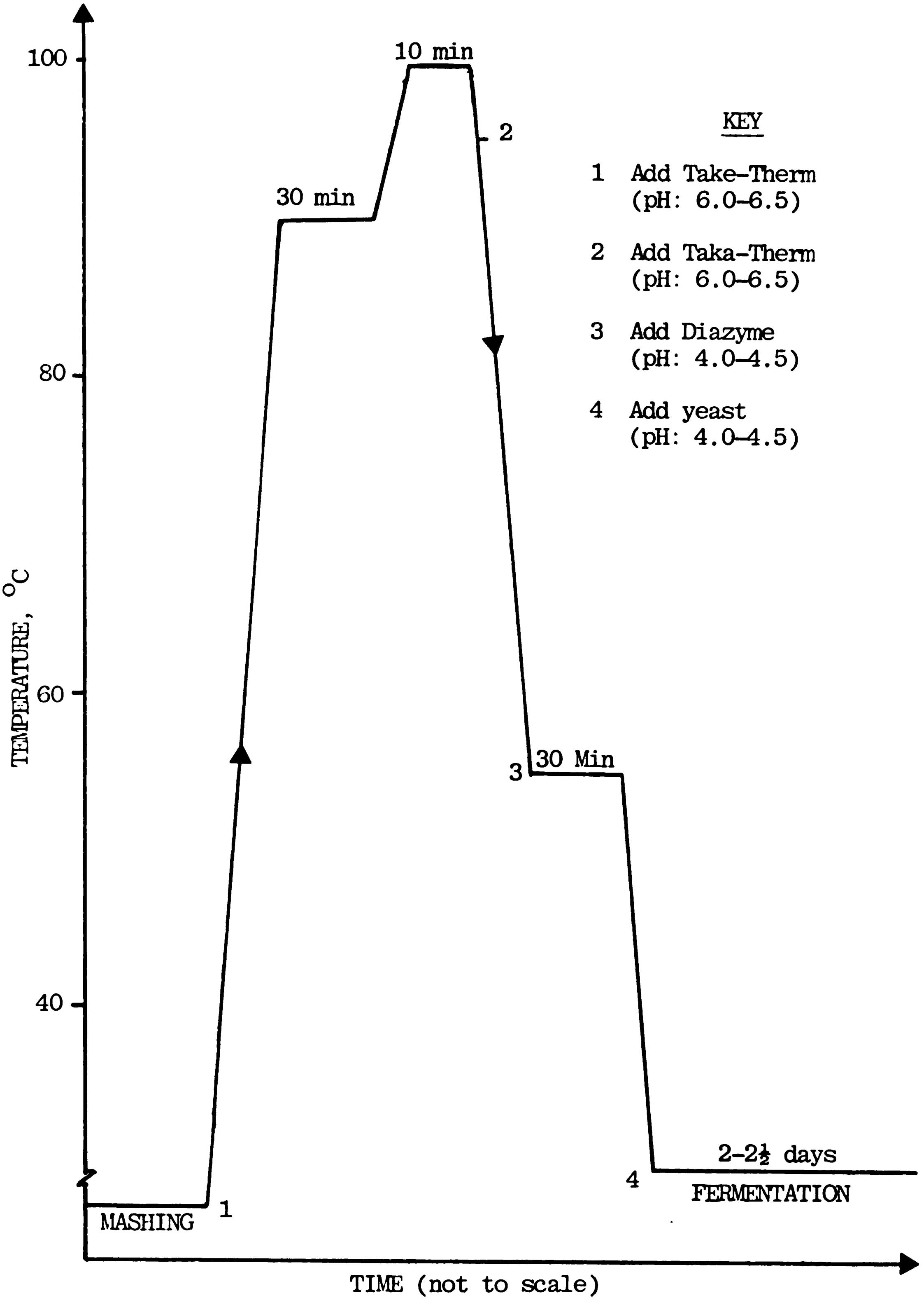


Figure 5.2 A temperature and pH control scheme for cooking corn for ethanol production.

$$n(C_6H_{10}O_5) \ + \ n(H_2O) \ \xrightarrow{\text{enzymes}} \ n(C_6H_{12}O_6). \qquad (7)$$

If the reaction is completed, 180 gm of sugar will be produced from 162 gm of starch and 18 gm of water.

5.2.3 Fermentation

Fermentation is the conversion of sugar (obtained in the raw material, e.g. molasses, or from the saccharification of starch or cellulose) to alcohol and carbon dioxide through the action of yeasts. The process must be monitored and adjusted for pH (4.0 - 4.5), nutrient availability to yeasts, and temperature. The fermentation temperature is typically $26^{o}C$ ($30^{o}F$) to $32^{o}C$ ($90^{o}F$). Although it is an anaerobic process, small amounts of oxygen promote yeast cell growth.

The "beer" produced after fermentation is usually of 8 to 12% alcohol concentration. Most bakers' yeasts currently used in fuel ethanol production will not survive in an alcoholic content of more than 12%. Therefore, if the sugar content of the saccharified mash is such that fermentation will yield beer of greater than 12% alcohol, the mash must be diluted with an adequate amount of water before adding yeast for fermentation. Some wine yeasts will tolerate alcohol concentrations up to 17%.

Fermentation efficiency depends on the process duration, pH, temperature, the completeness of the prior hydrolysis or saccharification process, and the level of yeast activity.

The chemical formula for fermentation is:

$$C_6H_{12}O_6 \xrightarrow{\text{yeast}} 2C_2H_5OH + 2CO_2. \qquad (8)$$

If 92 gm of ethanol and 88 gm of carbon dioxide result from the conversion of 180 gm of glucose, the reaction is complete.

5.2.4 Distillation

Distillation is the separation, by vaporization, of a liquid mixture of miscible and volatile substances into individual or groups of components (Badger and McCabe, 1936; Larian, 1958).

Separation is achieved through repeated vaporization and condensation of the liquid mixture until the desired concentration or composition is attained. In other words, separation depends on the transfer of mass from one homogenous phase to another. A concentration gradient acts as the driving force (McCabe and Smith, 1976). For distillation to occur, the composition of the liquid and vapor phases of the material at a given temperature and pressure should differ (Badger and McCabe, 1936; Larian, 1958). If, under any set of given conditions, they have the same composition, distillation cannot be used to separate the mixture.

5.2.4.1 Distillation methods

Differential or simple distillation: Vapor is withdrawn from contact with the liquid as it is formed, and condensed immediately (Badger and McCabe, 1936; Larian, 1958).

Equilibrium distillation: A definite proportion of the liquid is vaporized. This vapor is kept in intimate contact with the liquid until equilibrium is reached, at which point the vapor is withdrawn and condensed (Badger and McCabe, 1936; Larian, 1958).

Rectification of fractionation: Currently, this process is almost exclusively used for ethanol distillation and, therefore, will be treated in some detail.

According to Badger and McCabe (1936), rectification involves returning part of the condensate to the column, and bringing it into intimate countercurrent contact with vapors going up to the condenser. They describe a fractionating column as a mechanism for bringing vapors (going up) and liquids (coming down) into intimate countercurrent contact. The still, supplied with a heat source, generates the vapors.

Major parts of a distillation column are shown in Figure 5.3. The stripping and absorption sections can be separate columns, or combined (as shown). The stripping section rids the incoming beer of alcohol, while the absorption section extracts water from the vapor and sends it (water) down the column. The absorption section is also called the rectifier. Vapors cool to liquid form in the condenser. Condensed alcohol is stored in the accumulator and can be withdrawn and returned to the top of the tower as a reflux.

The process of rectification or fractionation on an ideal plate is illustrated in Figure 5.4. The figure shows a vapor curve and a liquid curve relating temperature to the composition of a binary mixture at constant pressure. The liquid phase, of composition x_1 must come in contact with the vapor phase of composition y_3 in the same binary. A mass and enthalpy exchange between the two phases leads to

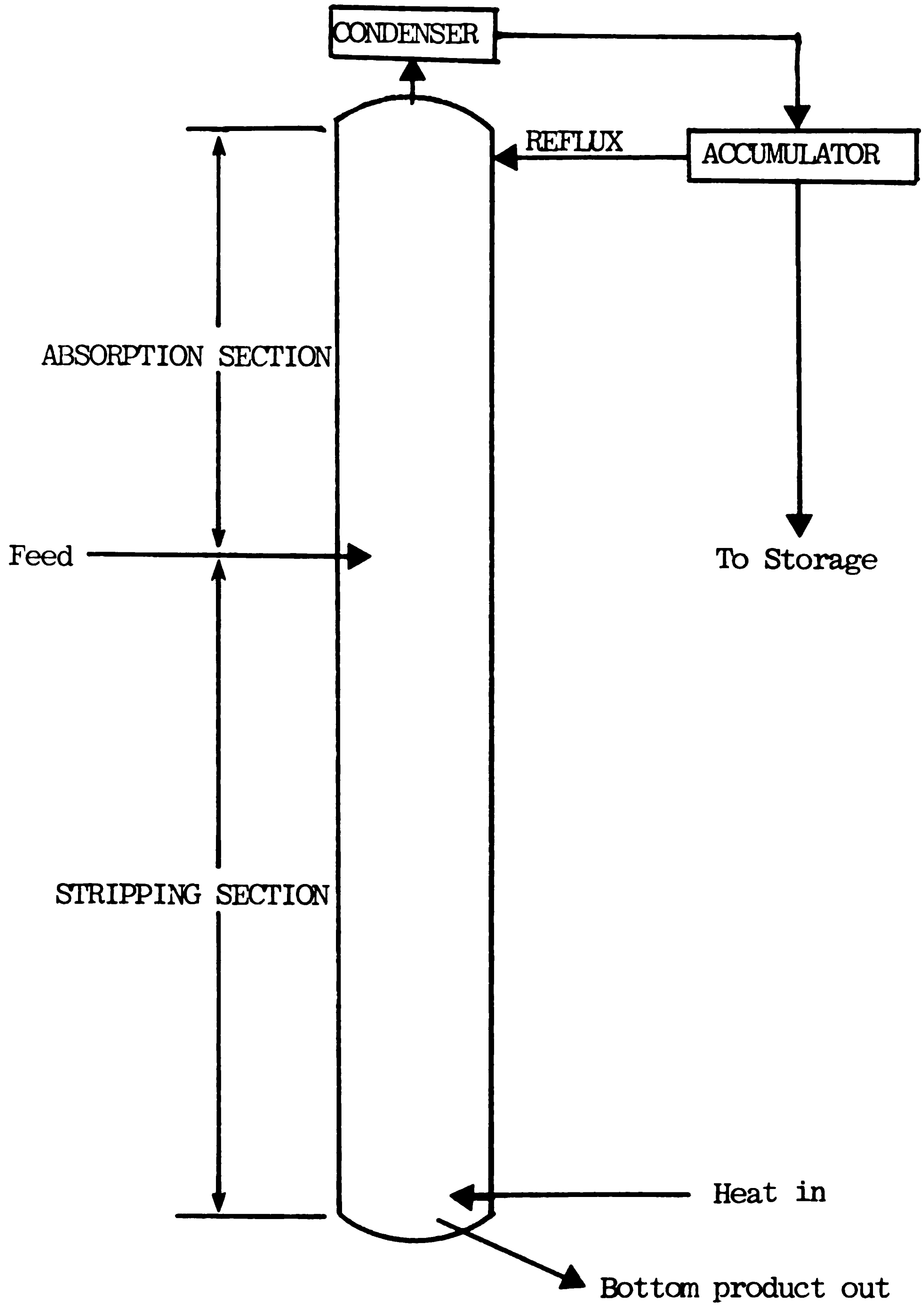


Figure 5.3 A fractionating column with stripping and absorption sections.

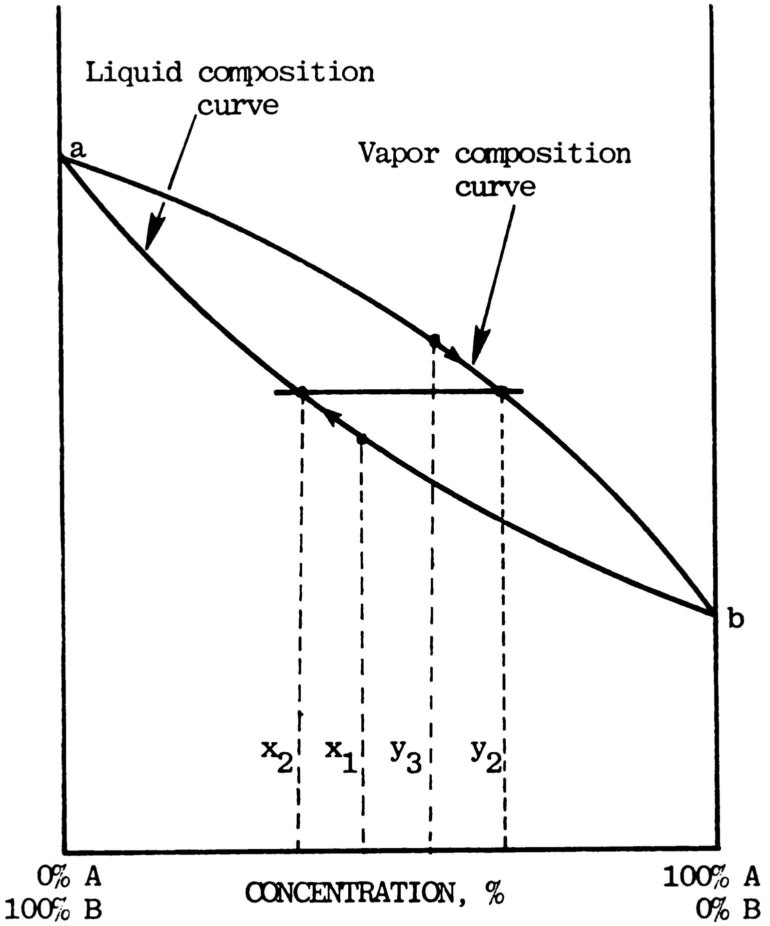


Figure 5.4 A boiling-point diagram showing rectification on an ideal plate.

Adapted from McCabe and Smith (1976).

equilibrium.

Equilibrium is established after the low-boiling component diffuses from the liquid to the vapor phase, and the higher-boiling component diffuses from the vapor to the liquid phase (Larian, 1958; McCabe and Smith, 1976). This process is then repeated; the liquid phase is brought into contact with vapor richer in the lower-boiling component than in the previous vapor phase, until all the components of the mixture have been separated into pure substances.

Each plate constitutes a stage. Once equilibrium is reached after each stage, the vapor becomes richer in alcohol (the lower-boiling component) and the liquid becomes richer in water (the higher-boiling component). At the top of the still, the vapors are collected and condensed to a liquid which may be any composition of ethanol up to 191 proof. Vapor leaves each stage at a lower temperature and the liquid at a higher temperature than when they entered (Larian, 1958).

Pure substances cannot be obtained in the alcohol rectification process, as will be seen later in this section.

A stage or plate provides intimate contact for the vapor and the liquid phases of the binary. A packed column will serve as a multistage contactor if the packed material is of a height equivalent to the number of stages needed to perform the function in a multistage unit (Larian, 1958). The number of perfect stages required can be determined by either the Sorel-Ponchon or the McCabe-Thiele methods; both are adequately described in the literature.

A multistage rectification unit comprises a multistage contact, a total or partial condenser and reboiler, a feed inlet and a product outlet (Figure 5.5).

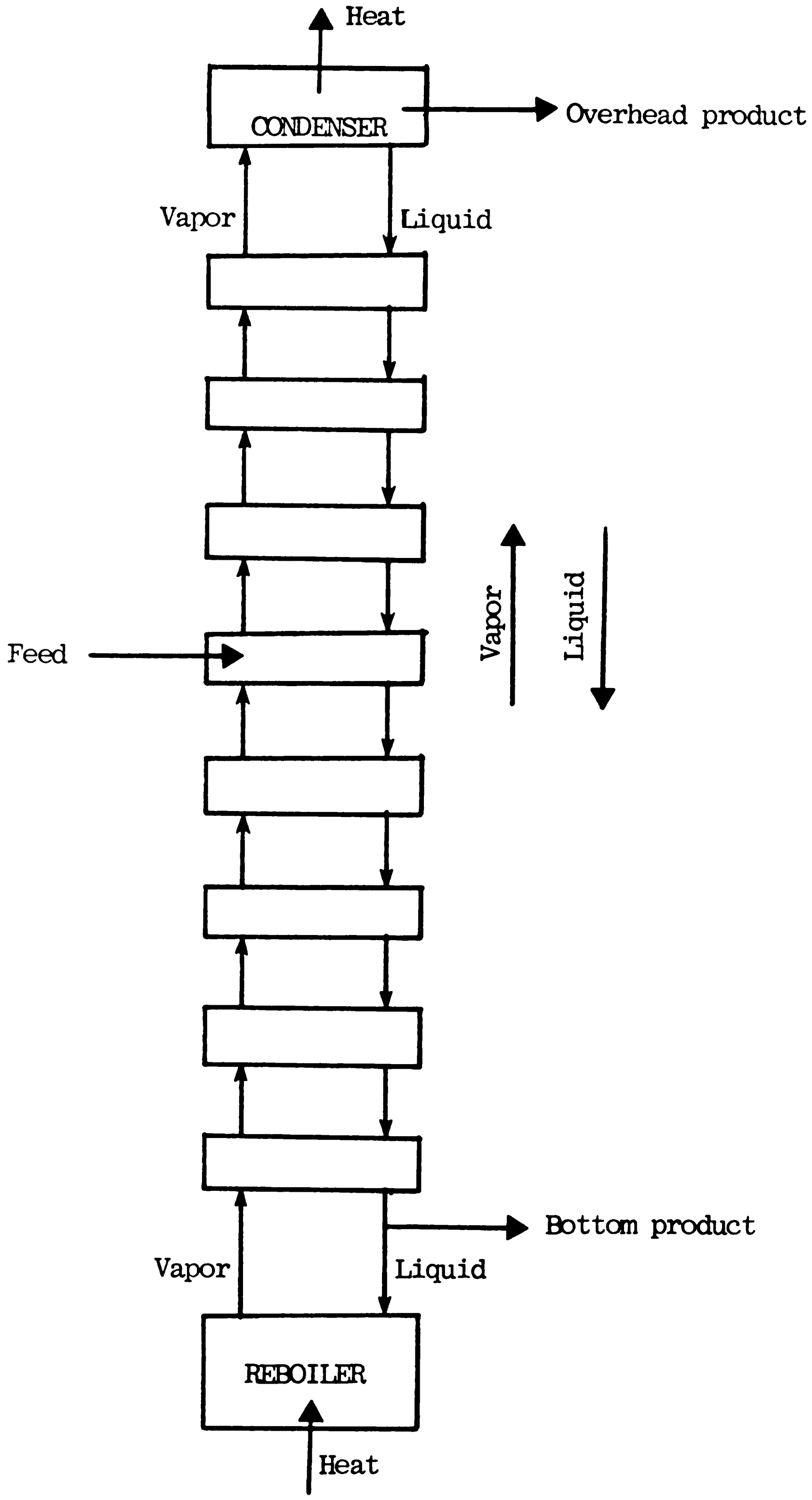


Figure 5.5 Schematic layout of a multistage rectifier. Adapted from Larian (1958).

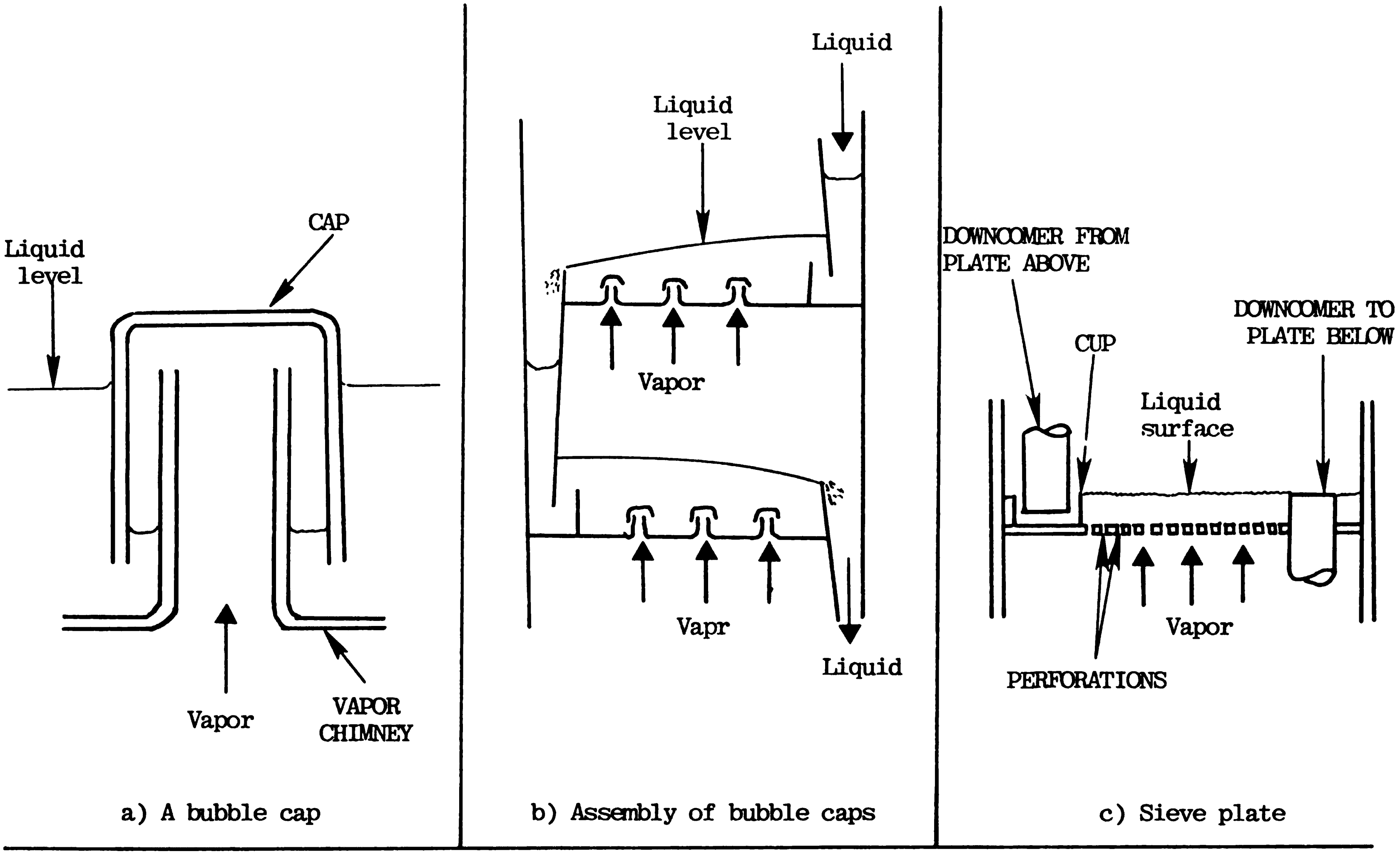
The condenser can be air- or water-cooled; the reboiler is essentially an evaporator and operates on steam. Intimate contact between the vapor and the liquid phases of the binary mixture can be achieved by bubbling vapor through the liquid, or by spraying the liquid into the vapor (Larian, 1958). In most alcohol distillation units, vapor is bubbled through the liquid (see Figure 5.6).

Figure 5.6 c) presents the arrangement of plates in a column. Beer or aqueous alcohol flows down the column through a downcomer, accumulates on the plate and in the cup, and overflows down the next downcomer to the plate below. Vapor, on the other hand, flows up the column through the perforations in the plate and strips the liquid of alcohol. This method forces intimate contact between the vapor and the liquid.

Vacuum distillation: Distillation is possible at lower temperatures under a vacuum. The technique modifies either the relative volatility or the degree of separation involved (Robinson and Gilliland, 1950). Vacuum distillation is significant because pressure, not temperature or molecular weight, most determines the rate of evaporation.

5.2.4.2 Special distillation techniques

At a concentration of 95.6% alcohol and 4.4% water (191.2 proof), alcohol and water form a constant boiling mixture (CBM) or azeotrope no longer separable by distillation at atmospheric pressure. Azeotropes have minimum or maximum boiling temperatures higher or lower than those of the components that comprise the azeotrope. At the azeotrope, the



a) A bubble cap

b) Assembly of bubble caps

c) Sieve plate

Figure 5.6 Bubbling vapor through liquid

Items a) & b) adapted from Larian (1958); c) adapted from McCabe and Smith (1976) liquid and vapor curves touch, sharing a common tangent. The composition of the vapor produced from an azeotrope is the same as that of the liquid (Figure 5.7).

With alcohol, a third component (usually benzene) can be added to the mixture in specific amounts to form a new compound. The components can then be separated under atmospheric pressure.

5.2.4.2.1 Azeotropic distillation

As noted, an azeotrope is a single phase, constant boiling mixture (CBM) that gives off vapor of identical composition.

Azeotropic distillation is done in the presence of a third component having the following properties (Larian, 1958):

a) immiscible or only partially miscible in the lower boiling of the liquids forming the binary system to be separated, but completely miscible in the higher-boiling liquid;

b) does not form a ternary azeotrope with the system; if it does, it must separate into two liquid phases when condensed; and

c) preferably, its boiling point should be lower than the lower-boiling liquid.

Separation of ethanol and water by azeotropic distillation: The ethanol-water azeotrope is typically a composition of 95.6% ethyl alcohol (Figure 5.7). The originator of the azeotropic process for commercial application is Sidney Young (Larian, 1958; Robinson and Gilliland, 1950). At the turn of the century, he observed that the first distillation product obtained at 64.85°C (148.73°F) was a ternary heterogenous azeotrope. At 68.2°C (154.8°F), he obtained a binary

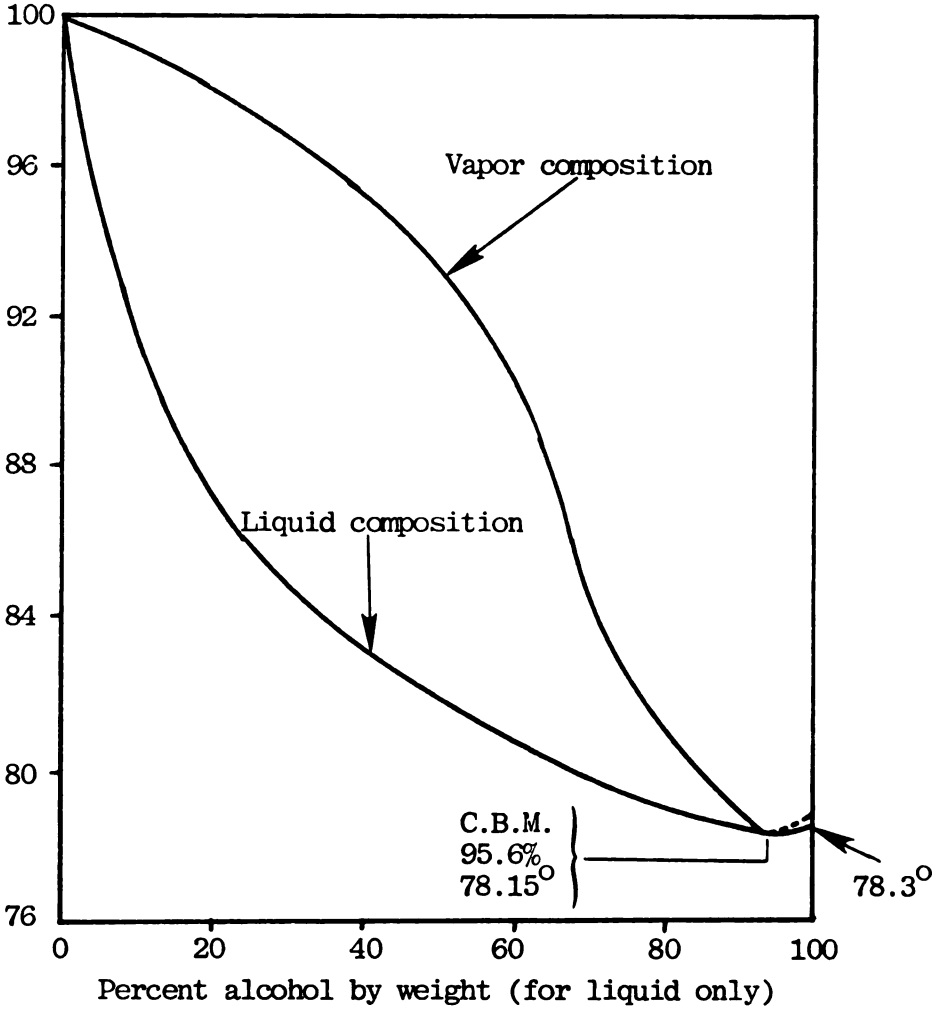


Figure 5.7 Temperature versus composition of vapor and liquid for alcohol-water at 760 mm.

Adapted from Shreve and Brink (1977)

azeotrope of benzene and alcohol. The residue produced at 78.4°C (173.1°F) was alcohol. (All the temperatures were at 1 atm.)

Larian (1958) described two dehydration entraining liquids for use in azeotropic distillation.

a) Ethyl ether: This is partly miscible in water and completely miscible in alcohol. It forms a heterogenous azeotrope with water which boils at 34.2°C (93.6°F) at 1 atm. It neither forms a binary azeotrope with alcohol nor a ternary azeotrope with water and alcohol. Its distillation components are a heterogenous binary azeotrope (boiling point, 34.2°C -- 93.6°F) and absolute alcohol (boiling point, 78.4°C -- 173.1°F). 454 kg (1,000 lb) of ether are distilled for every 0.45 kg (1 lb) of water removed.

b) Benzene: It is completely miscible with alcohol and immiscible with water. It forms a binary heterogenous azeotrope with water, a binary azeotrope with alcohol and a ternary heterogenous azeotrope with alcohol and water. The ternary azeotrope contains 18.5% alcohol, 74.1% benzene and 7.4% water.

A suitable entrainer should be selected based on economics. According to Larian (1958), use of an entrainer of a lower boiling point has a distinct advantage. The larger the temperature spread, the smaller is the number of perfect stages required to perform separation. On the other hand, the lower the boiling point of the entrainer, the greater the amount of entrainer to be used per quantity of water entrained.

5.2.4.2.2 Extractive distillation

Also called liquid-liquid extraction or solvent extration, extractive distillation is a process of separating mixtures of miscible liquids using a solvent as a separating agent (Larian, 1958). It is used where distillation and rectification are difficult or ineffective (McCabe and Smith, 1976). Extraction relies on differences in the solubilities of the components, as opposed to distillation which relies on differences in volatilities; consequently, extraction exploits chemical rather than vapor pressure differences (McCabe and Smith, 1976).

5.2.4.2.3 Alternatives to distillation of ethanol

Separation using adsorption agents, reverse osmosis, and ultrafiltration is currently being studied.

5.3 Raw materials

Ethyl alcohol can be produced from a variety of raw materials, including:

a) sacchariferous materials or raw materials that contain sugar, naturally, e.g. sugarcane or sugar beet;

b) amylaceous or starchy materials, including cereal grains, sweet potatoes and Jerusalem artichokes; and

c) cellulosic materials, e.g. wood.

While sugars can be directly fermented to alcohol, starches, hemicelluloses and cellulose must first undergo saccharification.

Starches can be saccharified using enzymes, but celluloses and hemicelluloses usually require one form or another of acid hydrolysis (see Figure 5.8).

Table 5.1 lists selected materials and their optimum alcohol yields.

Choice of raw material to use should be based on:

a) the yield of alcohol per quantity of material;

b) percent fermentable sugars obtainable and the yield per area of land; and

c) cost of the feedstock.

Generally, the feedstock material does not affect the quality or fuel value of the ethanol produced.

5.3.1 Sacchariferous materials

These materials are directly fermentable and usually have high yields per unit of land area (Nathan, 1978).

Molasses is about 50% sugar (Krochta, 1979) and, generally, no pretreatment energy input is needed before fermentation.

Sugarcane, a perennial grown in Florida, Texas, Louisiana, Hawaii, and Puerto Rico, has high biomass yields (Ernest, et al., 1979). The energy contained in sugarcane grown under favorable conditions is much more than the energy input; thus sugarcane is a real potential energy source (Nathan, 1978).

If sweet sorghum is also grown, the energy potential of sugar crops is 3 quads (Jones, et al., 1979). Without it, contributions from sugar crops will be small. Sweet sorghum is resistant to most

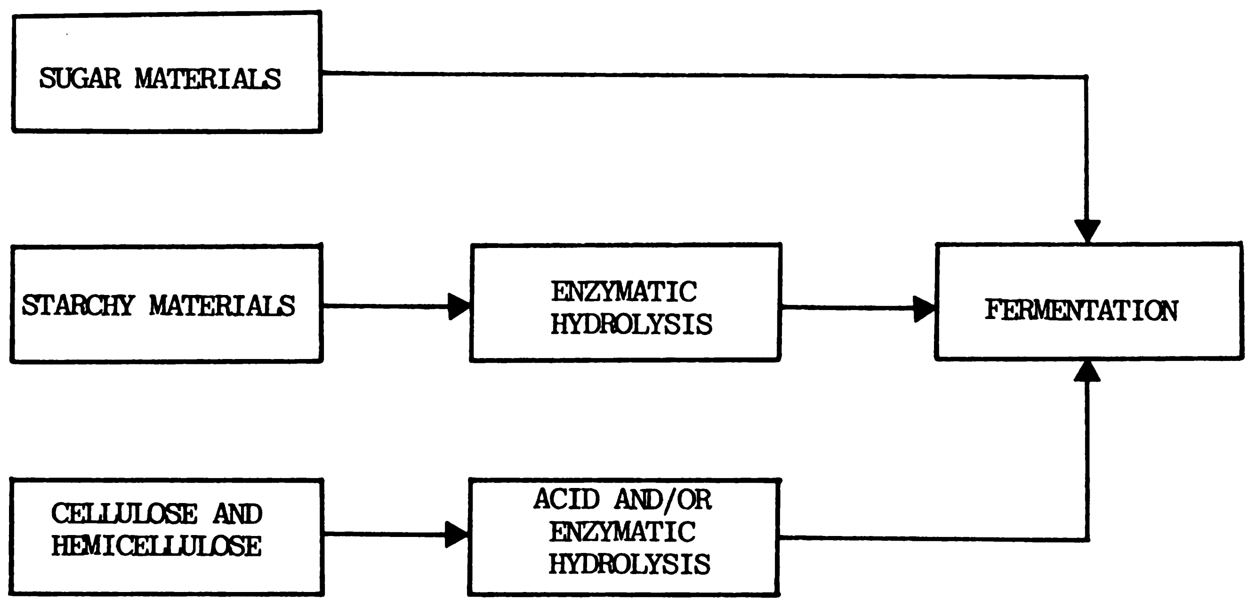


Figure 5.8 Feedstock routes to fermentation

Table 5.1 Yields of selected raw materials

Material	Yield
Barley	7.20 l/bu (1.9 gal/bu)
Corn grain	9.80 l/bu (2.6 gal/bu)
Grain sorghum	9.80 l/bu (2.6 gal/bu)
Jerusalem artichoke	1.90 l/bu (0.5 gal/bu)
Mandioc (cassava)	0.37 l/kg (88.0 gal/ton)
Molasses (beet)	0.40 l/l (0.4 gal/gal)
Molasses (cane)	0.31 l/kg (75.0 gal/ton)
Oats	3.79 l/bu (1.0 gal/bu)
Potato	0.12 l/kg (1.4 gal/cwt)
Rice	0.35 l/kg (85.0 gal/ton)
Rye	8.33 l/bu (2.2 gal/bu)
Sugar beet	0.09 l/kg (22.0 gal/ton)
Sugarcane	0.06 l/kg (15.0 gal/ton)
Wheat	9.80 l/bu (2.6 gal/bu)

diseases and insects, needs little fertilizer and water, and can be harvested with conventional farm machinery (Sklar, 1979).

Sugar beets and sweet sorghum have a wider geographical range than sugarcane (ERDA, 1977).

Fodder beet is a high yielding forage crop obtained by crossing two other beet species — sugar beet and mangolds (Earl and Brown, 1979). It is being experimented with extensively for alcohol production in New Zealand. Earl and Brown (1979) report that root yields are 15 to 20 ODT/ha on dry land and 30 ODT/ha on irrigated land, and that sugar yields of 64 to 70% root dry matter have been recorded. Using the 120 ODT/ha yield figure for their analysis, they showed that sugar production is about 15 ODT/ha or over 9,000 l/ha (963 gal/A). This compares to 4,000 l/ha (428 gal/A) for sugarcane and sugar beet, 2,300 l/ha (246 gal/A) for mandioc (cassava) and eucalyptus, 1,000 l/ha (107 gal/A) for wheat, and 2,300 l/ha (246 gal/A) for corn. The energy potential for fodder beet is obvious.

5.3.2 Amylaceous raw materials

Jones, et al. (1978) define starch as a lower molecular weight branched chain polysaccharide. Starches must be broken down into simple sugars (monosaccharides), e.g. glucose, before fermentation.

Yield of alcohol from grains depends on the starch content of the grain. The theoretical yield is 0.568 kg alcohol per kilogram of starch. Actually, the yield is about 90% of the theoretical value, or 0.51 kg alcohol per kilogram of starch (Klosterman, et al., 1977).

Sprout-damaged grain can be used for alcohol production if the grain does not lose too much starch from weathering or germination. Losses may be as high as 30 to 40% of the starch content (Klosterman, et al., 1977).

Corn starch is difficult to solubilize and so both cooking and conversion are needed. The starch content of rye, wheat, rye malt and barley malt can be solubilized and converted to sugar by infusion. During this process, grain is suspended in water while enzymatic conversion occurs under optimum conditions of temperature, time (duration), and pH (Unger, 1941).

Wheat's high gluten content causes excessive foaming during fermentation (David, et al., 1978). Special processing equipment and techniques are needed to handle it. Wheat contains sufficient beta-amylase (an important saccharification enzyme), but it is deficient in alpha-amylase (Prescott and Dunn, 1949).

5.3.3 Cellulosic raw materials

Principal sources of biomass residues are agricultural crop refuse, logging residues and collectable manure waste. However, sewage, urban wastes, paper pulp and cheese whey can be used to make alcohol. 1 kg (2.2 lb) of crop residues contains 0.8 kg (1.76 lb) of fermentable sugars.

Many species of timber can be used for alcohol production. The eucalyptus tree, with its low water requirement and high energy conversion rate is a good source (Sklar, 1979). In addition to live timber, wood wastes from milling and the pulp and paper industry provide a raw material for alcohol production.

Three factors may reduce the usefulness of crop residue as energy sources (Cervinka and Mason, 1979):

a) cost and energy needed for collection, transportation and handling;

b) their availability depends on the demand for crops; and

c) they have a seasonal availability.

Jones, et al. (1979) estimate that corn stover is potentially available in large quantities.

5.4 Scales of production

Generally, a facility that manufactures less than 3.79×10^6 l (1.00×10^6 gal) of ethanol per year is considered small scale. Large-scale operations produce at least 11.4×10^6 l (3.0×10^6 gal) annually.

5.5 By-products

Apart from carbon dioxide and distillers grains, fusel oil forms from 0.1 to 1.7% of the crude distilled spirit, and is mostly a mixture of amyl and isoamyl alcohols (Prescott and Dunn, 1949). It can be separated, and in whisky manufacture, usually is. Corn oil, another possible by-product, can be separated by wet-milling. Corn gluten, corn germ and fodder yeast can also be separated as by-products, but in most operations, this is not done. For operations less than 5,000 l (1,300 gal) of fermentation alcohol per day, carbon dioxide recovery is generally not feasible (Silver Engineering Co., undated).

Distillers feeds: These result from the fermentation residue. The reduced bulk resulting from starch removal (corn is about two-thirds starch) causes a three-fold increase in nutrient concentration (no nutrients are used up during fermentation).

The Distillers Feeds Research Council (DFRC) describes four feeds available for dairy supplement formulation. These result from the whole stillage -- the bottom product of the distillation process. On the average, whole stillage is 6% solids.

1) Distillers dried grains with solubles (DDGS): This fermentation residue results from processing and drying the whole dealcoholized stillage.

2) Distillers dried grains (DDG): These are the coarse fibrous materials separated by screen or centrifuge from the stillage, and dried.

3) Condensed distillers solubles (CDS): This is the liquid residue from screens and centrifuge condensed to 25-40% solid content. The liquid residue contains finely suspended material and water soluble nutrients.

4) Distillers dried solubles (DDS): This is obtained by drying condensed distillers solubles on drum driers.

Table 5.2 gives the nutrient levels of three distillers feeds obtained from corn fermentation to ethanol. In addition to the known nutrients, distillers feeds also possess cellulose digestion factors, urea-protein factors and some unknown growth stimulants (DFRC, undated). Distillers feeds also contain Grain Fermentation Factors (GFF). While these chemicals have not been identified, they are known to promote growth and other desirable qualities in livestock, especially in swine

Table 5.2 Typical composition of distillers feeds, from corn

	DDGS[1]	DDG[2]	DDS[3]
Moisture, %	9.0	7.5	4.5
Protein, %	27.0	27.0	28.5
Fat, %	8.0	7.6	9.0
Fiber, %	8.5	12.8	4.0
Ash, %	4.5	2.0	7.0
Nitrogen-free extract, %	43.0	43.1	47.0
Calcium, %	0.35	0.05	0.3
Phosphorus, %	0.95	0.37	1.6
Selenium, ppm	0.3	0.3	0.4
Choline chloride, gm/kg	3.4	1.0	5.8

Source: Distillers Feeds Research Council (undated)

1. Distillers dried grains with solubles
2. Distillers dried grains
3. Distillers dried solubles

and poultry (DFRC, undated).

Poos and Klopfenstein (1979) recommend separating solubles from grains, feeding the solubles to poultry and swine or using it as a liquid supplement, and feeding the grains to cattle.

Klopfenstein, et al. (undated) consider distillers dried grains (DDG) a source of naturally protected ruminant protein. This quality allows more protein to reach the lower digestive tract of the ruminant than does soybean meal protein, since the latter is more rapidly degraded. When DDG was fed in combination with urea, it was 50% more efficiently utilized by calves than was soybean meal.

5.6 Denaturing

Denaturing is the process of making alcohol unfit to drink as a beverage. The Bureau of Alcohol, Tobacco and Firearms (BATF) has a number of formulations that can be used to denature alcohol.

6.0 ENERGY ANALYSIS

6.1 Introduction

Some economists have reacted strongly against net energy analysis. This reaction appears to stem from a fear that energy is about to become the numeraire or measuring stick by which goods and services are evaluated -- a position traditionally occupied by money. Huettner (1977), for example, describes net energy analysis as an "energy theory of value" and postulates that non-energy inputs are not factors unless they change the energy content of the inputs. He reasons that society should rank alternatives on the basis of economic value rather than energy content.

Slesser (1973) points out that while it is not obvious globally, energy is the only commodity in ultimate limitation on a long term scale, and thus, energy analysis is needed to measure the cost of doing something in terms of this limited commodity. While Huettner (1976) disagrees with the ultimate limitation theory, Clark (1974) asserts that new energy requires energy to produce it.

An energy analysis is better equipped to forecast energy trends than an economic analysis. As an example, Slesser (1977) reported a 1972 National Petroleum Council conclusion that mining oil shale would be economically viable when the price of crude oil reached $6.00 per barrel. Crude oil currently sells for over $20.00 a barrel, but oil shale is not yet considered an economic alternative. Slesser (1977) makes a strong case for energy analysis, stating that given the framework of a data base, knowledge of technology and the dictates of Thermodynamics, it is much easier to forecast the future energy cost to manufacture an item than its economic cost.

The Colorado Energy Research Institute (1976) sums it up: "Normal economic decisions do not adequately identify hidden energy costs or resource depletion factors which are not measured in a system of monetary transactions." Gilliland (1975) notes that energy estimates will remain constant with changing dollar values, unless technological changes occur in process efficiencies.

In this study, energy analysis will be used as a tool to identify the efficiency of energy use in alcohol production and to devise ways and means of improving the input-output energy ration.

Slesser (undated) identifies three forms of energy analysis:

1. total aggregation;
2. input-output analysis; and
3. process analysis.

The third option, together with a control volume approach and net energy analysis criteria, will be used in this study.

6.2 Principles of Thermodynamics

Thermodynamics deals with the transformation of energy from one form to another.

A convenient thermodynamic system is a fixed collection of mass particles. The system may be open or closed. In a closed system, no mass crosses the boundary. An open system reacts with its environment and allows mass transfer across its boundaries. The open system may also be referred to as a control volume.

The laws of Thermodynamics are primitive, i.e., they cannot be derived in terms of more basic relationships. They are totally empirical.

The statement of the First Law of Thermodynamics by Smith and Van Ness (1975) is: although energy assumes many forms, the total quantity of energy is constant, and when energy disappears in one form, it appears simultaneously in other forms. Jones and Hawkins (1960) present this law as follows:

$$E_N + E_{M1} - E_{M2} = \Delta E \tag{9}$$

where E_N = net amount of energy added to the system as heat and all forms of work

E_{M1} = stored energy of mass entering the system

E_{M2} = stored energy of mass leaving the system

and ΔE = net increase in stored energy of the system

Perry and Chilton (1973) state the Second Law of Thermodynamics as: the entropy of any system and its surroundings, considered together, resulting from any real process is positive and approaches a limiting value of zero for any process that approaches reversibility. Entropy is a measure of the increase in the inability to do work or the unavailability of energy in a thermodynamic system. It can also be interpreted as a measure of the increase in disorder. Another way to state the Second Law of Thermodynamics is that all reversible processes lead to an increase in total entropy.

A thermodynamic analysis of a process allows for the determination of the energy efficiency of a real process. It enables one to estimate the minimum or ideal energy requirement for energy transformation to take place. It then becomes possible to identify the energy penalty of the process. The energy penalty is defined as the difference between the ideal requirement and the actual energy consumption of the given process. Slesser (1973) identifies this energy penalty as "energy subsidy" or "waste".

6.3 Boundaries of analysis

Introduction: Kirchner (1979) raised several issues pertinent to energy analysis:

1) What is the extent of the boundary?

2) Should excess feedstocks be used or should feedstocks be grown for fuel?

3) Should production energy come from coal, oil, biomass or natural gas?

4) Does the energy content of the feedstock have any meaning if our objective is to obtain liquid fuels?

These are critical questions and will be addressed in the next section.

6.3.1 Base data and assumptions

Drawing a boundary around a system has been the most controversial part of energy analysis. For this analysis, the following assumptions are used to help define the most appropriate boundary.

1) Corn is used as feedstock.

2) The feedstock is grown specifically to make ethanol and produce distillers grains for ruminant feed.

3) The distillers grains will be the only valuable by-product and, therefore, no commercial use will be made of the carbon dioxide resulting from fermentation.

4) The analysis considers farm energy inputs and, following net energy analysis criteria, the energy inputs into farm machinery and equipment.

5) Farm machinery or equipment have a 10-yr life span.

6) Transportation energy off-farm and total energy use at the alcohol plant are considered.

7) It is a commercial process producing not less than 3.785×10^6 l (1.00×10^6 gal) of ethanol per year.

The above assumptions and pointers lead to the boundary shown in Figure 6.1. Figure 6.2 shows an expanded form of the same boundary with the input-output items identified.

Except for electricity, no fuel is identified as the production energy source. Electricity is assumed to have resulted from a primary fuel at an efficiency of 33%. Energy inputs necessary to effect transformations at the alcohol plant are assigned thermal values so all input energy can be reduced to a common unit. From the analysis, the amount of fuel necessary for the desired transformations can be calculated, if the thermal efficiency of the conversion unit is known.

This analysis ignores the energy content of the feedstock (its heat of combustion) for three reasons. First, the energy content of

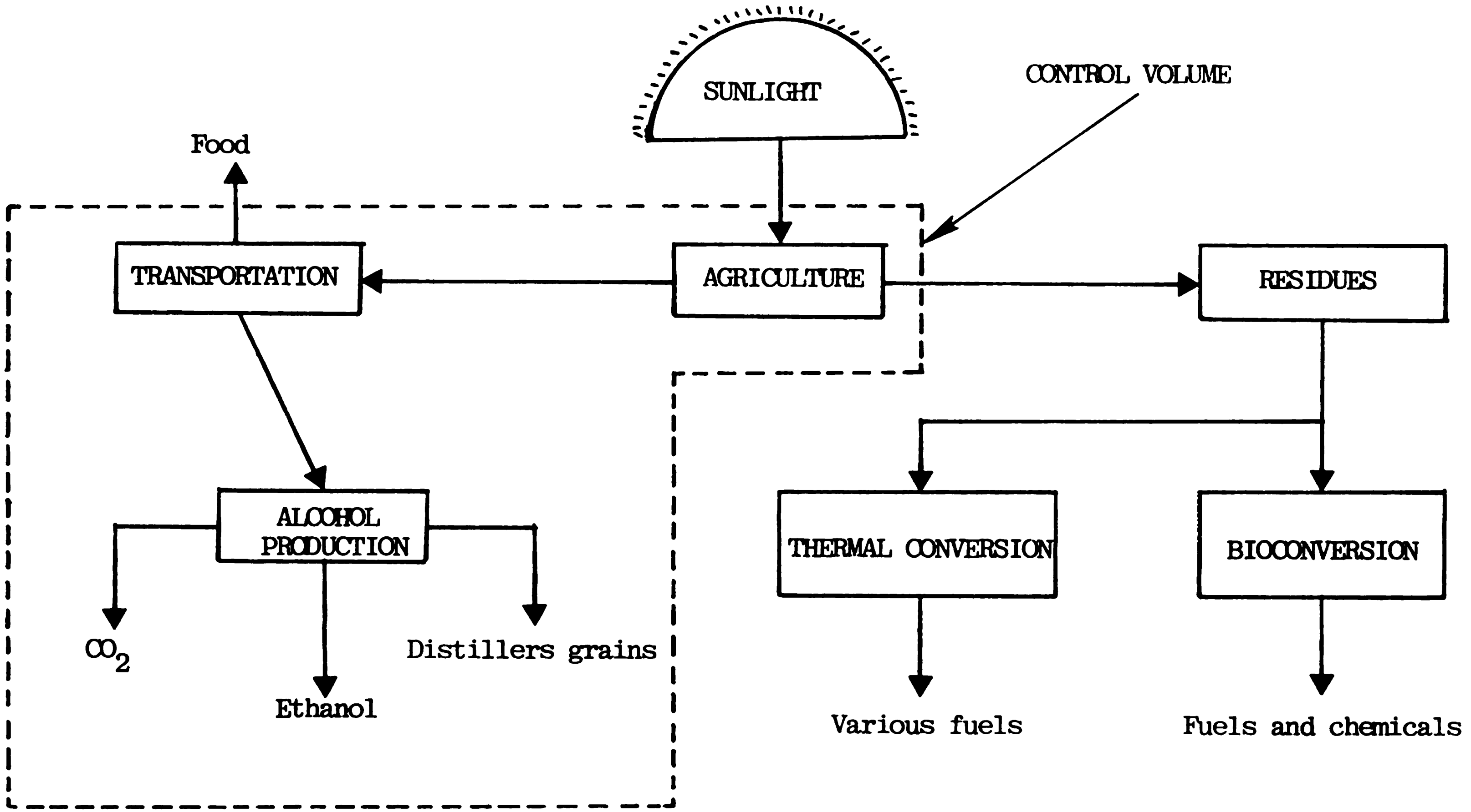


Figure 6.1 Boundary of analysis

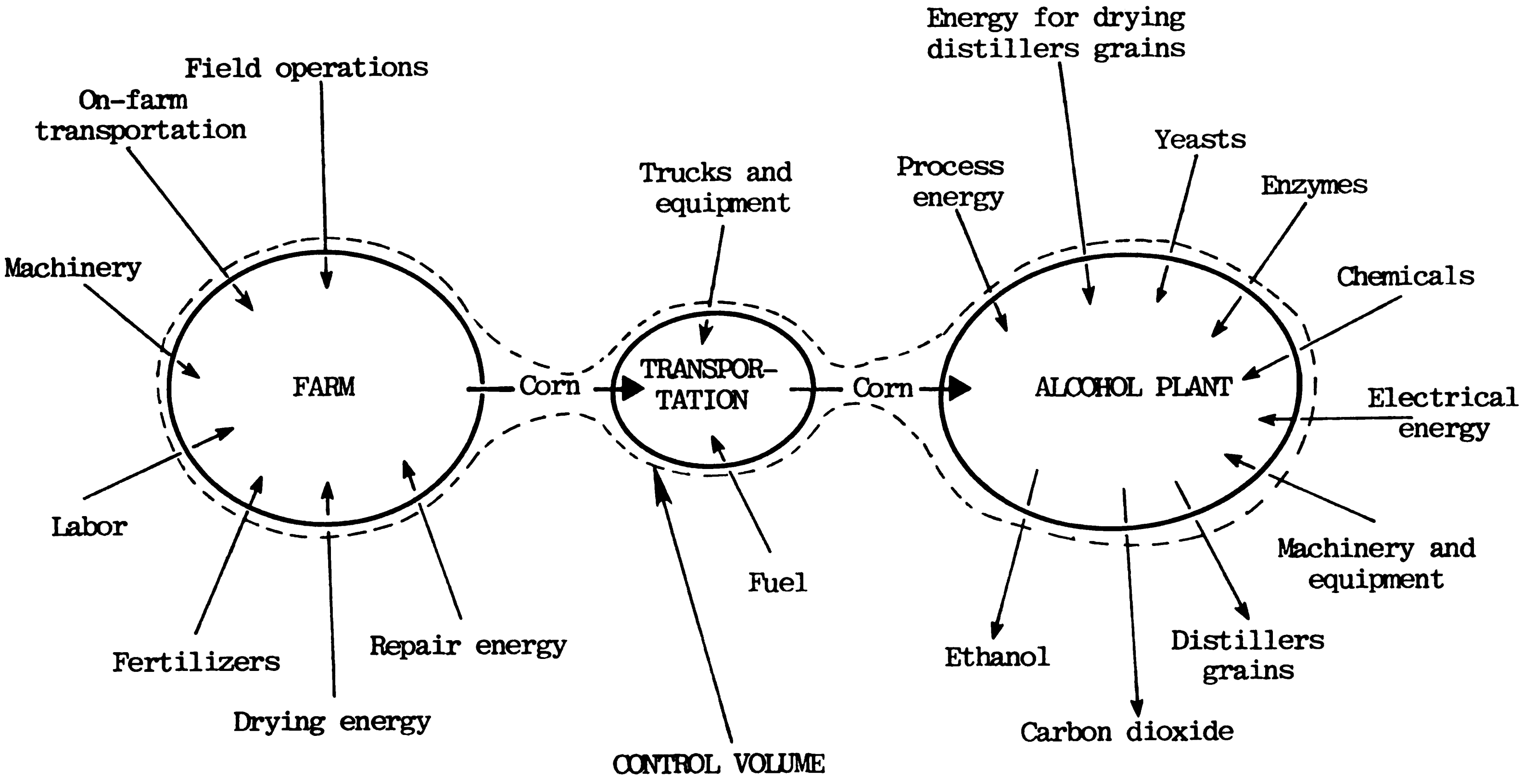


Figure 6.2 Boundary of analysis showing component items

corn does not derive solely from agricultural energy input (or cultural energy input, as it is also called), but mostly from solar energy which, in this analysis, is considered a free source of energy. Agricultural energy here is defined as all forms of energy other than solar insolation. Second, since corn does not cross the boundary of analysis, it does not directly contribute to the external energy changes of the system. It only does this indirectly through the primary and secondary products of the system. Third, corn is not normally combusted in order for its energy to be extracted.

The standard used for this analysis is that 9.46 l (2.50 gal) of ethanol result from processing 1 bu of corn weighing 25.5 kg (56.0 lb). Table 6.1 tabulates the ethanol properties used in this analysis.

6.3.2 Input-output evaluation

a) Farm input: Energy values are assigned to field operations, on-farm transportation, machinery, repairs, labor, nutrients and for drying the crop. It is assumed that whatever biomass is produced on the farm (except for corn kernels) remains on the farm and does not cross the boundary.

b) Off-farm transportation: Fuel and machinery are assigned energy values.

c) Alcohol plant input: Energy evaluations are made on process heat, yeasts, enzymes, chemicals (acids and alkalines), mechanical energy (usually electricity), machinery and equipment, ethanol and distillers grains. Even though carbon dioxide crosses the boundary of analysis, it is not assigned an energy value.

Table 6.1 Properties of ethanol

Chemical formula	C_2H_5OH
Molecular weight	46.1
Density[1]	0.793 kg/l (6.61 lb/gal)
Specific gravity, (15.6°C/15.6°C)[1]	0.794
Heat of combustion[2]	5,630 Kcal/l (84,600 Btu/gal)
Freezing point[2]	-114.6°C (-174.2°F)
Boiling point[2]	78.3°C (172.9°F)
Flash point[1]	12.8°C (55.0°F)
Stoichiometric air to fuel ratio[1]	9.0
Latent heat of vaporization[2]	220 Kcal/kg (364 Btu/lb)
Octane rating[3]	99

1. API (1976)
2. Bolz and Tuve (1976)
3. Baumeister, et al. (1978)

d) The total system: Ecological energy (associated with weather, sites, etc.) is ignored because it is negligible compared to industrial energy and difficult to quantify. Air and water inputs are assumed to have no heat of combustion and so are excluded. Internally-generated energies are minimal, except for the energy content of the feedstock, which is excluded for reasons noted earlier.

6.4 Methodology

6.4.1 Net energy analysis

The Colorado Energy Research Institute (1976) defines net energy as the energy made available to society by energy production processes after deducting energy lost to society as a result of these processes. Several variables are defined for net energy analysis.

On the input side, principal energy is the fuel or feedstock to be processed or transported (in this analysis, corn). External energy is that energy required from outside to operate the process and to make the materials needed to build the process.

On the output side, energy product refers to the processed or transported energy (ethanol and distillers grains, in this analysis); while the energy loss is the energy unavailable for further use as a result of the process.

6.4.2 Development of the governing control volume equation

The conservation laws of mass, momentum and energy can be applied to a specified mass or system of particles in a region which may or may not be moving in space. This region is referred to as the control volume and its boundary the control surface. In applying the conservation laws to a control volume, two basic approaches can be used. The Lagrangian approach focusses attention on a group of particles, identifies them at some point in time and follows these particles as they travel through space. The Eulerian approach focusses on a specific region in space and observes particles flowing through that space. In either case, the control volume may or may not be moving.

Potter and Foss (1975) state the following integral equation as it applies to the control volume used to analyze conservation laws:

$$\frac{DN_{sys}}{Dt} = \frac{d}{dt} \int_{cv} (\eta\rho)\, dV + \int_{cs} \eta\rho V_r \cdot \hat{n}\, dA \qquad (10)$$

$$\frac{d}{dt} \int_{cv} (\eta\rho)\, dV = \int_{cv} \frac{\partial}{\partial t} (\eta\rho)\, dV + \int_{cs} \eta\rho V_b \cdot \hat{n}\, dA \qquad (11)$$

where N = the extensive property of the system
η = the intensive property of the system
ρ = the material density
V_r = relative velocity of the system at the boundary
V_b = the velocity of the boundary at the control surface
dA = an elemental area
dV = an elemental volume.

Equation (10) is a statement of the Reynolds Transport Theorem.

Potter and Foss (1975) identify D/Dt as a substantial, material or total derivative. D/Dt can be represented as:

$$\frac{D}{Dt} = u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} + \frac{\partial}{\partial t}. \qquad (12)$$

The left side of equation (12) is a Langrangian concept; the right side is an Eulerian notion.

The general integral equation can be applied to alcohol production analysis. When the First Law of Thermodynamics is applied to an open system such as that shown in Figure 6.2, the resulting equation is (Potter and Foss):

$$\dot{Q} - \dot{W} = \frac{D}{Dt}\int_{sys} \eta\rho dV. \qquad (13)$$

For simplification, $\dot{Q}$ is defined as the time rate of the sum of the calorific energy inputs of the process (see Figure 6.2). $\dot{W}$ is the time rate of the work the system can do on its environment, and will relate all output quantities.

In terms of energy conservation, η, the intensive property, is further defined as:

$$\eta = \frac{V_i^2}{2} + gz + u \qquad (14)$$

where η = specific energy, or energy per unit mass
V_i = the velocity of the system referred to an inertial reference frame
g = the gravitational acceleration
z = height referred to a fixed datum
and u = internal energy per unit mass of the system.

V_i is zero for the system considered here, since the control volume is fixed; also, height variations are negligible and so z = 0. After expanding the right side of equation (13), the Reynolds Transport Theorem becomes:

$$\dot{Q} - \dot{W} = \frac{d}{dt} \int_{cv} (u\rho)\, dV + \int_{cs} u\rho\, V_r \cdot \hat{n}\, dA \qquad (15)$$

V_r is the velocity of material flows in the system. It is negligible for this process.

After making the necessary substitutions and integrating equation (15), the resulting equation is:

$$Q - W = \Delta U \qquad (16)$$

Equation (16) is used in this study to evaluate alcohol production. From the definitions following equation (13), a negative ΔU will indicate that the process has a positive net energy balance, while a positive ΔU will indicate that the process consumes more energy than is contained in its products.

6.4.3 Methodology used in this study

Net energy analysis is applied to the control volume of Figure 6.2. On the farm, all direct and indirect energy inputs are analyzed. Direct energy inputs include field operations (including tillage and seeding, herbicide and insecticide application, irrigation and harvesting), on-farm transportation, labor and repair energy. Indirect energy items are the energy cost of producing agricultural machinery and equipment and fertilizers.

Off-farm transportation energy is a combination of energy input into equipment, and the fuel consumption during transportation of feedstocks.

All energy inputs and outputs at the processing plant are evaluated.

6.5 Energy accounting

6.5.1 Farm energy input

Introduction: The data used here on field operations, on-farm transportation, fertilizers and on-farm drying are obtained from the Council of Agricultural Science and Technology (CAST) report of 1977 on energy use in agriculture. These data are for irrigated corn. Data for dry land corn are obtained from Myers, *et al*. (1979). Pimentel, *et al*. (1974) provided the basis for estimating farm labor energy consumption, while information from Doering III, *et al*. (1977) is used to calculate the energy used to manufacture agricultural machinery and equipment, and the energy required to repair them.

The CAST (1977) model is for conventional tillage and a production level of 296 bu/ha (120 bu/A). The data from Doering III, *et al*. (1977) are based on the machinery being used on 121 ha (300 A) of corn per year, for 10 years, at which time their value added is zero.

The actual figures used here are the result of recalculations.

6.5.1.1 Field operations

Energy consumption in field operations is equivalent to 1,100 Kcal/l (16,500 Btu/gal). Field operations include tillage and seeding, herbicide and insecticide application, irrigation and harvesting.

6.5.1.2 On-farm transportation

An on-farm transportation energy consumption of 251,000 Kcal/ha (403,000 Btu/A) converts into 90 Kcal/l (1,400 Btu/gal) of ethanol at a production level of 296 bu/ha (120 bu/A).

6.5.1.3 Fertilizers

The energy consumed in fertilizer production, transportation and application in amounts sufficient to support a corn crop of 296 bu/ha (120 bu/A) translates into 880 Kcal/l (13,200 Btu/gal) of ethanol.

6.5.1.4 Crop drying

CAST (1977) reports drying energy as 1.15 x 10^6 Kcal/ha (1.85 x 10^6 Btu/A) of corn. In terms of alcohol production, this amounts to 410 Kcal/l (6,200 Btu/gal).

6.5.1.5 Labor

Using Pimentel, et al. (1974) as a guide, it is estimated that a farm laborer consumes 550 Kcal/hr (2,180 Btu/hr) and that 22 hr/ha (9 hr/A) of human labor is required for corn production. These figures result in an energy input of 4 Kcal/l (60 Btu/gal) of ethanol, negligible compared to other farm inputs.

6.5.1.6 Machinery

Doering III, et al. (1977) estimate the energy required to produce farm machinery to be 77.3 x 10^6 Kcal (306.8 x 10^6 Btu) to farm 121 ha/yr (300 A/yr) for 10 seasons. On a seasonal basis, the energy input is 63,400 Kcal/ha (102,000 Btu/A) or about 20 Kcal/l (300 Btu/gal) of ethanol.

6.5.1.7 Repair energy

Similarly, repairs require 25.3 x 10^6 Kcal (10.0 x 10^7 Btu) of energy. This is equivalent to 7 Kcal/l (100 Btu/gal) of ethanol, and is negligible.

6.5.1.8 Total farm energy input for irrigated corn

Table 6.2 summarizes the total farm energy input for irrigated corn.

Table 6.2 Farm energy input for irrigated corn

		Kcal/l (Btu/gal)
Field operations:[1]		
Tillage and seeding	120 (1,800)	
Herbicide and insecticide	30 (450)	
Irrigation	920 (13,800)	
Harvesting	30 (450)	
		1,100 (16,500)
On-farm transportation[1]		90 (1,400)
Fertilizer		
Nitrogen (N)	780 (11,700)	
Phosphorus (P)	70 (1,050)	
Potassium (K)	30 (450)	
		880 (13,200)
Crop drying[1]		410 (6,200)
Labor[2]		negligible
Machinery[3]		20 (300)
Repair energy[3]		negligible
TOTAL		2,500 (37,600)[4]

1. Based on CAST (1977)
2. Based on Pimentel, *et al*. (1974)
3. Based on Doering, III, *et al*. (1977)
4. Total energy input for non-irrigated corn is 1,980 Kcal/l (29,700 Btu/gal).

6.5.1.9 Energy input for dry land corn

Myers, et al. (1979) arrived at a total (direct and indirect) energy consumption of 4.54×10^6 Kcal/ha (7.29×10^6 Btu/A) from an audit of the actual energy use on 11 Michigan corn producing farms. Only two of these farms irrigated corn. The data are used here to represent energy input into corn grown under little or no irrigation. The average yield was 242 bu/ha (98 bu/A). The Myers, et al. (1979) energy use total translates into 1,980 Kcal/l (29,700 Btu/gal) of ethanol.

6.5.2 Off-farm transportation energy input

Off-farm transportation energy is estimated at 270 Kcal/l (4,100 Btu/gal) of ethanol. It is likely that no more than 10% of this total is indirect energy (energy required to manufacture the vehicle and tires, and energy needed for repairs). Therefore, 243 Kcal/l (3,650 Btu/gal) of ethanol can be charged to direct fuel consumption during transportation of the feedstock. Assuming 1,200 bu of corn feedstock can be transported at a time, a truck with a fuel efficiency of 2.6 km/l (5.9 mi/gal) would transport the feedstock 770 km (478 mi) to a processing plant.

6.5.3 Plant process energy input

The most thorough plant process energy data to date are from Raphael Katzen Associates (1979). With some recalculations, process energy inputs are based on the results of their engineering study.

Electrical energy required is 300 Kcal/l (4,500 Btu/gal) of ethanol. Assuming an electrical generation efficiency of 33%, this amounts to a primary fuel energy of 900 Kcal/l (13,500 Btu/gal). The mashing, cooking and saccharification process requires 800 Kcal/l (12,000 Btu/gal), while distillation takes 1,500 Kcal/l (22,500 Btu/gal). It takes 150 Kcal/l (2,300 Btu/gal) more to recover the distillers grains by-product.

Thus, the total plant energy use, excluding drying of distillers grains, is 3,410 Kcal/l (51,700 Btu/gal) of ethanol.

6.5.3.1 Drying of distillers grains

Based on information from Bohler Bros. of America, Inc. (Vogelbusch), the energy required to dry the distillers grains is calculated as 1,200 Kcal/l (18,000 Btu/gal).

6.5.3.2 Other plant inputs

Yeasts, enzymes, and chemicals to control pH are used in relatively small quantities. Diazyme is used at the rate of 0.032 l/bu (8.98×10^{-3} gal/bu) of corn. This is equivalent to 3.59×10^{-3} l of

Diazyme per liter of ethanol (3.59×10^{-3} gal/gal).

Take-Therm is used at the rate of 1.63 gm/l (0.014 lb/gal) of ethanol.

Yeast application does not exceed 2.4 gm/l (0.02 lb/gal) while chemical application for pH control is 15 gm/l (0.12 lb/gal) of ethanol or less, under normal operating conditions.

While these items take energy to produce, because they are used in such small quantities, their energy input is negligible compared to energy use in other parts of the plant.

Lacking adequate information, the indirect energy used for alcohol plant equipment manufacture is not analyzed here. Indirect energy for an alcohol plant manufacturing 500,000 l (132,000 gal) of ethanol or more per year, over a stretch of 15 to 20 years, will be at most 10% of the direct energy use at the plant.

6.5.3.3 Summary of plant energy inputs

Table 6.3 summarizes the total energy input at the alcohol plant.

6.5.4 Process energy output

The products yielded by the fermentation and distillation processes are based on using 15.5% m.c. corn of 65% starch content. A starch to sugar conversion rate of 90% and a sugar to ethanol conversion rate of 50% are typical standards, and are used here. The products, on an ethanol yield basis, are 0.81 kg/l (6.73 lb/gal) for distillers grains and 0.71 kg/l (5.92 lb/gal) for carbon dioxide. The density of

Table 6.3 Plant energy inputs

	Kcal/l (Btu/gal)
Mashing, cooking and saccharification[1]	800 (12,000)
Distillation[1]	1,500 (22,500)
Fermentation	0 (0)
Recovery of the distillers by-product[1]	150 (2,300)
Drying of distillers grains[2]	1,200 (18,000)
Electricity[1]	900 (13,500)
TOTAL	4,550 (68,300)

1. Based on Raphael Katzen Associates (1979)
2. Based on Bohler Bros. of America, Inc. (1979)

ethanol is 0.79 kg/l (6.61 lb/gal).

6.5.4.1 Distillers dried grains with solubles (DDGS) -- energy value as ruminant feed

The heat of combustion of distillers grains is not used for output energy in this study because the energy contained in this by-product is not normally extracted through combustion. Therefore, the by-product and the feedstock are treated consistently, since the heat of combustion factor was ignored in an earlier analysis.

A more logical way to analyze the energy value of DDGS will be to compare its protein content to that of soybean meal (SBM) -- 28% to 45% -- and use the resulting ratio of 0.54 to determine the energy required to produce and process enough soybeans to provide 0.54 kg (1.19 lb) SBM. Then, the value of the distillers grains is the energy input for SBM multiplied by the DDGS production rate of 0.81 kg/l (6.73 lb/gal) of the alcohol production process.

However, this semi-idealized scheme is not very satisfactory. This is because, while DDGS contains 28% protein and SBM contains 45% protein, ruminant feeding trials at the University of Nebraska have shown that the protein in DDGS is 1.37 times better utilized by ruminants than that of SBM (Klopfenstein, et al., undated; Poos and Klopfenstein, 1979; Waller, et al., 1980). This is because the protein from DDGS is a naturally protected protein source for ruminants. Thus, in spite of its lower protein content, only 1,066 kg (2,346 lb) of DDGS is required to provide the same amount of protein obtained from 909 kg (2,000 lb) of SBM (Klopfenstein, et al., undated). This means that 1.0 kg (2.2 lb) of DDGS replaces 0.85 kg (1.87 lb) of SBM. Therefore, the energy value of 1.0 kg (2.2 lb) of DDGS is the energy it would take to cultivate and process enough soybeans to provide 0.85 kg (1.87 lb) of SBM.

Based on Myers, et al. (1979), the farm energy input for soybean production is estimated at 1,120 Kcal/kg (2,000 Btu/lb) of soybean meal. Relating to alcohol production of DDGS, this is equivalent to an energy input of 770 Kcal/l (11,600 Btu/gal).

Based on information from the American Soybean Association and the American Feed Manufacturers Association, the energy required to process soybeans to soybean meal is estimated at 2,200 Kcal/kg (4,000 Btu/lb) or, in terms of quantity of distillers grains obtained from the alcohol production process, 1,500 Kcal/l (22,500 Btu/gal) of ethanol.

Therefore, the total value of distillers dried grains resulting from ethanol production is 2,270 Kcal/l (34,100 Btu/gal).

6.5.4.2 Summary of energy outputs

Table 6.4 presents a summary of the energy values of the outputs of the fermentation and distillation processes.

Table 6.4 Process energy output

	Kcal/l (Btu/gal)
Ethanol	5,630 (84,600)
Distillers grains (10% m.c.)	2,270 (34,100)
Carbon dioxide	- -
TOTAL	7,900 (118,700)

6.5.5 Summation

Returning to equation (16) derived earlier, the energy input, identified as Q in that equation, is shown in Table 6.5, and in Figure 6.3.

Table 6.5 Total energy input (Q)

	Irrigated corn	Dry land corn
	Kcal/l (Btu/gal)	
Farm energy input	2,500 (37,600)	1,980 (29,700)
Off-farm transportation	270 (4,100)	270 (4,100)
Plant energy input	4,550 (68,300)	4,550 (68,300)
TOTAL	7,320 (110,000)	6,800 (102,100)

The capacity of the output products to do work on their surroundings, identified as W in equation (16), is 7,900 Kcal/l (118,700 Btu/gal), from Table 6.4. ΔU, therefore, is -580 Kcal/l (-8,700 Btu/gal) for irrigated corn, and -1,100 Kcal/l (-16,600 Btu/gal) for dry land corn. By an earlier definition of ΔU, the process evolves a net energy of +580 Kcal/l (+8,700 Btu/gal) for irrigated corn, and +1,100 Kcal/l (+16,600 Btu/gal) for dry land corn.

Since the alcohol production process is irreversible, then (according to the Second Law of Thermodynamics presented earlier), the input energy must exceed the output energy; in other words, the process should lose energy. However, the results of this analysis show that

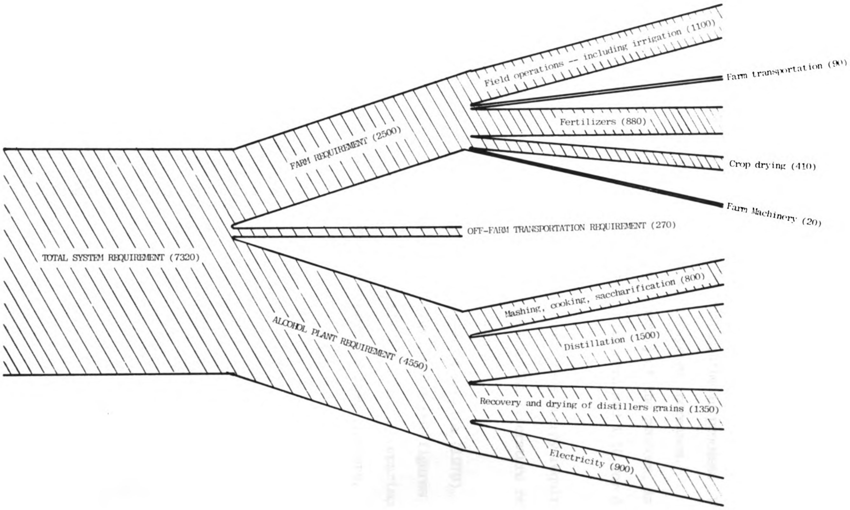


Figure 6.3 Energy requirements in a total alcohol production system (Kcal/l)

energy is not lost; instead, a small amount of energy is gained. While this appears to violate both the First and Second Laws of Thermodynamics, it must be recognized that a major energy input crossing the boundary of the control volume has not been included in this analysis. This is the energy from the sun that drives the photosynthetic process. When this is considered, the entropy of the total system increases.

The gain (output energy/input energy) of the process, in terms of total energy use, is 1.08 for irrigated corn and 1.16 for dry land corn.

The results of this study show a much less energy requirement than that of previous investigators cited in the literature review section, except for Stroup and Miller (1978).

Chambers et al. (1979), Bohler Bros. of America (1979), and Stroup and Miller (1978) all show alcohol energy requirement figures within 11% of the results obtained here. Table 6.6 shows a comparison of the results obtained here and those from previous investigators.

Table 6.6 Comparison of reported alcohol production energy requirement by various researchers[a]

Ofoli	1.00
Stroup and Miller (1978)	0.98
Bohler Bros of America (1979)	1.07
Chambers, et al. (1979)	1.11
Krochta (1979)	1.31
David, et al. (1978)	1.56
Kendrick and Murray (1978) — corn as a flow resource	1.91
Thimsen, et al. (1978)	2.16
Hofman (1979)	2.51
Kendrick and Murray (1978) — corn as a stock resource	2.60
Reilly (1978) — Low analysis	3.01
High analysis	3.35

a. Based on Ofoli

7.0 IMPROVING THE ENERGY BALANCE: A DISCUSSION

Introduction: Even though the energy accounting of the previous chapter shows a positive balance, this balance can be improved. Some of the techniques that can be used to do this will be discussed and evaluated in the following sections. Projected impacts, if any, on the energy accounting results obtained in Chapter 6 will also be presented.

7.1 Energy accounting with new developments

7.1.1 Distillation

As noted in Chapter 5, the recovery of ethanol from the fermentation broth takes two steps:

1) distillation to 190 or 191 proof, or the azeotrope, and

2) azeotropic distillation or dehydration, using a third component (usually benzene) to anhydrous alcohol.

In some commercial plants, a third step follows the azeotropic distillation to enable the recovery and reuse of the third component.

Ladisch and Dyck (1979) point out that most of the distillation energy is consumed in distilling above 85% ethanol (170 proof). Two promising techniques -- use of dehydrating agents and liquid-liquid extraction -- reduce the distillation energy input significantly.

7.1.1.1 Limited distillation processes

1. Dehydrating agents: Ladisch and Dyck experimented with dehydrating aqueous ethanol with various materials using the principle of preferential absorption of water. Their result for calcium oxide (CaO) shows a total of 700 Kcal/l (10,500 Btu/gal) distillation energy. This included 530 Kcal/l (7,960 Btu/gal) for distillation to 89% ethanol, 120 Kcal/l (1,800 Btu/gal) for heat needed to regenerate $Ca(OH)_2$ and 50 Kcal/l (740 Btu/gal) to evaporate the water released during regeneration. If this is successful commercially, the gain registered in Chapter 6 will be improved to 1.32 for dry land corn and 1.21 for irrigated corn. The use of cellulose as a dehydrating agent further improves the gain to 1.38 and 1.27, respectively. Calcium oxide dehydrated the 89% ethanol to 99^{+}%. By using cellulose, 88.8% ethanol was dehydrated to 96.4%.

Two of the dehydrating agents tested by Ladisch and Dyck are of particular interest -- cracked corn and cornstarch. By using cornstarch, 73.7% ethanol was dehydrated to 99.0%; cracked corn dehydrated 77.0% ethanol to 97.7%. Vapor contact time for these materials was 14 sec for cornstarch and 5 sec for cracked corn. The potential is obvious and should be researched for large-scale and/or commercial applications.

2. Liquid-liquid extraction: A method of solvent extraction, liquid-liquid extraction can be used to recover ethanol from water. The principle is based on the preferential transfer of one component of the original mixture to a third added component. Two factors are pertinent to extraction (Hanson, 1979). The first, D, is the distribution coefficient, and is a measure of the solvent's ability to extract

a particular solute. The mathematical formulation is:

$$D = \frac{y}{x} \tag{17}$$

where x and y are the concentrations of the solute in the raffinate and the extract phases, respectively, at equilibrium.

The second factor, α, is the separation factor. It is a measure of the selectivity of a solvent for the components of the solution. The separation factor of a solvent for solute A as against solute B is represented as:

$$\alpha_{AB} = \frac{D_A}{D_B} \tag{18}$$

The farther away α_{AB} is from unity, the easier it is to separate component A from component B by liquid-liquid extraction.

While this method has been used mostly in other chemical processes, it has application in alcohol distillation and dehydration, especially in the production of Gasohol, where gasoline can be used as an extraction agent.

7.1.2 Fermentation

Yeast growth rate and ethanol production rate are severely suppressed if the ethanol content of the fermentation broth increases much above 10%. Cysewski and Wilke (1977) term this phenomenon "ethanol or end-product inhibition." To overcome this, they boiled off water and ethanol during fermentation, under vacuum so that yeast-range temperatures could be maintained. The only problem they encountered with this system was that carbon dioxide had to be compressed up to atmospheric pressure.

The fermentation was continuous and fresh medium was fed into the fermenter as water and ethanol were boiled off. From the results of this process, they reached the following conclusions:

a) ethanol inhibition is eliminated;

b) concentrated sugar solutions can be fermented at an extremely fast rate;

c) the yeast cell recycle and vacuum systems combined to provide an ethanol productivity level almost twelve times that of conventional practice; and

d) ethanol solutions of beer going into the still were more concentrated (16-20%) than in conventional practice.

Items c) and d), especially, have the potential of reducing distillation energy significantly, since they reduce the total amount of water that must be removed from beer during distillation.

Faust and Knecht (1979) experimented with a continuous one-stage operation in a mixed loop reactor, using an adapted yeast strain not affected by elevated temperatures ($37^{o}C$ -- $98^{o}F$) and, while reducing fermenter residence time to 3 hr at a pH of 4.5 - 5.0, reported no infections, no reduction in yield or productivity, no pretreatment of the molasses feedstock used, and no need for sterility precautions.

Conventional fermentation does not consume energy, generally speaking. However, any process that improves fermentation productivity or reduces the residence time of the mash in the fermentor has the potential to improve the overall system, energetically. The amount of energy needed to gain this improvement should be measured against the reduction or increase in the total energy of the system.

7.2 Methane production

Chemapec, Inc., a New York subsidiary of a Swiss corporation, is the only commercial process known to develop methane as a by-product of the alcohol production process. The methane is produced during the waste water (spent beer) treatment process. The volume is 1.3 m^3 (45.9 ft^3) of methane per bushel of corn. This amounts to 11,400 Kcal (45,200 Btu) per bushel of corn, or 1,200 Kcal/1 (18,000 Btu/gal) of ethanol. While this is a significant energy production and has the potential of increasing the gain stated in Chapter 6 to 1.41 for dry land corn and 1.29 for irrigated corn, it must be evaluated along with the extra energy required to add a methane digester and related systems to the alcohol plant, and the amount of energy required to run it.

7.3 Heat recovery potential

By the astute use of heat exchangers, heat can be tapped from several points of the alcohol production process and recycled to other parts of the plant. A heat exchanger is a mechanism for transfering heat from a hot fluid to a colder one or vice versa. In a pure heat exchanger, the fluids do not mix and heat transfer is achieved through a separating wall (Rohsenow and Choi, 1961). Heat exchanger efficiency is typically 90% and above.

Researchers often advocate use of heat exchangers to recycle heat during distillation and cooking processes at the plant. In fact, they are already being used extensively in many commercial processes. However, the heat evolved during the fermentation process has been largely ignored.

According to Shreve and Brink (1977), the fermentation process evolves 88.94 x 10^6 Kcal (3.53 x 10^8 Btu) for every 3785 l (1000 gal) of 190 proof alcohol produced and that this evolution usually takes 60 hr. This quantity of energy averages out to 382 Kcal/l (5,880 Btu/gal) for every hour of the fermentation process.

Not only can this energy be used to subsidize the distillation process through the employment of a suitably designed system, but it also has the potential to completely replace the energy usually required to dry the distillers grain by-product.

7.4 Wet corn processing

To save the energy utilized in drying corn on the farm to 15.5% m.c., it has been proposed that wet corn processing be used in the alcohol plant. While this appears to be attractive, its practicality has not been fully established. There is the danger of spoilage during storage, for example; its effect on fermentation has not been studied. To prevent spoilage in storage, a controlled atmosphere storage may become necessary, which may require more energy than was originally used to dry the corn. Conversely, the carbon dioxide evolved during the fermentation process can be used to achieve this storage.

Processing wet corn can be done in conjunction with the Ladisch and Dyck dehydration process if cracked corn is used to dehydrate ethanol before processing. This will require, however, that the corn be first dried. In terms of energy use, this is viable, since the energy saved from only partially distilling the fermentation broth and dehydrating it (800 Kcal/l -- 12,000 Btu/gal) is about twice as much as the energy used to dry the corn (410 Kcal/l -- 6,200 Btu/gal).

7.5 Fossil fuel-free operation

Introduction: Even though the energy analysis of Chapter 6 appears to yield a positive net energy balance, if process energy is supplied by fossil fuels, an examination of the inputs and outputs shows that alcohol requires more premium fuel for its production than it yields. The term premium fuel, as used here, signifies highly versatile and portable fuels; for example, natural gas or petroleum.

While all inputs come from premium fuels, the only premium fuel output is ethanol. This does not mean that distillers grains have no fuel value. They do, but they do not constitute a premium fuel, by the definition here.

By premium fuel analysis, 7,320 Kcal/l (110,000 Btu/gal) of ethanol is used up to produce 5,630 Kcal/l (84,600 Btu/gal), an energy loss of 1,690 Kcal/l (25,400 Btu/gal), for irrigated corn. Dry land corn has a better energy balance, but it still shows a loss of 1,170 Kcal/l (17,600 Btu/gal).

Unless alternative methods that use much less energy are developed commercially for distillation and dehydration, ethanol is bound to make the energy crisis worse rather than better.

Another, and perhaps a more practical way to make ethanol a net premium energy producer, using current technologies, is to eliminate as much fossil fuel input as possible so that less priority fuel goes into the system than comes out of it. The potential for doing this is discussed in the following sections.

7.5.1 Use of biomass

While residues have some fuel value, fuel is needed to collect and transport them to the production site. Again, an energy study is required of the cost of making the residues available for the alcohol production process.

Miller (1979) reports that the residue yield from 1.00 ha (2.47 A) of corn at 247 bu/ha (100 bu/A) could provide as much as 12.6×10^6 Kcal (50.0×10^6 Btu). Even if only 50% of this energy is recoverable, and an additional 50% of the recovered energy is used up in the recovery process, this still leaves 3.15×10^6 Kcal (12.50×10^6 Btu) which translates into 3,330 Kcal/l (50,000 Btu/gal) of ethanol. This has the potential of replacing 73% of the total alcohol plant energy, even at the low recovery efficiency assumed here (see Table 6.5).

Where feedstock availability enables the plant to process sugarcane to alcohol, the sugarcane bagasse is a valuable biomass resource that will provide plant process energy. At 52% m.c., this product is valued at 2,218 Kcal/kg (4,000 Btu/lb). At a conversion rate of 80%, 910 kg (2,000 lb) of this material will provide enough energy to process 338 l (89 gal) of ethanol at the plant. At 12% m.c., sugarcane bagasse has a value of 4,050 Kcal/kg (7,300 Btu/lb). Under the same conditions as the 52% bagasse, this same product will process

616 l (163 gal) of ethanol.

These are only two examples. Wood chips and other biomass can be used to replace premium fuels currently used in processing feedstocks to alcohol. Systems that will enable biomass use on a commercial basis are necessary and deserve some research.

7.5.2 Solar energy -- heat and electricity

Solar energy provides a tremendous resource for generating heat and electricity for many areas of energy consumption, including the processing of feedstocks to alcohol. However, its uncertain availability makes it an improbable source for commercial alcohol plants in many areas of the United States. Where economical, it can be used to provide non-fossil fuel energy input for the process.

Photovoltaics, the direct transformation of sunlight into electrical energy, holds some promise since even on overcast days, some electricity can still be developed. Its cost, however, is prohibitive and makes it an unlikely candidate for near-term utilization.

7.6 Coal as an abundant fossil fuel source

Compared to petroleum sources of energy, coal is abundant in the United States. Its availability is well assured. The only real concern about it is its pollution potential, especially as coal containing progressively higher levels of sulfur is being mined. Assuming that the pollution problem is adequately resolved, coal could supply all of the plant process energy, and also fulfull some on-farm energy needs.

Since coal does not qualify as a premium fuel by the definition used here, its use for alcohol production gives ethanol a premium fuel output to input ratio of 3.0 for dry land corn and 2.5 for irrigated corn.

To obtain these ratios, it was assumed that coal will provide 20% of the farm energy input, 100% of the plant process energy input, but none of the off-farm transportation input. In computing these percentages, only primary processes (except electricity) were assumed to be an efficient use of coal. For example, to convert coal to fertilizers, it first must be converted to a petroleum base, and so becomes a secondary process. However, coal can be directly converted to heat to dry farm crops.

7.7 Straight alcohol versus Gasohol

The distillation of beer from 8-12% alcohol concentration to anhydrous alcohol consumes 30 to 60% of the total plant energy. As observed earlier, most of this energy is used up in distilling beyond 170 proof. Since Gasohol requires essentially anhydrous alcohol for trouble-free operation, burning straight alcohol at or below 190 proof will significantly reduce the distillation energy input. Since many researchers agree that an engine either specifically designed or adequately modified to run on straight alcohol is more efficient than one designed to burn gasoline, use of straight alcohol will be a better utilization of liquid fuel resources than the use of Gasohol.

Several factors make burning straight alcohol in properly designed or modified engines attractive. A partial listing follows:

1) Alcohol can be burned leaner.

2) Because of alcohol's high octane content, compression ratios can be as high as 13, significantly increasing the useful power output of the engine (Kirik, 1979).

3) Sensitivity to moisture, critical in alcohol blends, ceases to be a factor. Ken Schmitt (Alternative Energy Limited, Colby, Kansas), testing an engine modified to run on straight alcohol, found that the most efficient operation was at 185 proof. At this proof, water content of the fuel is 7.5%.

4) Alcohol burns more completely than gasoline.

5) Alcohol burns cooler than gasoline (Kirik, 1979).

Some disadvantages of burning straight alcohol are:

1) Cold starting problems are likely to be encountered. This also occurs with alcohol blends.

2) Because of the high heat of vaporization of ethanol, the intake air may need to be preheated to help solve the cold running problem.

3) Plastic parts in the fuel system must be replaced. This is usually not necessary with alcohol blends.

7.7.1 Performance of spark-ignition engines fueled with ethanol

There is always the temptation to compare the fuel efficiencies of ethanol and gasoline on the basis of their heats of combustion. According to Sladek (1978), the heat value of a fuel is not a sole determinant of fuel efficiency. Fuel efficiency is also a function of the energy content of the vaporized fuel in the combustion chamber, the thermal efficiency of combustion, and what he terms the "cylinder filling factor" which is related to the number of gas molecules created by the combustion process.

Bossong (1978) reported the research results of Urbano Ernesto Stumpf, a Brazilian alcohol expert. Stumpf found that pure alcohol delivers 18% more useful power than gasoline while the fuel is being consumed at a rate 15 to 20% higher than gasoline. Thus, from an energy standpoint, neither fuel had a clear-cut advantage.

8.0 DISCUSSION AND ANALYSIS

8.1 Fuel quality

Often, the common procedure, when doing an energy analysis such as this or when comparing fuels, is to reduce all inputs to their heat values without accounting for fuel quality. Inevitably, the process has its flaws, but many times it is the only way to avoid comparing oranges to apples, to use the traditional expression.

The Colorado Energy Research Institute (1976) identifies these factors as energy quality determinants:

1) location;
2) form;
3) time of availability;
4) convenience of use;
5) substitutability;
6) transportability;
7) storability; and
8) availability (or scarcity), among other factors.

This qualitative measure of energy is subject to individual interpretations.

Berg (1974) provides this mathematical basis for determing the quality of a fuel:

$$A = E - T_oS + p_oV - D \qquad (19)$$

where A = the thermodynamic availability of the fuel

E = the energy content of the fuel

T_o = the final temperature at equilibrium with the atmosphere

S = the entropy of the fuel

p_o = the final pressure at equilibrium with the atmosphere

V = the volume of the fuel

and D = the maximum useful work one could obtain from diffusion processes.

While equation (19) provides an objective relationship immune to individual biases, it would be difficult to find S and D values in standard handbooks for some biomass materials legitimately called fuels.

Therefore, the reduction of energy forms to their heat values is, in many cases, the only viable way to make comparisons. However, when interpreting results, one must be aware of the fuel qualities involved.

8.2 Use of best performing regional crops

If ethanol is to help solve the energy crisis, then feedstocks selected for processes must be good performers in the localities where they are grown, both in terms of the energy needed to grow them and their yields. Table 8.1 gives the yield and energy requirements of several alcohol feedstocks and the states where they were grown in the year 1974.

All the crops differ significantly in both yield and energy requirement, depending on where they were grown. Surprisingly, more energy is consumed in obtaining smaller yields. While Maine required only 22.6% of the energy needed in South Dakota, yields were nearly

Table 8.1 Comparison of 1974 yields and production energy inputs of some ethanol feedstocks and growing areas

	1974 yield	Energy use, %[a]
	bu/ha (bu/A)	
Corn:		
Nebraska	168 (68)	100.0
Iowa	198 (80)	50.8
Winter wheat:		
Oklahoma	52 (21)	100.0
Montana	126 (51)	45.8
Sorghum:		
Oklahoma	94 (38)	100.0
Missouri	126 (51)	50.7
	kg/ha (tons/A)	
Potatoes:		
S. Dakota	7,727 (8.5)	100.0
Maine	11,818 (13.0)	22.6
Sugar beets:		
Minnesota	10,364 (11.4)	100.0
California	23,636 (26.0)	51.2
Sugarcane:		
Louisiana	19,091 (21.0)	100.0
Hawaii	86,182 (94.8)	35.5

Source: Krochta, 1979.

a. Energy use percentage is based on first state listed under each crop.

153% of South Dakota's potato yields. Similarly, Hawaii produced 451% more sugarcane per land area than Louisiana, but used only 35.5% of the energy required to produce the crop in the latter state. Obviously, in the national interest, an alcohol plant using sugarcane as feedstock should use Hawaiian sugarcane if transportation energy costs are reasonable.

8.3 Merits and shortcomings of ethanol

The following factors, among others, combine to make alcohol, either straight or in blends, an attractive partial solution to the energy crisis. All comparisons are with gasoline.

1) Environmental: Alcohol reduces carbon monoxide and oxides of nitrogen exhaust emissions by about 50%. It burns cleaner and cooler and, comparatively, lacks disagreeable odors.

2) Availability: It is derived from a renewable domestic resource.

3) Technical: Net or straight alcohol burns cooler than gasoline and, because it is a pure chemical, does not degrade in storage (Kirik, 1979). Alcohol has a lower volatility and its high heat of vaporization minimizes the chance of storage fires.

Shortcomings: Alcohol has disadvantages, as identified in Section 7.7, but they are not permanent. As Simmonds (1919) wrote, the disadvantages of alcohol can be removed, but its distinct advantages remain.

8.4 Food versus fuel

In spite of the fact that no food is consumed in making alcohol, and that the by-products from corn fermentation and distillation can be used to feed livestock, the effect alcohol production will have on food supplies, for both man and livestock has not been extensively studied. Arguments that people in many parts of the world live in hunger and that the world population is increasing are valid.

For example, the extraction of starch from corn for making alcohol reduces the bulk of the material by 60 to 70%, depending on the starch content of the grain. Even though no nutritional value has been lost, the question of how to make up that lost bulk arises. It makes no difference whether the high protein residue is fed to humans or to livestock.

The Department of Energy (DOE), in its 1979 report on alcohol fuels, did not expect any real conflict between food and fuel before 1985. However, if the alcohol movement keeps gaining momentum, it may be too late to resolve the issue at that time. After all, there is just so much set-aside land (usually less productive) capacity in the United States. Perhaps this is what makes it critical that the efforts to develop technically and economically feasible ways of converting cellulose to ethanol succeed.

8.5 The cellulose potential

Cellulose, the most abundant material on earth, has no known value for human food. It includes wheat straw, sugarcane bagasse, farm residues, municipal wastes, animal feedlot wastes, etc.

According to Humphrey (1977), the estimate of cellulose fixation through the photosynthetic process is 22.7 x 10^{12} kg (50.0 x 10^{12} lb) per year; its energy potential is more than four times the worldwide crude oil utilization of 1975.

The United States has an estimated 4.5 x 10^{11} kg (1.0 x 10^{12} lb) per year of recoverable cellulose residue. This translates into 2.3 x 10^{11} l (6.1 x 10^{10} gal) of ethanol per year, at a ratio of 0.4 kg ethanol per kilogram of residue.

To tap this immense resource, at least five organizations are doing research that will permit a feasible transformation of cellulose to ethanol. The organisations are: the United States Army Natick Laboratory; the University of California at Davis (under Wilke); the University of Pennsylvania (under Humphrey) in collaboration with General Electric Corporation; Purdue University (under Tsao); and, the Gulf Oil Chemicals Company.

Brooks, et al. (1978) also report work being done on the direct microbial conversion of pretreated wood to ethanol.

The two obstacles to cellulose conversion are its strong crystalline structure and its protective lignin seal.

9.0 CONCLUSIONS

1. In terms of total energy inputs and outputs, ethanol production yields energy, using conventional techniques. The energy yield can be further improved, by the use of such techniques as limited distillation followed by preferential absorption.

2. While ethanol production, using conventional techniques, consumes more premium fuel energy than it yields, there are several ways to remedy the situation. Biomass can be used to provide process energy. Coal is abundant currently, and has the potential of increasing the premium fuel yield of ethanol by a factor of 3.0 for dry land corn, and 2.5 for irrigated corn. Thus, the premium fuel balance can be positive if premium fuels are not used for the alcohol plant processes.

3. While solar energy may do little more than complement process energy, biomass and coal have the potential to replace all scarce fossil fuel inputs except, possibly, in some parts of the farm production system. Coal is not regarded as a scarce fossil fuel for this analysis.

10.0 RECOMMENDATIONS FOR FURTHER RESEARCH

Several alternative separation techniques require little or no distillation. Before these techniques can be applied to commercial processes, further research on the design, construction and operation of the necessary systems and equipment is needed.

Commercially applicable fermentation procedures that reduce fermenter residence time (perhaps by using catalysts) will greatly increase the rate of productivity of the alcohol process. Research is needed here.

The effects on the food market (cost and availability of food) of large-scale alcohol production using food-valued feedstocks has yet to be determined. While there are many hypotheses and speculations, an objective study of the topic is imperative.

BIBLIOGRAPHY

BIBLIOGRAPHY

Alich, J.A., Jr., R.E. Inman (1974). Effective utilization of solar energy to produce clean fuel. Final report submitted to the NSF Research Applied to National Need Program, by SRI International, Menlo Park, CA.

Allsup, J.R., D.B. Eccleston (1979). Ethanol/gasoline blends as automotive fuel. Bartlesville Energy Technology Center, U. S. Dept. of Energy, Bartlesville, OK.

American Petroleum Institute (1976). Alcohols: a technical assessment of their application as fuels. API publication # 4261, July, 1976.

Badger, W.L., W.L. McCabe (1936). <u>Elements of Chemical Engineering</u>. McGraw-Hill Book Company, New York, N.Y.

Baumeister, T., <u>et al</u>. (1978). <u>Mark's Standard Handbook for Mechanical Engineers</u>. McGraw-Hill Book Company, New York, N.Y.

Berg, C.A. (1974). A technical basis for energy conservation. <u>Technology Review</u>, February, 1974.

Bergland, B. (1979). Production of fuel grade ethanol from grain. Statement before the Committee on Science and Technology, May 4, 1979.

Bliss, C., D.O. Blake (1977). Silvicultural biomass farms, Vol. 5: Conversion processes and costs. Mitre Technical Report # 7347, for the Energy Research and Development Administration.

Bolz, R.E., G.L. Tuve (1976). <u>Handbook of Tables for Applied Engineering Science</u>, 2nd edition. CRC Press, Cleveland, OH.

Bossong, K. (1978). Gasohol -- are alcohol fuels in our future? Citizens' Energy Project, Report series # 24, Washington, D.C.

Brooks, R.E., W.D. Bellamy, T. Su (1978). Bioconversion of plant biomass to ethanol. Report to the U. S. Dept. of Energy, by G.E. Corporate Research and Development., Schenectady, N.Y., March, 1978.

Carlson, R., <u>et al</u>. (1979). Studies on the economic potential of on-farm energy production systems. Interim report on Possible Energy Production Alternatives in Crops/Livestock Agriculture, Washington University.

Carvalho, A.V. de, Jr., et al. (undated). Energetics, economics, and prospects of fuel alcohols in Brazil. Centro de Tecnologia Promon, Rio de Janeiro, Brazil.

CAST (1977). Energy use in agriculture: now and for the future. Council of Agricultural Science and Technlogy, report # 68, August, 1977.

Cervinka, V., D. Mason (1979). Alcohol fuels and agricultural systems. Long Range Planning Unit, California Dept. of Food and Agric. Paper presented at the Alcohol Fuels Technology 3rd International Symposium. Asilomar, CA., May 28-31, 1979.

Chambers, R.S., et al. (1979). Gasohol: does it or doesn't it produce positive net energy? Science, 206 (4420), Nov. 16, 1979, pp. 789-795.

Chemapec, Inc. (undated). Industrial alcohol by continuous fermentation and vacuum distillation with low energy consumption. Company literature.

Clark, W. (1974). It takes energy to get energy: the law of diminishing returns in effect. Smithsonian, 5 (9), Dec., 1974, pp. 84-90.

Colorado Energy Research Institute (1976). Net energy analysis: an energy balance study of fossil fuel resources. CERI, Golden, Colo.

Colorado Energy Research Institute (1976). Net energy analysis: an energy balance study of fossil fuel resources, summary report. CERI, Golden, Colo.

Cysewski, G.R., C.R. Wilke (1977). Rapid ethanol fermentations using vacuum and cell recycle. Biotechnology and Bioengineering, Vol. 19, pp. 1125-1143.

David, M.L., et al. (1978). Gasohol: economic feasibility study. Prepared for the Energy Research and Dev. Center, Lincoln NE., by the Dev. Planning and Research Associates, Inc., Manhattan, KS.

Diehn, B. (1979). Alcohol fuels from agricultural materials. Legislative Office of the Science Advisor, Senate Fiscal Agency, inquiry # L-1, Lansing, MI.

Distillers Feed Research Council (undated). Distillers feeds. DFRC, Cincinnati, OH.

Distillers Feed Research Council (undated). Feed formulation. DFRC, Cincinnati, OH.

Distillers Feed Research Council (undated). Make more milk with distillers feeds. DFRC, Cincinnati, OH.

DOE (1979). The report of the alcohol fuels policy review. U. S. Dept. of Energy, June, 1979, Washington, D.C.

Doering III, O.C., T.J. Considine, C.E. Harling (1977). Accounting for tillage equipment and other machinery in agricultural energy analysis. Agricultural Exp. Station, Purdue University. W. Lafayette, IN.

Earl, W.B., W.A.N. Brown (1979). Alcohol fuels from biomass in New Zealand -- the energetics and economics of production and processing. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

ERDA (1977). Fuels from biomass. Energy Research and Dev. Administration Solar Program Assessment: environmental factors, March, 1977.

Ernest, R.K., et al. (1979). Mission analysis for the Federal Fuels from Biomass Program, Vol. 3: final report on feedstock availability. Prepared by SRI International, Menlo Park, CA., for the Dept. of Energy, Jan. 1979.

Faust, U., R. Knecht (1979). Novel continuous fermentation process for ethyl alkohol. Uhde GmbH, West Germany. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

Gilliland, M.W. (1975). Energy analysis and public policy. Science, 189 (4208), Sept. 26, 1975, pp. 1051-1056.

Hanson, C. (1975). Solvent extraction -- an economically competitive process. Chemical Engineering, May 7, 1979, pp. 83-87.

Hofman, V. (1979). Gasohol. Coop. Ext. Service, North Dakota State University, Fargo, ND.

Huettner, D.A. (1976). Net energy analysis: an economic assessment. Science, 192 (4235), April 9, 1976, pp. 101-104.

Huettner, D.A. (1977). Ultimate limits on the uses of energy analysis. Paper presented at the First International Conference on Energy Use Management, Tucson, Ariz., October, 1977.

Humphrey, A.E. (1977). Fermentation technology. Chemical Engineering Progress, 73 (5), pp. 85-91.

Jones, J.B., G.A. Hawkings (1960). Engineering Thermodynamics. John Wiley and Sons, N.Y.

Jones, J.L., et al. (1978). Mission analysis for the Federal Fuels from Biomass Program, Vol. 5: final report on the biochemical conversion of biomass to fuels and chemicals. Prepared by SRI International, Menlo Park, CA. for the U.S. Dept. of Energy, Dec., 1978.

Jones, J.L., et al. (1979). Mission analysis for the Federal Fuels from Biomass Program, Vol. 6. Prepared by SRI International, Menlo Park, CA. for the U.S. Dept. of Energy, Jan. 1979.

Katzen, R., J.R. Messick, G.D. Moon, Jr. (1979). Biomass processes systems evaluation and economic analysis. Raphael Katzen Associates, Cinicinnati, OH. Paper presented at the 3rd Annual Biomass Energy Systems Conference, Colo. School of Mines, Golden, Colo., June 5-7, 1979.

Kendrick, J.G., P.J. Murray (1978). Grain alcohol in motor fuels -- an evaluation. Agric. Exp. Station, Univ. of Nebraska, Lincoln, NE.

Kirchner, E.A. (1979). Testimony before the National Alcohol Fuels Commission at Indianapolis, IN., Aug. 6, 1979. A.G. McKee Co., Chicago, IL.

Kirik, M. (1979). Alcohol as motor fuel. Paper presented at the 9th International Congress of Agricultural Engineers, Michigan State Univ., East Lansing, MI., 1979.

Klopfenstein, T., et al. (undated). Distillers grains as a naturally protected protein for ruminants. University of Nebraska, Lincoln, NE.

Klosterman, H.J., et al. (1977). Production and use of grain alcohol as a motor fuel -- an evaluation. North Dakota Farm Research, 35 (2), pp. 3-9, Nov.-Dec., 1977.

Kohan, S.M., et al. (1979). Mission analysis for the Federal Fuels from Biomass Program, Vol. 4: final report on the thermochemical conversion of biomass to fuels and chemicals. Prepared by SRI International, Menlo Park, CA., for the U.S. Dept. of Energy, Jan, 1979.

Korff, J.H., Bohler Bros. of America, Inc., Power Alcohol Division of Vogelbusch. Personal communication.

Krochta, J.M. (1979). Energy analysis for ethanol from biomass. Western Regional Research Center, Science and Education Adm., USDA, Berkely, CA. From: Proceedings of the 2nd International Conference on Energy Use Management. Fazzolare and Smith (editors), Pergamon Press, New York, N.Y.

Ladisch, M.R., K. Dyck (1979). Dehydration of ethanol: new approach gives positive energy balance. Science, 205 (4409), Aug. 31, 1979.

Larian, M.G. (1958). Fundamentals of Chemical Engineering Operations. Prentice Hall, Englewood Cliffs, N.J.

Lawrence, R.D. (1979). Emissions from Gasohol fueled vehicles. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

Love, P., R. Overend (1978). Tree Power: an Assessment of the Energy Potential of Forest Biomass in Canada. Ministry of Energy, Mines and Resources, Canada.

McCabe, W.L., J.C. Smith (1976). Unit Operations of Chemical Engineering. McGraw-Hill Book Company, New York, N.Y.

Merva, G.E. (1975). Physioengineering Principles. AVI Publishing Company, Westport, Conn.

Miles Laboratory, Elkhart, IN. Company literature on enzymes.

Miller, D.L. (1979). The corn belt — an energy belt? Corn Annual, 1979 edition, pp. 24-29.

Miller, D.R. (1979). Gasohol, the now fuel. Vulcan Cincinnati, Inc., Cincinnati, OH.

Mitre Corporation (1978). Comparative economic assessment of ethanol from biomass. Study prepared for the U.S. Dept. of Energy by the Mitre Corp. Metrek Division, McLean, VA.

Myers, C.A., et al. (1979). Michigan farm energy audit and education program, phase I. Agric. Eng. Dept., Michigan State Univ. Final report to the Michigan Energy Administration, Michigan Dept. of Commerce, Lansing, MI.

Nathan, R.A., editor (1978). Fuels from sugar crops. Technical Information Center, U.S. Dept. of Energy, Washington, D.C.

Park, W., G. Price, D. Salo (1978). Biomass-based alcohol fuels: the near-term potential for use with gasoline. Study prepared for the U.S. Dept. of Energy, by the Metrek Division of the Mitre Corporation.

Perry, R.H., C.H. Chilton, eds. (1973). Chemical Engineers' Handbook, 5th edition. McGraw-Hill Book Company, New York, N.Y.

Pimentel, D., et al. (1974). Workshop on research methodologies for studies of energy, food, man and environment, phase I. Cornell Univ., Ithaca, N.Y.

Pischinger, G., N.L.M. Pinto (1979). Experiences with the utilization of ethanol/gasoline and pure ethanol in Brazilian passenger cars. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

Poos, M.I., T. Klopfenstein (1979). Nutritional value of by-products of alcohol production for livestock feeds. Coop. Ext. Service, University of Nebraska, Lincoln, NE.

Potter, M.C., J.F. Foss (1975). Fluid Mechanics. John Wiley and Sons, New York, N.Y.

Prescott, S.C., C.G. Dunn (1949). Industrial Microbiology. McGraw-Hill Book Company, New York, N.Y.

Pye, E.K., A.E. Humphrey (1979). Production of liquid fuels from cellulosic biomass. University of Penn., Philadelphia, PA.

Raphael Katzen Associates (1979). Grain motor fuel alcohol: technical and economic assessment study. Prepared by Raphael Katzen Associates, Cincinnati, OH., for the Dept. of Energy.

Reilly, P.J. (1978). Economics and energy requirements of ethanol production. Iowa State University, Ames, Iowa.

Robertson, E.E. (1977). Bioconversion: Fuels from Biomass. Franklin Inst. Press, Philadelphia, PA.

Robinson, C.S., E.R. Gilliland (1950). Elements of Fractional Distillation. McGraw-Hill Book Company, New York, N.Y.

Rohsenow, W.M., H. Choi (1961). Heat, Mass and Momentum Transfer. Prentice Hall, Englewood Cliffs, N.J.

Schmitt, K., Alternative Energy Ltd., Colby, KS. Personal communication.

Segal, M.R. (1979). Gasohol: the alcohol fuels. Science Policy Research Division, Congressional Research Center, issue brief # IB748087.

Shreve, R.N., J.A. Brink, Jr. (1977). Chemical Process Industries. McGraw-Hill Book Company, New York, N.Y.

Silva, J.G. da, G.E. Serra (1978). Energy balance for ethyl alcohol production from crops. Science, Vol. 201, Sept. 8, 1978, pp. 903-906.

Silver Engineering Co. (undated). Plants for the production of fermentation alcohol. Company literature, Silver Engineering Works, Inc., Denver, Colo.

Simmonds, C. (1919). Alcohol -- Its Production, Properties and Applications. McMillan and Company, London, U.K.

Sklar, S. (1979). Alcohol fuels: the most often asked questions -- a political and technical overview of the "American Alcohol Issue". The National Center for Appropriate Technology, Washington, D.C. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

Sladek, T.A. (1979). Ethanol motor fuels and "Gasohol". Colorado School of Mines, Mineral Industries Bulletin, 21 (3), May 1970.

Slesser, M. (undated). Energy accounting -- preliminary survey of the state of the art. Univ. of Strathclyde, Glasgow. Study for the International Federation of Institutes of Advanced Study (IFIAS).

Slesser, M. (1973). Energy analysis in technology assessment. Paper presented at the First International Congress on Technology Assessment, the Hague, May 1973.

Slesser, M. (1977). Energy analysis. Science, Vol 196, April 15, 1977, pp. 259-261.

Smith, J.M., H.C. Van Ness (1975). Introduction to Chemical Engineering Thermodynamics, 3rd ed. McGraw-Hill Book Company, New York, N.Y.

Stone. C.L. (1979). What do we do when the wells run dry? Synthetic Fuels Program, California State Legislature. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

Stout, B.A. (1979). Biomass for fuels. Michigan State Univ., East Lansing, MI. Paper prepared for the Agricultural Research Institute, Washington, D.C.

Stout, B.A., T.L. Loudon (1976). Energy from organic residues. Agric. Eng. Dept., Michigan State Univ., East Lansing, for the UNEP/FAO Seminar on Residue Utilization.

Stroup, R., T. Miller (1978). Feasibility of ethanol from grain in Montana. Montana Agric. Exp. Station, Bozeman, MT.

Teague, C. (1978). Congress looks to Gasohol in search of fuel options. Energy/Environment, April 29, 1978, p. 1033.

Thimsen, D.P., et al. (1979). Production and use of fuel ethanol from corn or wheat. Agric. Ext. Service, Univ. of Minnesota.

Tsao, G.T. (1979). Technology readiness of LORRE at Purdue University regarding production of alcohol fuels from grain and cellulosic materials. Hearing before the National Alcohol Fuels Commission, Indianapolis, IN., August 6, 1979.

Unger, E.D. (1941). The development and design of a continuous cooking and mashing system for creal grains (Thesis). Case School of Applied Science, Cleveland , OH. In: Food for Thought, by Willkie and Kolachov.

Waller, J.C., et al. (1980). Effective use of distillers dried grains in feedlot rations with emphasis on protein considerations. Michigan State University, East Lansing, Mi.

Wilke, C.R., H.W. Blanch (1979). Process development studies on the bioconversion of cellulose and production of ethanol. Univ. of California, Berkeley, CA.

Willkie, H.F., P.J. Kolachov (1942). Food for Thought. Indiana Farm Bureau, Inc., Indianapolis, IN.

Yang, V., et al. (undated). Cassava fuel alcohol in Brazil. Centro de Tecnologia Promon, Rio de Janeiro, Brazil.

GENERAL REFERENCES

Allsup, J.R. (1977). Experimental results using methanol and methanol/gasoline blends as automotive engine fuels. Technical Information Center, U.S. Dept. of Energy.

BATF (1978). Ethyl alcohol for fuel use. Bureau of Alcohol, Tobacco and Firearms (BATF), ATF P 5000 1 (9-78).

Bechtold, R., B. Pullman (1979). Driving cycle comparisons of energy economies and emissions from an alcohol and gasoline fueled vehicle. Paper presented at the Alcohol Fuels Technology 3rd International Symposium. Asilomar, CA., May 28-31, 1979.

Bojnowski, J.H., D.L. Hanks (1979). Low-energy separation processes. *Chemical Engineering*, May 7, 1979, pp. 67-71.

Bungay, H.R. (1979). Fuels from fermentation of biomass. Dept. of Chemical and Environmental Engineering, Rensselaer Polytechnical Inst., Troy, N.Y.

Chambers, R.S. (1979). The small scale fuel-alcohol distillery: general description and economic feasibility workbook. ACR Process Corp.

Conservation Foundation (1975). Net energy analysis can be illuminating. *Conservation Foundation Letter*, October, 1975.

Eckert, E.R.G., R.M. Drake, Jr. (1972). *Analysis of Heat and Mass Transfer*. McGraw-Hill Book Company, New York, N.Y.

Grainey, M.W. (1979). Alcohol fuel technology and the National Energy Act. Oregon Dept. of Energy. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

Hall, F.W. (1975). A methodology for determining energy requirements on Michigan farms using farm records (Thesis). Dept. of Agric. Eng., Michigan State Univ., E. Lansing, MI.

Heichel, G.H. (1973). Comparative efficiency of energy use in crop production. Connecticut Agric. Exp. Station, bulletin # 739.

Henderson, S.M., R.L. Perry (1974). *Agricultural Process Engineering*, 3rd ed. AVI Publishing Company, Westport, Conn.

Illinois Farm Bureau (1978). Gasohol — current status and potential for the future. IFB Commodities Division Research Report, Feb. 1978.

McKee & Co., A.G. (1978). Preliminary engineering and cost analysis of Purdue/Tsao cellulose hydrolysis (solvent) process. Report to the U.S. Dept. of Energy, by A.G. McKee and Co., Chicago, IL., Oct. 1978.

Menrad, H. (1979). A motor vehicle powerplant for ethanol and methanol operation. Volkswagenwerk AG Research Division, Wolfsberg, W. Germany. Paper presented at the Alcohol Fuels Technology 3rd International Symposium, Asilomar, CA., May 28-31, 1979.

PedCo International, Inc. (undated). Ethanol production units for power alcohol -- process overview. PedCo International, Chester Towers, Cincinnati, OH. Company literature.

Schooley, F.A., et al. (1978). Mission analysis for the Federal Fuels from Biomass Program, Vol. 1. Prepared for the U.S. Dept. of Energy by SRI International, Menlo Park, CA., Dec., 1978.

Southwell, P.H., T.M. Rothwell (1977). Analysis of output/input energy ratios of food production in Ontario. Univ. of Guelph School of Engineering.

Strong, R.M. (1909). Commercial deductions from comparison of gasoline and alcohol tests on internal-combustion engines. U.S. Geological Survey Bulletin # 392. In: Alcohol -- Its Production, Properties and Applications, by Simmonds, McMillan and Company, London, U.K., 1919.

Tyner, W.E., M.R. Okos (1978). Alcohol production from agricultural products: facts and issues. Coop. Ext. Service, Purdue Univ., W. Lafayette, IN.

Wang, D.I.C., et al. (1979). Direct microbiological conversion of biomass to ethanol and chemicals. M.I.T., Dept. of Nutrition and Food Science, Cambridge, MA.

APPENDIX

APPENDIX

Amyl alcohol	any of eight isomers of the chemical formula $C_5H_{11}OH$
Anhydrous alcohol	water-free alcohol
Azeotrope	a constant boiling mixture whose vapor has the same composition as the liquid from which it came
Barrel	42 U.S. gallons
Denature	make alcohol unfit to drink as a beverage
Ethyl alcohol (ethanol)	a two-carbon member of the alcohol family
Hydrolysis	a decomposition process that involves splitting a chemical bond and adding elements of hydrogen and oxygen from water
Mashing	the mixing of ground corn or other starch raw material with water to form a slurry
Methyl alcohol (methanol)	a one-carbon member of the alcohol family
Proof	a measure of alcohol concentration that is twice the percentage of alcohol, by volume, e.g., 70% alcohol is 140 proof
Saccharification	the conversion of starches to sugars
Straight alcohol	unblended, engine-grade (usually 160-200 proof) alcohol that can be burned in properly designed engines
Tonne	long ton (2,200 lb)