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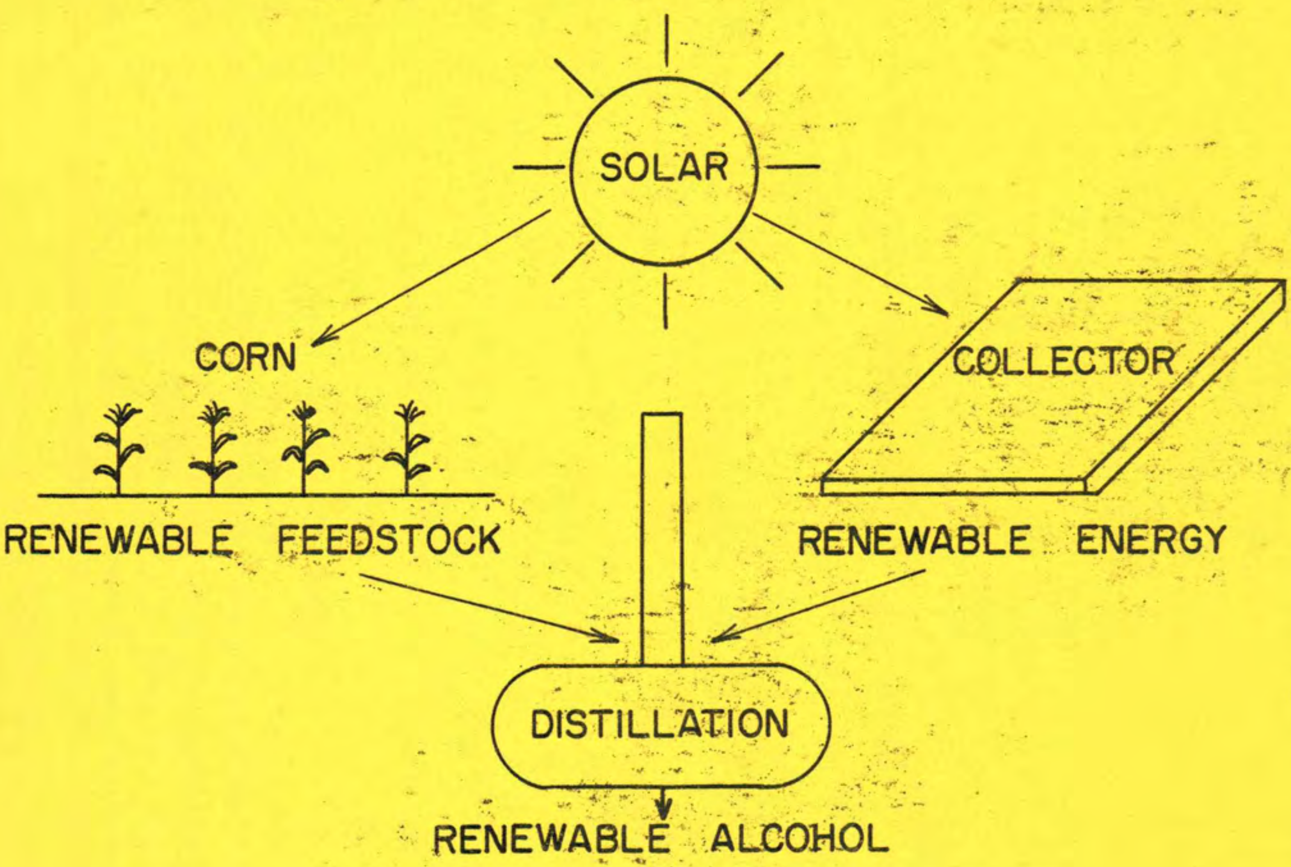
FINAL REPORT

ASSESSING SOLAR ASSISTED ETHANOL PRODUCTION IN THE STATE OF IOWA



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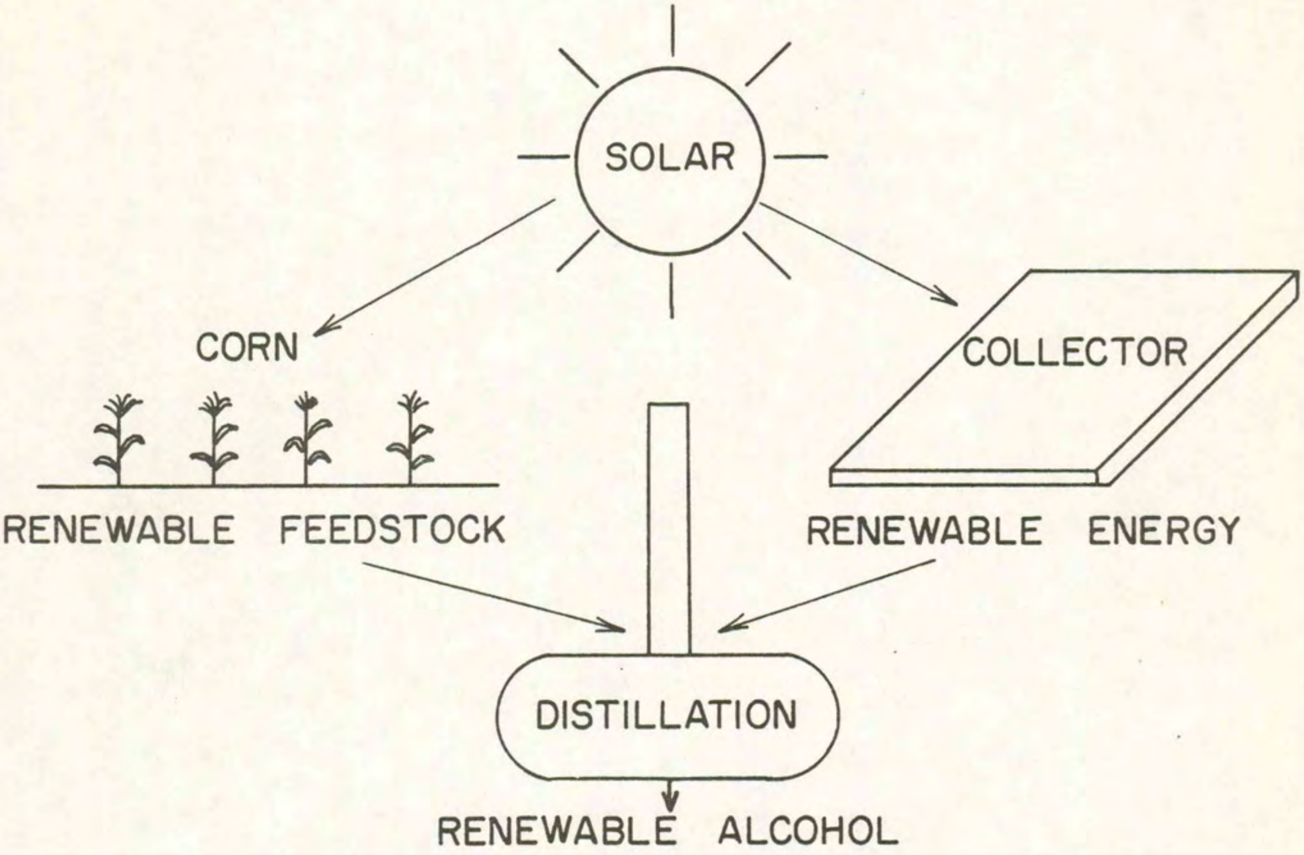

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Foreword

The financial support of the Iowa Energy Policy Council is acknowledged, but The University of Iowa assumes complete responsibility for the contents.

ABSTRACT

The purpose of this investigation was to assess the role of solar energy in fuel alcohol (ethanol) production in the State of Iowa. The investigation examined literature for applications involving solar energy in production of fuel alcohol, availability of solar energy and corn to establish the potential to produce fuel alcohol from these quantities, fermentation process to optimize the liquefaction temperature and time to produce a mixture of water and alcohol, theory and experimental studies to distill a high proof alcohol, simulation models to enable system parameters and scale-up designs to be studied, energy balance associated with production of corn and fuel alcohol, conceptual designs of solar assisted fuel alchol production, and economics related to production of fuel alcohol utilizing solar energy.

The results of these studies are presented in this report. An overall summary of these findings indicate that the utilization of solar energy is technically feasible and yields a more favorable energy balance. However, the economics of these solar assisted systems are favorable only for certain applications and conditions.

ACKNOWLEDGMENTS

This investigation received assistance from numerous people besides that from the Iowa Energy Policy Council and the authors' own contributions. A. N. Shekar contributed to the energy balance and simulation model studies. R. M. Hafez assisted in gathering information about availability of solar energy and corn as well as drying of distillers grain. The fermentation process study was performed by C. P. Burkhart. W. B. Stipanovich and Prof. D. L. Spencer provided assistance in erection of the collector array and consultation on solar collector thermal performances and costs. Distillation modelling was partially performed by S. Leung. Prof. J. O. Osburn provided consultation on fermentation and the distillation modelling. Partial financial support from The University of Iowa Vice President Office is gratefully acknowledged as is the equipment support of The Division of Energy Engineering in the College of Engineering. The Graduate College provided computer time which enabled simulation models to be developed and reports to be prepared. Rick Chandler of CPI Sales, Cedar Rapids, Iowa, aided greatly by donating two liquid pumps to this project. Prof. James Buck, Division of Information Engineering of the College of Engineering assisted in formulating the economic analysis. The College of Engineering Mechanical and Electrical shops devoted numerous hours to this project making possible the development of the solar distillation unit as a research instrument. Finally, the staff members of the Publications Office must be cited for their assistance in bringing this report together.

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1. INTRODUCTION

1.1 Energy Concerns and Alcohol Fuel

Interest in alternative fuels has been increasing since the oil embargo of 1973-1974. Fuel alcohol (ethanol) has emerged as the immediate alternative fuel and appears attractive as a supplemental fuel for conventional fossil petroleum products. There are, however, several questions about the production and utilization of fuel alcohol which remain unanswered. On farm or farm cooperative fuel alcohol production holds promise for taking the Iowa farmer toward less reliance on external sources of fuel. Shortages of fossil fuel during either planting or harvesting season could significantly reduce crop yields, which provides ample incentive to find alternative liquid fuels.

1.2 Solar Energy and Energy Balance

The energy balance debate on fuel alcohol production has not been resolved, and is addressed in this report. One way of attaining a favorable energy balance is to use renewable energy sources in the production of fuel alcohol. The renewable energy contribution to fuel alcohol production can be excluded or discounted in the energy balance. Utilizing "free" solar energy for process heat in the fermentation and distillation of corn to fuel alcohol cycle reduces the nonrenewable energy inputs, and creates a more favorable energy balance. Much interest has been shown in the concept of solar fuel alcohol distillation, however, no compiled source of information on theory, design, or experiment is known.

1.3 Objective

The objective of this report is to examine the facets of fuel alcohol production that can be assisted by solar energy with particular emphasis on those within the State of Iowa. Topics of cooking, fermentation, distillation, solar collector types, and production rates are covered. Results from experiments, simulation models, and calculations bearing upon the above topics are presented.

1.4 Organization of Report

The report is subdivided into several sections related to the corn to fuel alcohol production process. First, previous literature and fuel alcohol producers as related to utilization of solar energy are surveyed. Next the relations between the solar energy and corn availability are examined. Solar energy availability is important when integrating solar energy into fuel alcohol production for the sun grows this years corn, and the sun will assist the following year in turning the corn into fuel alcohol. Chapters 4, 5, and 6 address fermentation, distillation, and modeling solar distillation systems, respectively. The ideas concerned with fuel alcohol energy balance are discussed in Chapter 7. Chapter 8 presents conceptual designs of solar energy utilization in the corn to fuel alcohol process. Economics of solar assisted fuel alcohol production is the topic of Chapter 9. Chapter 10 draws upon the entire report to make conclusions and recommendations.

2. LITERATURE SURVEY

2.1 Introduction

The purpose of this literature survey is to review the literature and previous distillation units relating to solar assisted ethanol production. Other studies [1-9] have presented discussions on fuel alcohol production, with most of these studies citing that renewable energy sources, including solar energy, could be utilized in the production of process heat. These studies can be consulted for further reference. In view of the extent of the literature survey, a lack of information on solar assisted ethanol production and a pronounced need for this information was found. Generally, the information available was from small manufacturers who tend to make claims which appear somewhat questionable. The largest misnomer was that vacuum distillation saves energy in distillation. Actually, vacuum distillation increases the energy required to boil fuel alcohol in the distillation process (since the latent heat of vaporization is higher at vacuum pressure), decreases the height of the distillation column for a given alcohol-water separation, and extends the highest attainable ethanol-water solution for a given column design. The relationship of these three effects of vacuum operation to energy consumption is far from clear. The above mentioned facts can be verified by examining several references or handbooks [10-12].

2.2 Literature Search

The Solar Energy Research Institute (SERI) data base comprised of all major technical data bases was searched for technical information on solar and vacuum distillation of fuel alcohol from 1967 to present. As noted later, vacuum distillation makes feasible the utilization of solar energy via low cost flat plate solar collectors. A study [13] concerned with the effect of vacuum operation on the efficiency of packed fractioning columns was located. This study presents limited data on ethanol-water mixtures and sites several investigations concerned with ethanol-water mixtures. Due to the dates, location of these investigations ranging from 1920 to 1945 is difficult. A library search for the references has been initiated.

A literature search was performed at The University of Iowa. With the aid of references in the above mentioned study several articles on vacuum distillation were located. These articles [10,14,15] presented either ethanol-water property data or modeling techniques of ethanol-water physical properties. Other articles [16-19] discussed distillation optimization and performance either with different types of distillation columns or pressures. Finally, a useful general reference on trouble shooting distillation columns was located [20].

2.3 Field Survey

Next an effort was made to locate operating distillation units that utilize solar energy. Only three solar assisted distillation units were located and operational data was not available on any of these systems.

When operating a solar distillation unit, there are two possibilities for distillation: atmospheric or vacuum distillation. Atmospheric distillation is based on the greenhouse effect as described in Refs. [21-24]. In these greenhouse units, as depicted in Fig. 2.1, the fermented alcohol-water mixture with dissolved solids is introduced directly into the top of a solar collector. The alcohol-water mixture flows down the heated absorber panel where the alcohol is evaporated. The evaporated alcohol condenses on the glazing and runs down to a collector header. The alcohol on the glazing reduces transmittance of the glazing and accumulated impurities on the absorber panel will reduce the effectiveness of the panel to absorb solar energy. This solar energy application appears to be a very labor intensive process, and impractical for even a small scale operation.

The other solar energy application for atmospheric distillation employs a concentrating collector to produce either a high temperature fluid (180 F and above) or low pressure steam. Experience with solar energy low pressure steam distillation is reported in Ref. [25]. Concentrating collector methods seem promising, however, several problems such as purity of steam make-up water, the intermittent solar energy due to clouds, and collector tracking need to be addressed.

The greatest foreseeable disadvantage to solar assisted atmospheric distillation pertains to operation in the absence of solar energy. For the greenhouse collector, very little can be done, whereas in the other systems a thermal energy storage or back up energy system can be associated with the distillation unit. Thermal energy storage technology is not

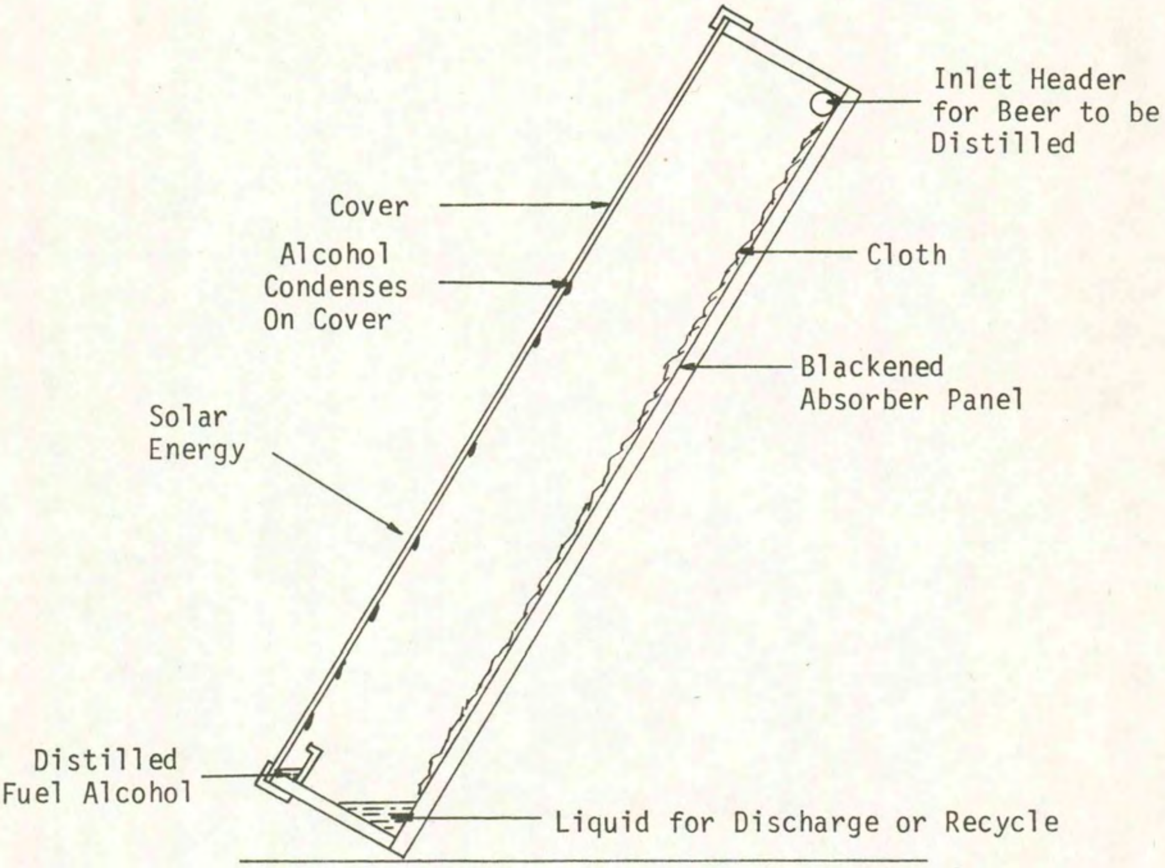

Figure 2.1 Greenhouse Solar Still

advanced at the temperatures required for atmospheric distillation, which is one problem of concentrating collector application. Hence, solar assisted continuous operation will be extremely difficult with atmospheric distillation units that rely totally on solar energy for process heat.

Continuous operation of a solar distillation unit is highly desirable for several important reasons:

1) Start up and shut down requires labor, which increases the cost of production.

2) Start up and shut down heat losses can not be ignored.

3) Start up and attainment of the quality of alcohol desired are not easy processes.

4) With an average of eight hours of useful solar energy per day, the distillation unit capital investment will be idle for at least two thirds of the equipment life time if no back up energy system is installed. This decreases the return on the investment.

The above four reasons illustrate the need for continuous operation vacuum distillation unit assisted by solar energy. At vacuum operating temperatures several methods of thermal energy storage can be utilized so that stored solar energy is available in the absence of solar energy. Thermal energy storage for continuous vacuum operation is discussed in more detail later in this report. Unfortunately, no information exists on a solar assisted continuous operation vacuum distillation unit prior to this study.

2.4 Conclusion

In conclusion, there is a lack of reliable and complete information on any type of fuel alcohol solar distillation unit, and no published research data has been located. It appears that based on the available methods for utilization of solar energy, a vacuum distillation unit with a lower operating temperature appears attractive. This report attempts to provide the necessary data for determining the feasibility of such a unit.

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3. SOLAR ENERGY AND CORN AVAILABILITY

3.1 Introduction

The feasibility of utilizing solar energy in the process of converting corn to ethanol is, among other factors, dependent on the availability of solar energy and corn. If neither solar energy nor corn exists in sufficient quantity, then the process may not warrant investment of time, money, and other resources. The availability of solar energy and corn within the State of Iowa is examined in the succeeding two sections. In each section, the discussion considers some of the factors which govern the availability, the source of data, and the results for each quantity. The final section examines the correlation between solar energy and corn production.

3.2 Solar Energy

3.2.1 Introduction

The purpose of this study is to evaluate the availability of solar energy in the State of Iowa. The amount of solar energy incident on a surface located on the earth is dependent on various factors which include seasonal effects, transmittance of the atmosphere, climate, and orientation and location of the surface. Seasonal effects are attributed to the rotation of the earth about the sun and the inclination of the earth on its rotational axis. Thus, the sun path is high in the sky during the summer and low in the winter. Humidity which creates a haze in the air scatters and absorbs solar energy as it passes through the atmosphere. Furthermore, pollution consisting of dust, smoke plumes, jet air trails, and chemical particles in suspension in the air forms a screen that decreases the amount of solar energy available on the earth. Climatological conditions include clouds which have a significant effect of attenuating the solar energy. An indicator of the sky clearness is called the cloud factor. The orientation of the surface with respect to the North-South axis affects the amount of time during which the surface is exposed to the sun. The tilt angle or angle of inclination of the surface relative to the horizontal influences the angle of incidence of the solar rays and, therefore, the amount of solar energy received by the surface.

The total solar energy incident on a surface is conveniently divided into three components, namely, direct, diffuse, and reflected. The amount of extraterrestrial solar energy which directly passes through the atmosphere and irradiates a surface is called the direct or beam component. A portion of the extraterrestrial energy is scattered as it passes through the atmosphere and, therefore, is referred to as diffuse energy. In addition, the reflected component represents solar energy reflected in the direction of the surface by the surrounding ground surface and may be particularly important in the presence of snow. Solar energy values appear under different formats: instantaneous, hourly, daily, monthly, and yearly. Instantaneous values represent the amount of energy that is available at that instant of time whereas the other values are for the energy averaged over a specific time interval, for example, a day or year. Since solar energy does not vary significantly over an hourly period, hourly and daily values are more useful.

It is of interest to be able to describe the availability of solar energy in terms of these factors. The following discussion focuses on the sources of information for solar energy. This is then succeeded by a comparison of results from these sources and a recommendation for typical values of solar energy in Iowa.

3.2.2 Sources of Solar Insolation Data

Solar energy data are found under two general categories, namely, actual measurements and predicted or estimated data. Since 1950, a network of stations has been monitoring solar energy with the assistance of the National Weather Service. Some stations reported hourly values and others reported daily values. As of 1973, 67 stations were still monitoring, and of these only 29 kept both hourly and daily values. The data accumulated during the last 20 years are of questionable quality since the instruments were seldom calibrated after 1960 and inadequate support prevented a thorough recording of solar energy measurements [1]. Solar energy values from 1977 to January 1979 were obtained from the National Climatic Center [2] for three locations near Iowa: Omaha, Nebraska; Columbia, Missouri; and Madison, Wisconsin. These values represent daily solar energy received by a horizontal surface. Predicted or estimated data were obtained from two sources, namely, charts or tables presented in several solar energy books [1,3,4], and a model which was converted to a computer code. The model includes such factors as seasonal variations, surface orientations, cloud cover, ground reflection, as well as altitutde and latitude of the location. The model was developed from recommended correlations appearing in Ref. [3] and is referred to as model A.

3.2.3 Results and Discussion

Representative measurements of total solar energy for Madison, Wisconsin obtained from Ref. [1] are presented in Fig. 3.1 and correspond to daily values of solar energy incident on a horizontal surface. The data displayed in Fig. 3.1 show the variability of solar energy from day to day and are useful in the simulation models where it is necessary to estimate the number of consecutive days of sun or clouds. Measurements for Omaha, Nebraska and Columbia, Missouri display similar trends but the values are poorer in quality. Estimates of solar energy for the three locations are 600 Btu/ft^2 and 2500 Btu/ft^2 for winter and summer, respectively, for a horizontal surface. Daily averages of solar energy incident on a horizontal surface for each month for Iowa were extrapolated from 26 reactivated stations [1] and are shown in Fig. 3.2. The solar energy values for winter and summer 600 Btu/ft^2 and 2100 Btu/ft^2, respectively. Daily solar energy over the entire year is estimated to be 1311 Btu/ft^2. This value was estimated from cloud cover measurements and statistical correlations for Iowa at different locations [1]. The results in Fig. 3.2 are the most reliable values of solar energy available at the present and are currently being used in solar systems designs.

Solar energy results were computed from model A for the minimum and maximum latitudes in Iowa (40.6 and 43.6 deg.), and with a south facing surface of tilt angle equal to 0 and 90 deg. as measured from a horizontal surface. Results were also generated for an average latitude of 42.1 deg. with tilt angles of 40 and 60 deg. A plot of these results is shown in Fig. 3.3. These values represent daily averages of solar energy available under clear sky conditions. In the event of clear skies, the cloud factor

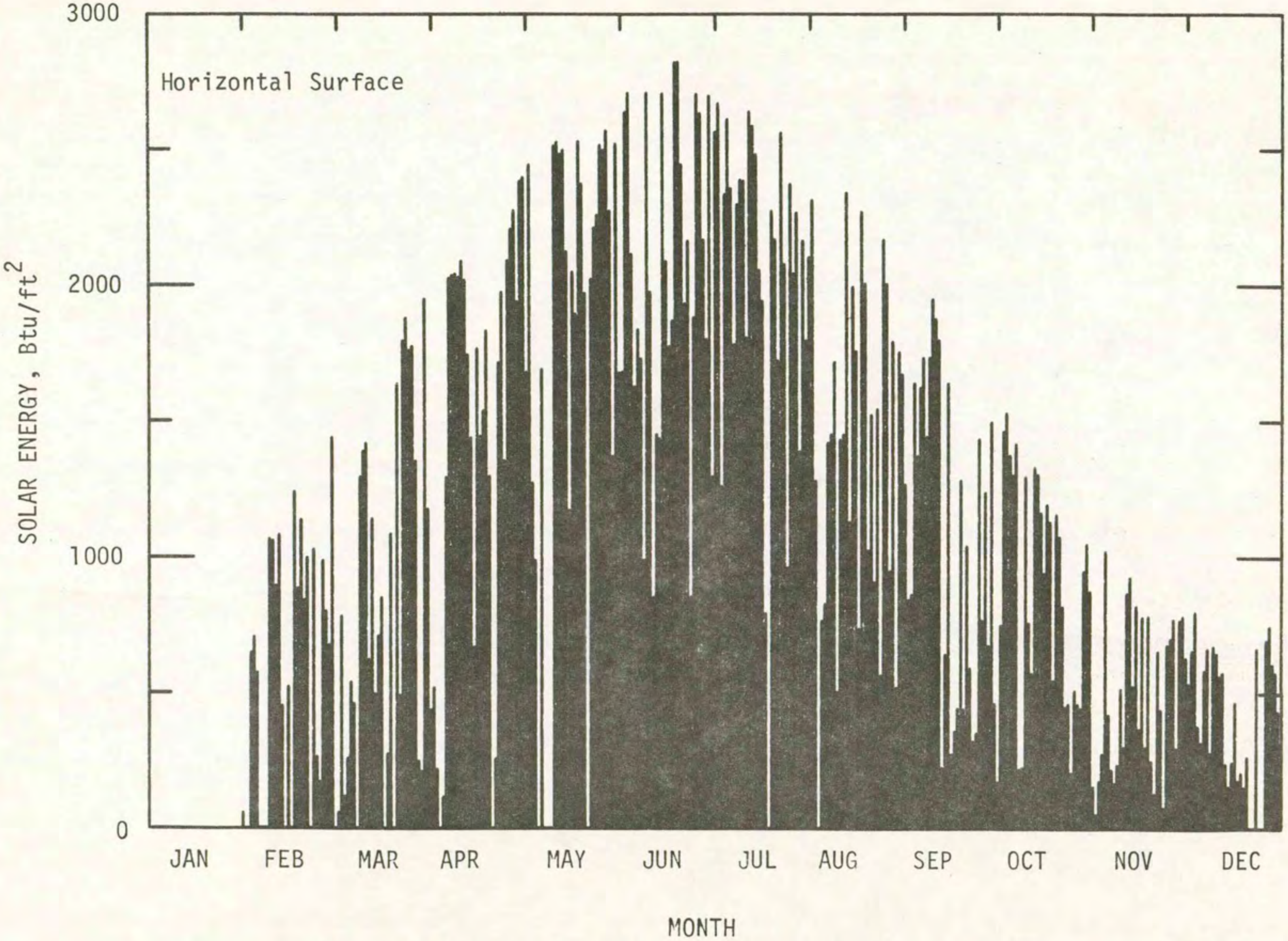

Figure 3.1 Solar Energy Measurements for Madison, Wis.

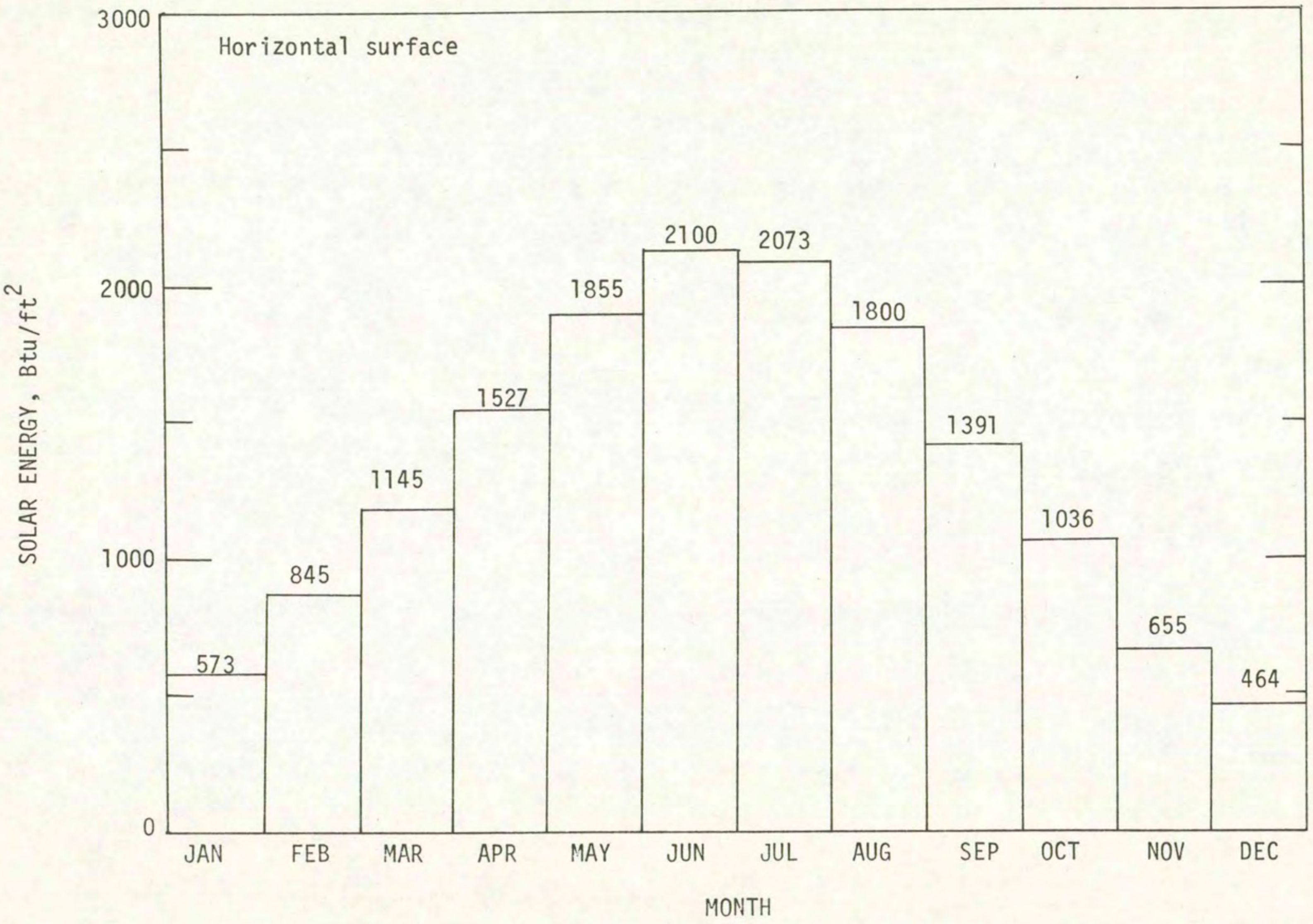

Figure 3.2 Daily Averages of Solar Energy for each Month in Iowa

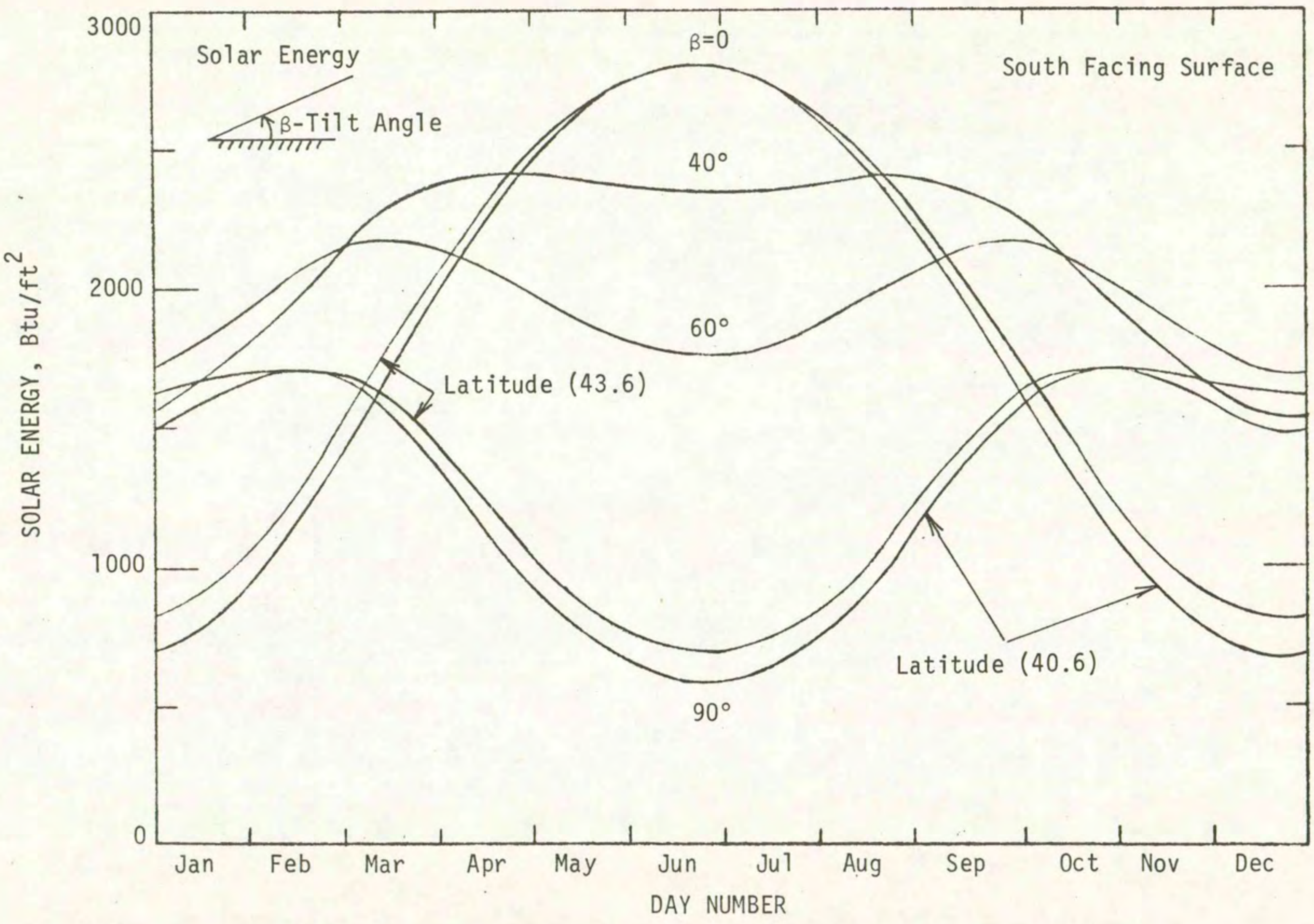

Figure 3.3 Daily Average Solar Energy

is equal to unity which represents ideal conditions. The curves are similar for both latitudes at different tilt angles. The results in Fig. 3.3 for the case of a horizontal surface compare favorably with those in Fig. 3.1 under clear sky conditions. It can be stated that within the limitations of available data and model, solar energy does not vary across Iowa. Another observation to be made is that during summer, a horizontal surface receives more energy than a vertical one. During winter, the opposite is true. For example, the solar energy incident on a horizontal surface is approximately 2800 Btu/ft^2 whereas a vertical surface intercepts 550 Btu/ft^2. This behavior is due to the variation of the path traversed by the sun in the sky during the four seasons. Hence, the surface needs a larger tilt angle in winter as compared to a smaller tilt angle in the summer in order to maintain the sun rays perpendicular to it. Table 3.1 presents a comparison of the theoretical daily clear sky solar energy values obtained from model A and another computer code developed in Ref. [1] which is referred to as model B. The two models give similar values depending on the accuracy of the correlations used. Solar energy results from Fig. 3.2 are also presented in Table 3.1 for comparison purposes.

The monthly averaged cloud factor coefficients are also presented in Table 1. These coefficients were obtained by taking the estimated monthly available solar energy values of Fig.3.2 and dividing them by the clear sky solar energy results given by model A. These results are the monthly averages although cloudiness can be concentrated during a short period of time as observed in Fig. 3.1. On an annual basis, Iowa has an average cloud factor of 0.71.

Table 3.1

Solar Energy and Cloud Factor Results

	Estimated*	Model A*	Model B*	Cloud Factor
Jan 21	573	962	947	0.64
Feb 21	845	1383	1412	0.64
Mar 21	1145	1897	1851	0.63
Apr 21	1527	2395	2272	0.66
May 21	1855	2690	2250	0.71
Jun 21	2100	2798	2646	0.76
Jul 21	2073	2683	2532	0.78
Aug 21	1800	2375	2242	0.78
Sep 21	1391	1884	1787	0.77
Oct 21	1036	1374	1347	0.80
Nov 21	655	965	941	0.71
Dec 21	464	811	781	0.63
Yearly	1311	1268		0.71

*Results for daily solar energy for a horizontal surface and a latitude of 40 degrees, Btu/ft^2.

3.2.4 Conclusions

Solar energy availability in Iowa has been examined on the basis of measurements, estimated data, statistical analyses, and models. One purpose of this section is to recommend the most reliable reference for solar energy information. Measurements of solar energy obtained from the National Climatic Center reveal that the instruments used were seldom calibrated during the last 20 years. Although the values are unreliable, the National Climatic Center used them in an extensive statistical analysis and provided the most dependent estimates of solar energy available at the present time. These estimates were combined with model results for a clear sky to determine the cloud factor for Iowa. According to the National Climatic Center, a horizontal surface in Iowa receives an average of 1311 Btu/ft^2 every day of the year. This values represents 71 per cent of the solar energy available under clear sky conditions. The reduction is due to the variation in transmittance of the atmosphere and climatic conditions. Results from model A indicate that the yearly average solar energy incident on a vertical surface is estimated to be 1268 Btu/ft^2 under clear sky conditions, whereas the yearly average for a horizontal surface is 1772 Btu/ft^2 under the same conditions. This study reveals that several locations around Iowa should be activated for recording solar energy data so that accurate predictions can be made.

3.3 Corn Availability

3.3.1 Introduction

The purpose of this study is to evaluate some of the factors affecting corn production with particular emphasis on the State of Iowa. Although the examination of all the factors is beyond the scope of this study, an attempt will be made to enumerate some of the more relevant ones. Political decisions of national and international level have some effect on the agricultural sector and, therefore, might influence corn production and prices. Agricultural factors can be subdivided into two categories: human decision making and agricultural technologies which consist of various corn hybrids, soil quality, fertilizers, and insecticides. Finally, climatic conditions which include rainfall and storms are of interest because of their association with solar energy. The sources of information for analysis purposes are cited in the next section. This is followed by a discussion and interpretation of the data.

3.3.2 Sources of Data

Data related to corn production for the period of 1969-1981 were gathered according to the factors cited above. Corn production, utilization, export, and carryover data for the U.S. were supplied by the United States Department of Agriculture through the Johnson county extension service [5]. Also furnished by this source were the mid-month average prices received by Iowa farmers. These prices were gathered through the Iowa Crop and Livestock Reporting Service by randomly selecting grain elevators across Iowa and averaging the prices obtained. Area of land planted with corn for all purposes as well as area of land harvested for corn not used for silage were obtained on a district by district basis for Iowa through the Iowa Corn Promotion Board and the Iowa Department of Agriculture [6,7]. Corn production and yield data on a district basis were also obtained from Refs. [6,7].

Climatic data for Iowa were obtained from the U.S. Environmental Data Service [8]. The data consisted of monthly maximum and minimum temperatures and rainfall amounts for Iowa. Storm data and unusual weather conditions were reviewed from reports by the National Climatic Center [9].

Agricultural information was gathered from articles in farming and other magazines [10,11]. The information consisted of major outbreaks of corn borers (insects) as well as reports of drought effects on agriculture. Information on the human parameter was obtained by interviewing farmers.

3.3.3 Results and Discussion

Data for corn production, utilization, export, and carryover for the U.S. are presented in Fig. 3.4. Utilization represents the amount of corn that is being locally consumed whereas carryover is the amount of corn remaining in storage from the previous year. The data are plotted for the month of October of the corresponding year. Production varied during the 1969-1973 period between 4200 and 5500 million bushels of corn. After 1973, production increased by 28 per cent in the 1974-1980 period with dips occurring in 1974 and 1977 due to drought and insect problems as discussed later. Exports have been increasing due to an increase in trade with foreign countries and accounted for 17 percent of the production in 1979. Due to the increase in production, carryover increased by 150 percent between 1975 and 1980 after a 50 percent decline in the previous five years.

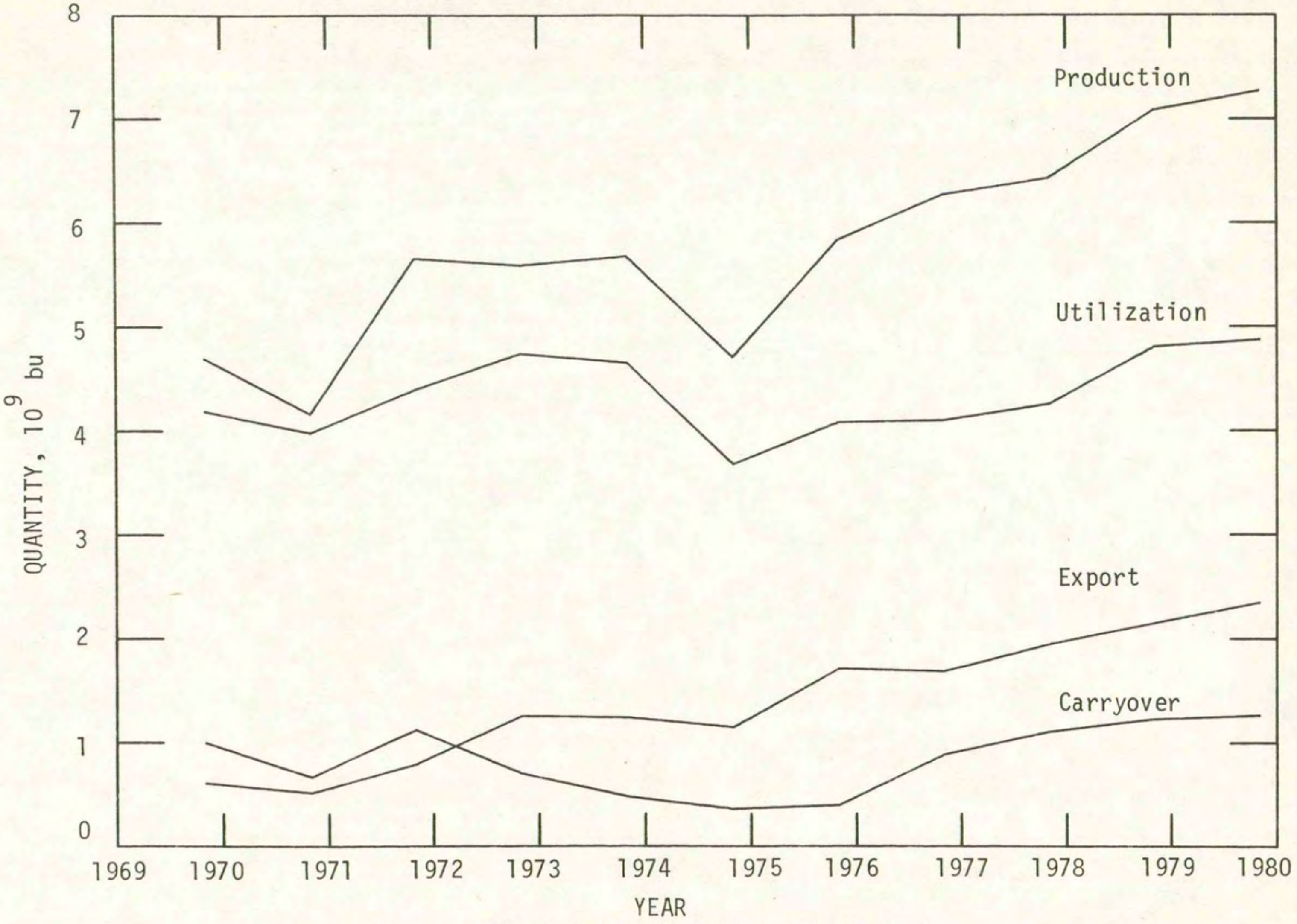

Figure 3.4 Corn Distribution for the U.S.

Area planted and harvested for Iowa are displayed in Fig. 3.5 and corn production and yield appear in Fig. 3.6. The data are presented for the nine districts in Iowa for the period lasting from 1969 to 1981. Analysis of these data reveals similar trends for all districts and combined graphs for Iowa are presented in Figs. 3.7 and 3.8. In Iowa, the area planted for corn has increased by 30 percent over the last eleven years with a leveling off observed in the last four years. This trend confirms the belief that growing space is limited unless urban areas are converted into fields. This unlikely prospect will limit the corn production unless the yield is increased or if corn replaces other crops. In 1979, the total area harvested was 12.7 million acres. Production for Iowa as shown in Fig. 3.5 increased by 88 percent in the eleven year period. The yield increased by 44 percent for the period of 1970 to 1979 with a drop from 127 to 110 bu/acre for 1980 due to hot and dry weather conditions.

Mid-month average prices for corn in Iowa are displayed in Fig. 3.9. Analysis of the prices reveals a sharp rise starting around June 1973. No one reason seems to justify this increase other than it followed a major increase in all food items during the same period [12]. On the other hand, major political events may have contributed indirectly to this behavior. The oil embargo of 1973 raised the prices of fuel used on the farm. However, the embargo implemented in October 1973 contributed to already increasing prices but did not appear to trigger the rise. Another example of the effect of political events on corn production is the embargo on gain shipments to the USSR occurring in January 1980. Although prices dropped immediately, they were higher two months afterwards than before

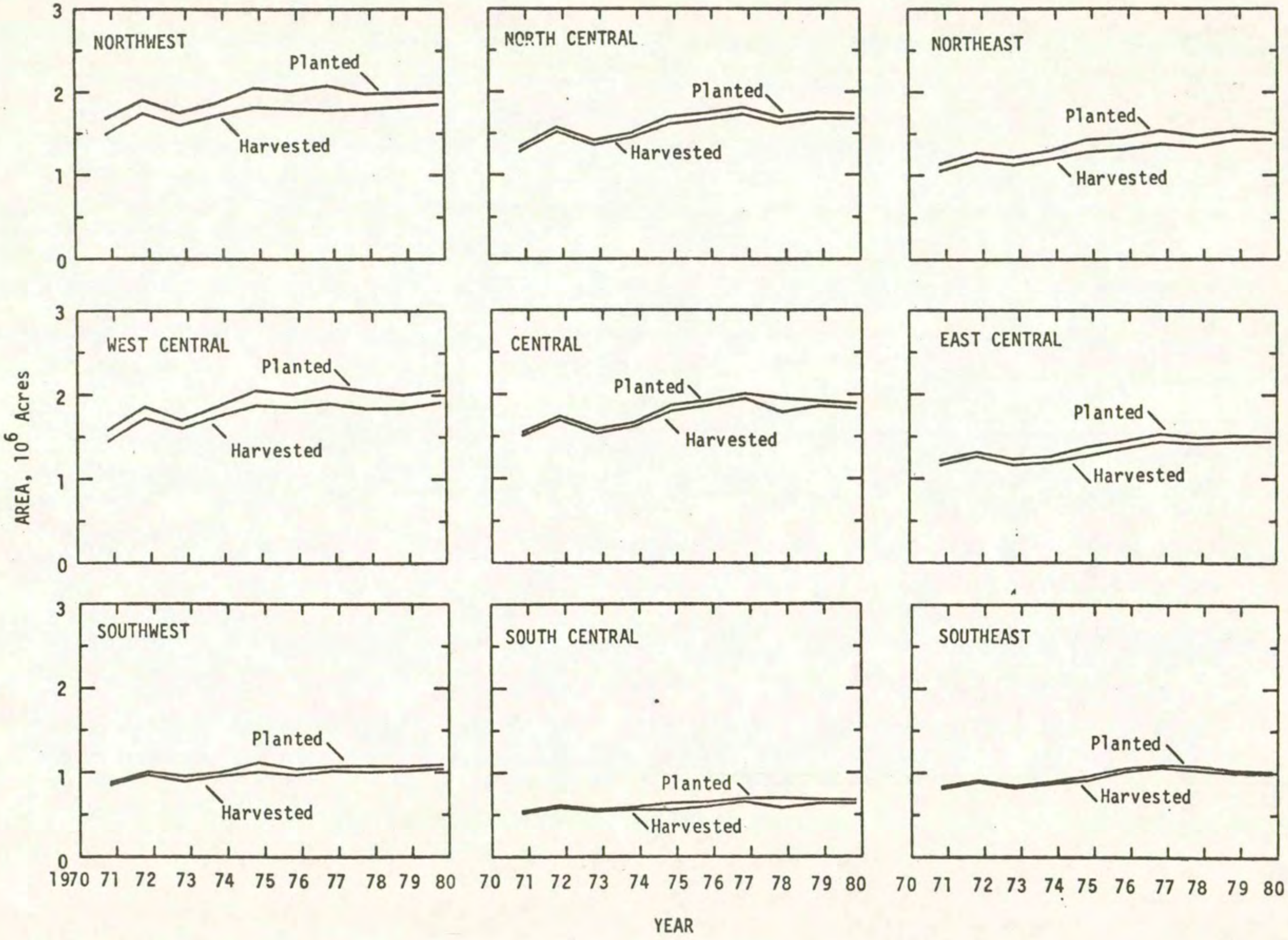

Figure 3.5 Area Planted and Harvested for Iowa

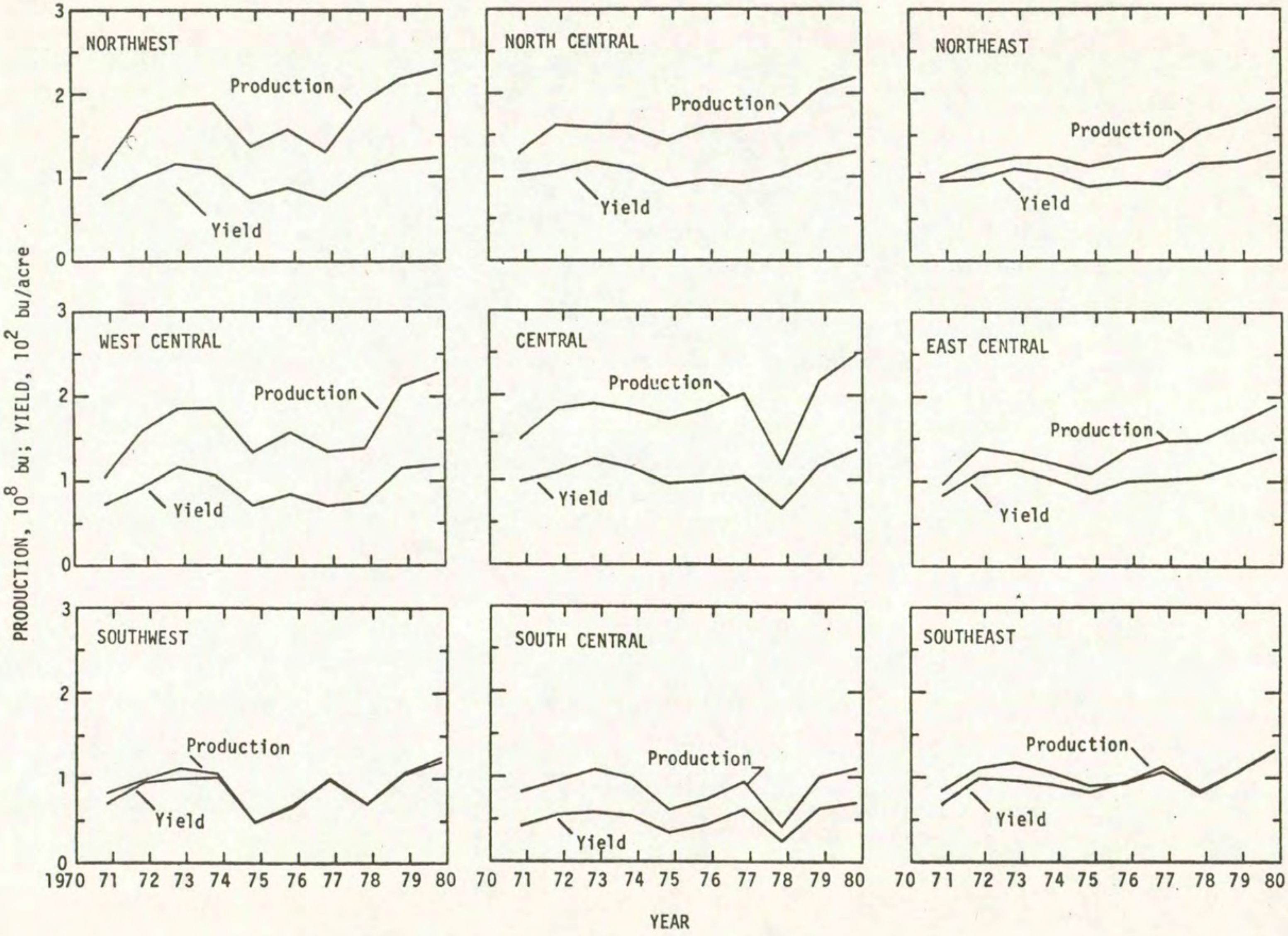

Figure 3.6 Corn Production and Yield for Iowa

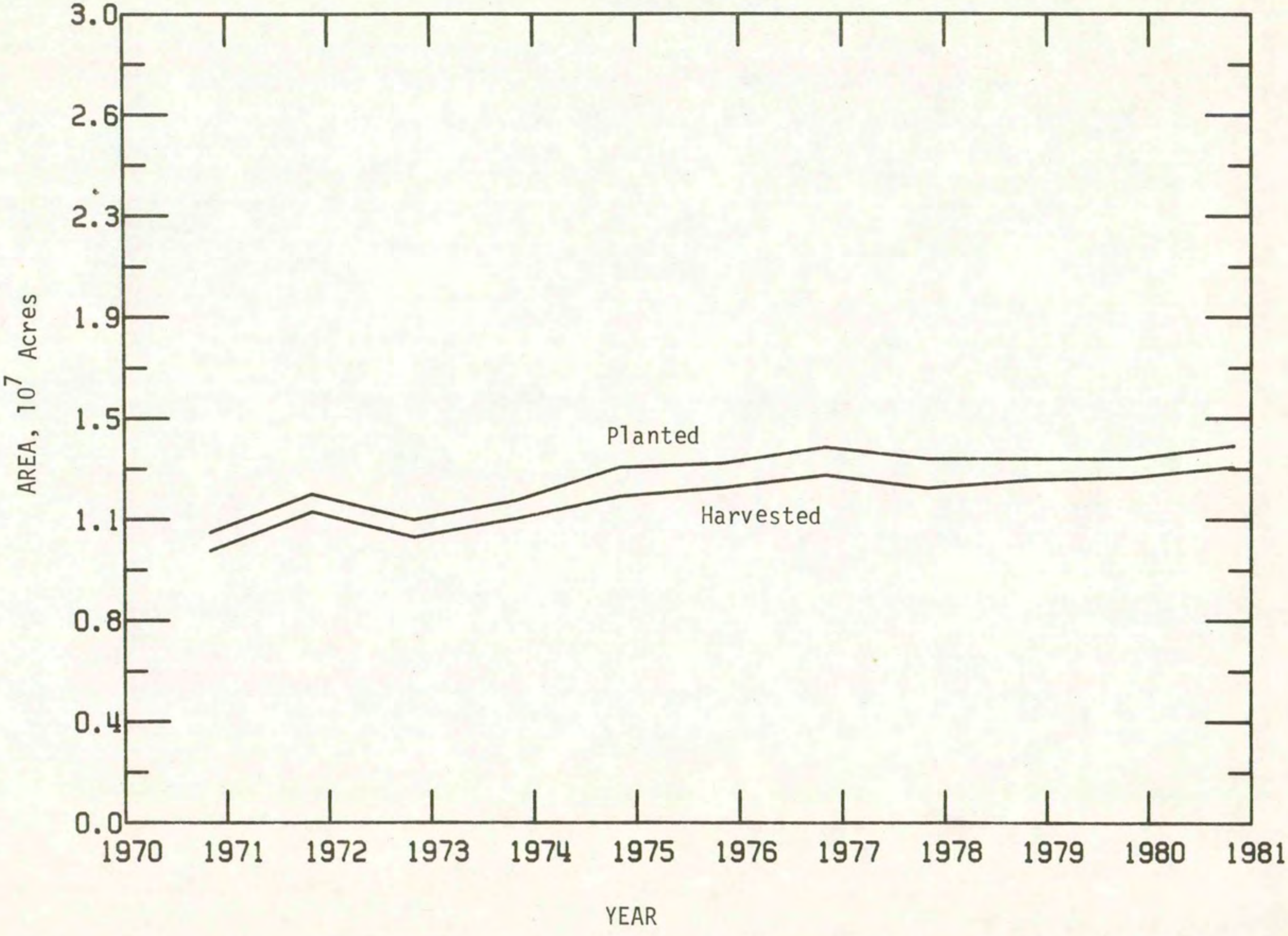

Figure 3.7 Area Planted and Harvested

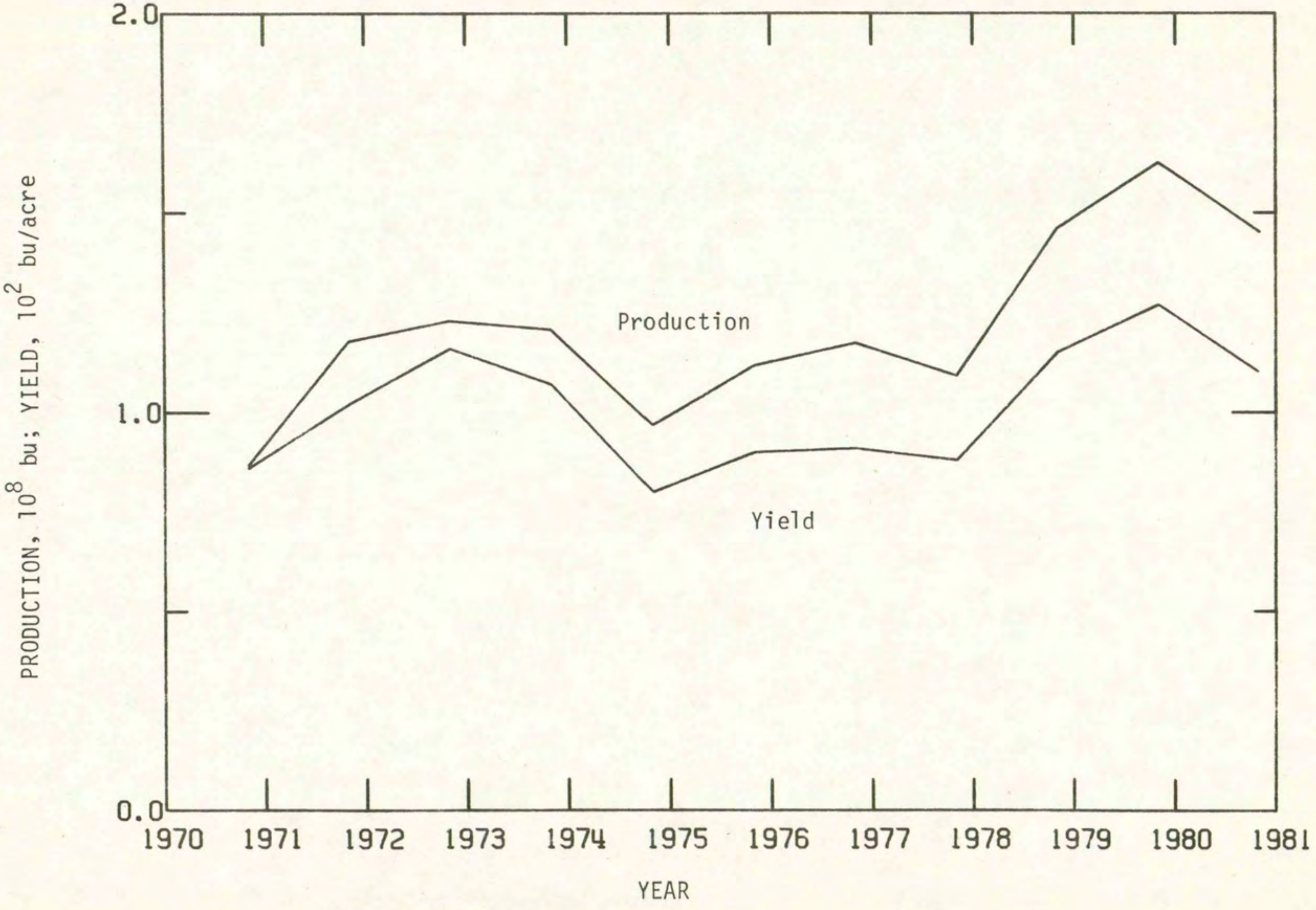

Figure 3.8 Production and Yield of Corn in Iowa

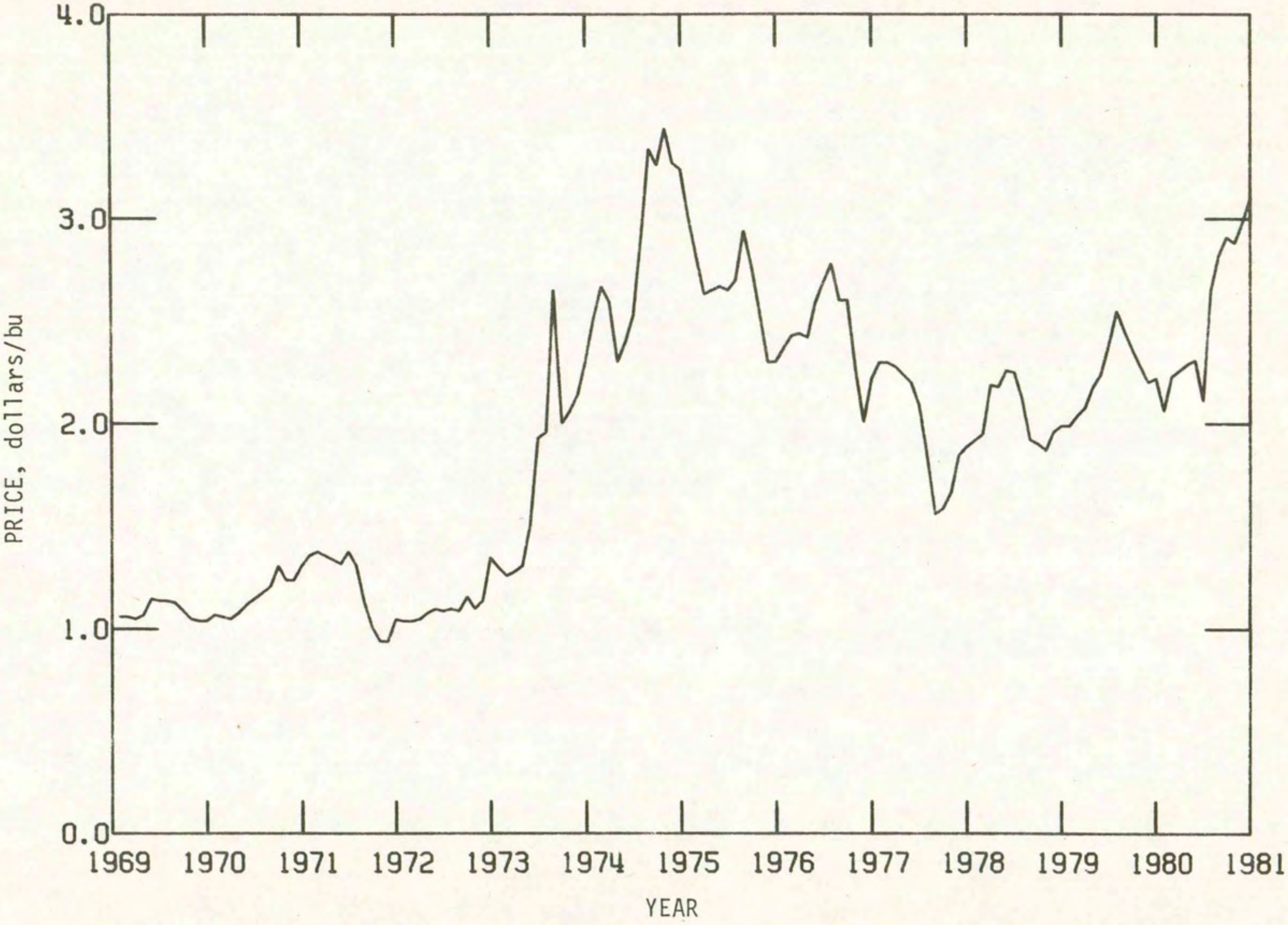

Figure 3.9 Monthly Average Prices of Corn Received by Farmers

the embargo as shown in Fig. 3.9. Prices generally declined after 1975 with a minimum reached in 1977. Since that time, prices generally increased with a current value of around \$3.15/bu. There is some question as to how much incentive do prices constitute in corn production. Many farmers feel that prices are maintained artificially low and that they cannot seem to cover their expenses, although this is not reflected by the area planted and harvested. Prices undergo a cyclic process in which they generally increase during harvest time and fall during the planting and growing season. This behavior accounts for the local fluctuations in prices.

Agricultural parameters seem to have significant influence on corn production. Soil quality would affect the yield because of the fertility of the land. No survey is yet available for Iowa although it is being conducted at this time [13]. Available land for corn planting has not increased significantly in the last decade whereas production is on the rise as seen in Figs. 3.4 and 3.5. This is attributed to improvements in fertilizer and chemical technologies as well as discoveries of new corn hybrids. Pesticides and weed controllers have to be applied very carefully and at the right time. In some instances, these chemicals were not applied properly. In 1977, an outbreak of European corn borers spread across the corn belt causing heavy damages to the crop. Usually two generations of corn borers develop during a crop. But in 1977, due to unseasonably warm weather, the growing period was long enough to allow for a third generation to mature. Since pesticides were not used to prevent the last generation from developing, the plunge in production is quite apparent for Iowa with the exceptions of the northeast districts as shown in Fig. 3.6.

Human factors have a significant impact on corn production. Depending on how fast the crops are harvested and the fields prepared in the fall, the farmer will be left with a certain amount of time to plan and plant the next crop. In the process of planning, a farmer has to make decisions regarding several questions: when and if to apply fertilizers, the costs of fertilizers and nitrogen stabilizers, and whether to increase the soil pH? The answers to these questions, varying from one farmer to another, will decide the yield for the year. Climatic conditions affect greatly the four stages in the corn production cycle which is divided into four periods as shown below.

STAGES	DURATION
PLANNING	End of November to mid-Aril
PLANTING	Mid-April and lasts 50 days
GROWING	March to August
HARVEST	Mid-September to end of November

Corn does not grow below an ambient temperature of 50 F [14]. The rate of growth increases until the air temperature reaches 86 F where it levels off. The concept of growth is better translated into growing degree days (GDD) defined by the following relation:

$$GDD = \Sigma(T_{ave}-50)$$

where $T_{ave} = (T_{max} + T_{min})/2$, $50 < T_{ave} < 86$. For $T_{ave} > 86$ F, then $T_{ave} = 86$ F, and for $T_{ave} < 50$ F, $T_{ave} = 50$ F.

A typical number of GDD for Iowa ranges from 2200 to 2700. Thus, a larger value of GDD would mean a shorter growing season. Cold weather in the spring can delay the planting season, and therefore, the corn will have a shorter time span to grow. In Fig. 3.10, the monthly maximum and minimum temperatures for each district in Iowa for the period of 1975 to 1979 reveal that the period in which the temperature is between 50 and 86 F is of the order of five months, from May to September. Thus, with a daily average temperature of 68 F, GDD is equal to 2700. The trend in the data shows that the temperatures across Iowa are fairly uniform on a monthly basis. Furthermore, the growing time for corn coincides with substantial storm activities in Iowa. Windstorms, hail, and flashfloods can cause severe damages to corn crops since the corn is above ground and most vulnerable. In Fig. 3.11, rainfall is plotted for each district. From the plot, it appears that 1974 was a dry year. Comparing the average rainfall for Iowa for the years 1974 and 1979 during the months of July and August, a significant difference appears. In the month of July, rainfall amounted 2.62 inch in 1974 whereas in 1979, 4.78 inch of rain fell in Iowa. Similarly, for the month of August, 4.70 inch of rain fell in 1974 as compared to 6.01 inch in 1979. The difference in averages seem to explain the sharp decline in production in the nation as well as in Iowa for 1974 as shown in Figs. 3.4 and 3.8, respectively. That year was referred to as the dust bowl of 1974 as compared to the dust bowl of the 1930's. Corn prices also increased more rapidly for that year as seen in Fig. 3.9.

Plants have a photosynthesis efficiency of 1 to 2 percent [15], which implies that only 1 to 2 percent of solar energy incident on a plant is

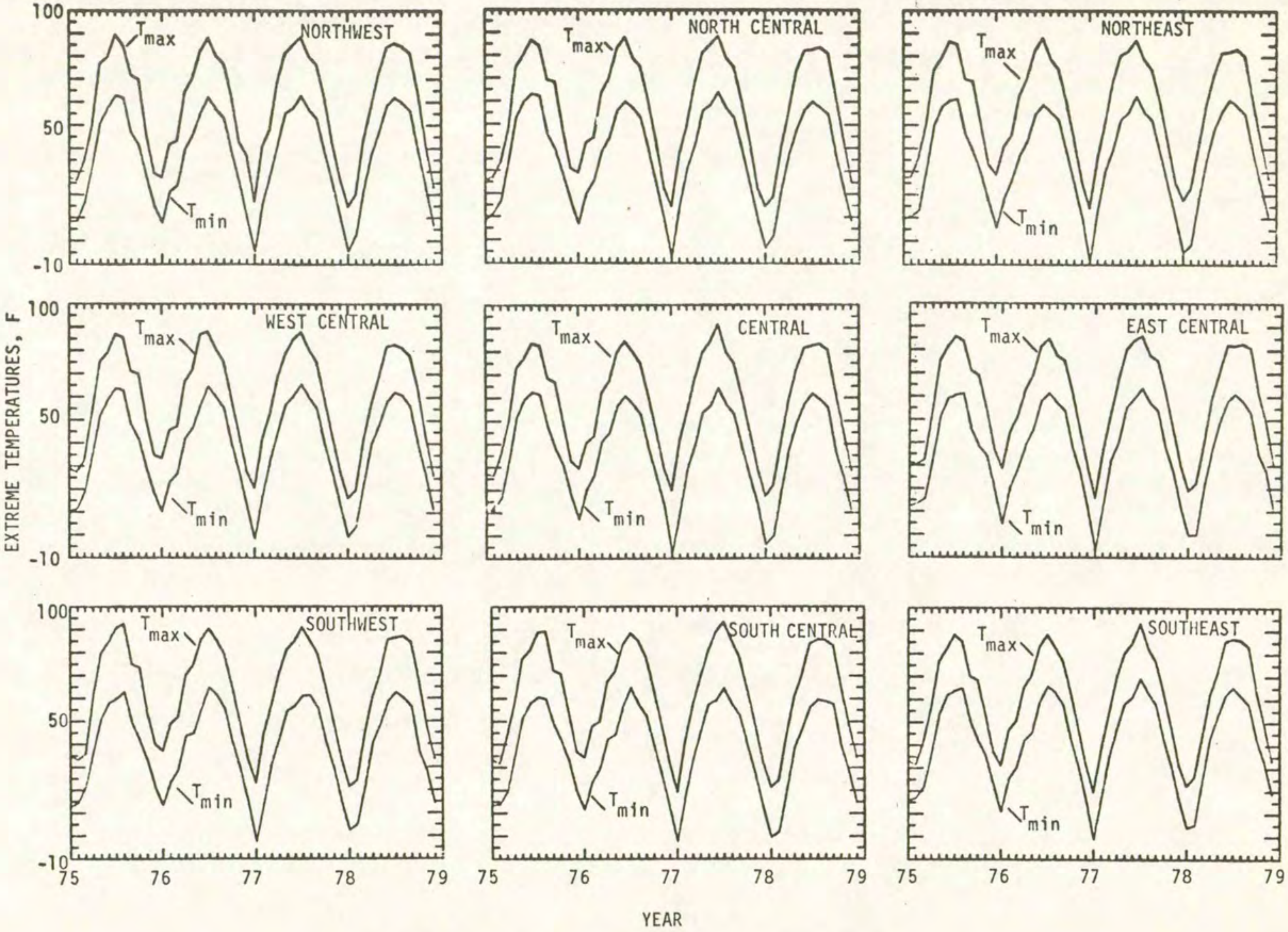

Figure 3.10 Extreme Temperatures for Iowa

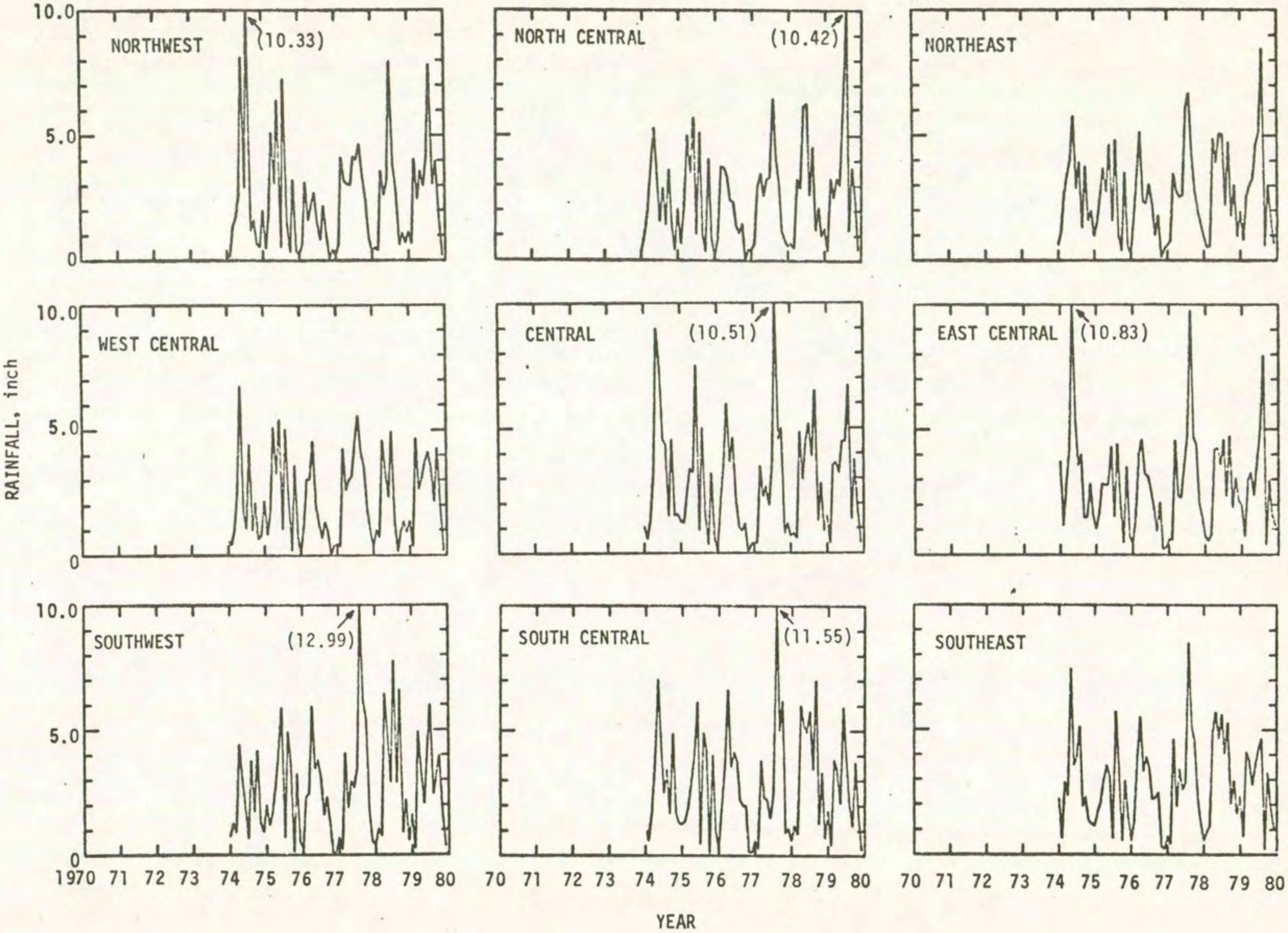

Figure 3.11 Rainfall in Iowa

used in the growing process. Several studies are being conducted in countries like Japan to increase the photosynthesis efficiency in plants like rice and corn [15]. By increasing this efficiency, it may be possible to speed up the growing process with less dependency on the climatic conditions.

3.3.4 Conclusions

Several factors affecting corn production have been listed and discussed. The quantity of corn available on the market is dependent on three major factors: climate, area available for planting, and yield per acre. The climatic factors affecting corn growing are rainfall and monthly average temperatures which should be above 50 F but less than 85 F. The area available for planting corn is limited. The prospect of any increase in area will be dependent on whether corn is favored over soybeans or other crops. Increase in prices of corn due to a rise in demand for alcohol production or exports might provide the incentive to farmers to plant corn instead of other crops. The yield of corn is largely dependent on the soil fertility as well as on breakthroughs in plant engineering. The discovery of new corn hybrids with fast maturing rates and usage of improved fertilizers are responsible for the increase in production over the last decade. It may be beneficial to examine the total agricultural sector before definitive statements can be made about the potential of growing corn in Iowa. In summary, with a yield of approximately 125 bu/acre and 14 million acreas of land devoted to corn growing as in 1979, corn production is around 1700 million bu.

3.4 Correlation

The purpose of this section is to examine the correlation between solar energy availability and corn production in Iowa. From the discussion on solar energy, the daily average of solar energy available in Iowa is of the order of 1311 Btu/ft^2 for a horizontal surface. From the discussion on corn availability, a question arises: would more solar energy imply an increase in corn production? The State of Arizona receives 1900 Btu/ft^2 or 45 percent more solar energy than Iowa [16]. However, growing corn in the Western United States might prove to be an impossible task. The reason is that climatic conditions and soil quality are more conducive to corn growing in Iowa. Although the sun is essential for any plant to survive, the amount of energy needed is not directly proportional to the rate of growth. Another factor affecting corn production is rainfall. Droughts have a significant influence on the amount of corn produced in a year as noted in the discussion on corn availability. Some herbicides are water dependent and their effect is negligible in the event of a dry growing season. Artificial irrigation would partly solve these problems but would contributed to an increase in cost of production and may lead to a rise in the salt content of the soil. On the other hand, an increase in rainfall might affect the corn in a negative way known in the agricultural sector as the drowning of a crop. For example, corn growing in equatorial regions will face serious problems as the corn will not dry due to excess moisture that characterizes the climate and, therefore, will spoil. In general, a location with high rainfall averages has a lower solar energy average since the humidity creates a haze which reduces the amount of solar energy reaching the earth.

In summary, solar energy and corn growing seem to be related but a delicate balance must exist between rainfall, solar energy, and air temperature. In the event of a major breakthrough in the improvement of the photosynthesis efficiency of a plant, corn growing will become a faster process and will be less dependent on climatic conditions.

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4. FERMENTATION PROCESS ANALYSIS

4.1 Introduction

The traditional methods for producing alcohol from sugars are being transformed into an energy efficient industrial process as the demand for fuel alcohol increases. Recent technological breakthroughs and re-application of standard technology have now begun to make this process feasible from the perspective of the net energy balance. For the present project the application of solar technology is responsible for the increased energy efficiency of fuel alcohol production. For the same reason the present fermentation process deviates from the standard practice. Due to the temperature available for heating with solar energy the evaluation of liquefaction efficiency, traditionally focusing on the starch conversion, was widened in scope to consider the amount of "boughten" energy used. The evaluation technique and results are discussed later.

The conversion of starch to ethanol involves three general processes, namely, preparation, liquefaction, and fermentation. The procedures for each process are briefly examined in the following disucussion. The preparation stage consists of procurement of the grain (corn in this study), grinding the grain to around 16-mesh size, and preparing a slurry of grain and water with typically 10-30 gallons of water/bu of corn. Liquefaction involves heating of the slurry to the gelatinization temperature range of the starch (150-300 F) followed by addition of an alpha/beta-amylase enzyme at 150-200 F to convert the starch to dextrins. The conversion of the dextrins to glucose (a fermentable sugar) occurs via addition of the enzyme glucoamylase traditionally at 140 F. Recent advances in enzyme technology have reduced this temperature, facilitating concurrence of this final conversion with the fermentation. Therefore, the conversion process is discussed in detail in the fermentation section. The first step in the fermentation process consists of cooling the mash to approximately 90 F which is followed by addition of the yeast to convert the glucose and water to ethanol and carbon dioxide in an exothermic reaction (heat is liberated). The final product is a 5-15 percent by volume ethanol/water solution and distillers grain (DG). Utilization of the DG entails a fourth process concerned with drying of the grain which is examined in a later discussion.

4.2 System Description

The following section gives a description of the two systems utilized for liquefaction and fermentation. Bench scale experiments were utilized to perform most of the preliminary research and temperature optimization studies. A one gallon bench scale vessel was fitted with an exterior jacket through which heat was added to the system via an electric heater. Cooling was accomplished by circulating cold water through the jacket. A small mixer that could be removed for the fermentation process was inserted in the vessel to provide agitation during cooking. With the mixer removed the vessel was fitted with a CO_2 vent and a temperature sensor and then sealed. All temperatures were measured with thermistors, including that used to regulate the heat input, which was accomplished by an electrical temperature control in line with the heater.

In addition, a cooker/fermenter with a 50 gal capacity was constructed to provide beer for the distillation unit. The production schedule required only one batch per week. This low production demand enabled the incorporation of the cooker and fermenter in the same vessel. As a result of this incorporation, equipment not normally associated with one of the processes may be found in the vessel as it is necessary for the other (see Fig. 4.1). The vessel was insulated as well as fitted with a sealable lid and heating coils. The heating coils, 100 ft in length, were of 5/8 inch copper tubing and utilized both for heating and cooling. Tap water at 45 F was used as the cooling fluid. The heating fluid was water rather than steam so as to be compatible with the capabilities of the solar collector. When the heating requirements of the system exceeded the capabilities of the collector or when solar energy was unavailable, additional heat was added to the system using an electrical heater as discussed in more detail in Chapter 5. Agitation was supplied by an electric mixer, fitted with a propeller, located 5 inch from the bottom of the vessel and an impeller positioned 8 inch below the surface of the fluid. The propeller provided circulation in the lower portion of the vessel, preventing settling of the grain. The impeller in the upper portion forced the slurry over the heating coils to provide uniform and efficient heat transfer. Two temperature sensors were placed in different regions of the vessel to make sure that the agitation was sufficient to prevent temperature gradients. Additionally, a pH probe was installed for monitoring of that variable, although it was found later that enzymes were available that required no pH adjustment.

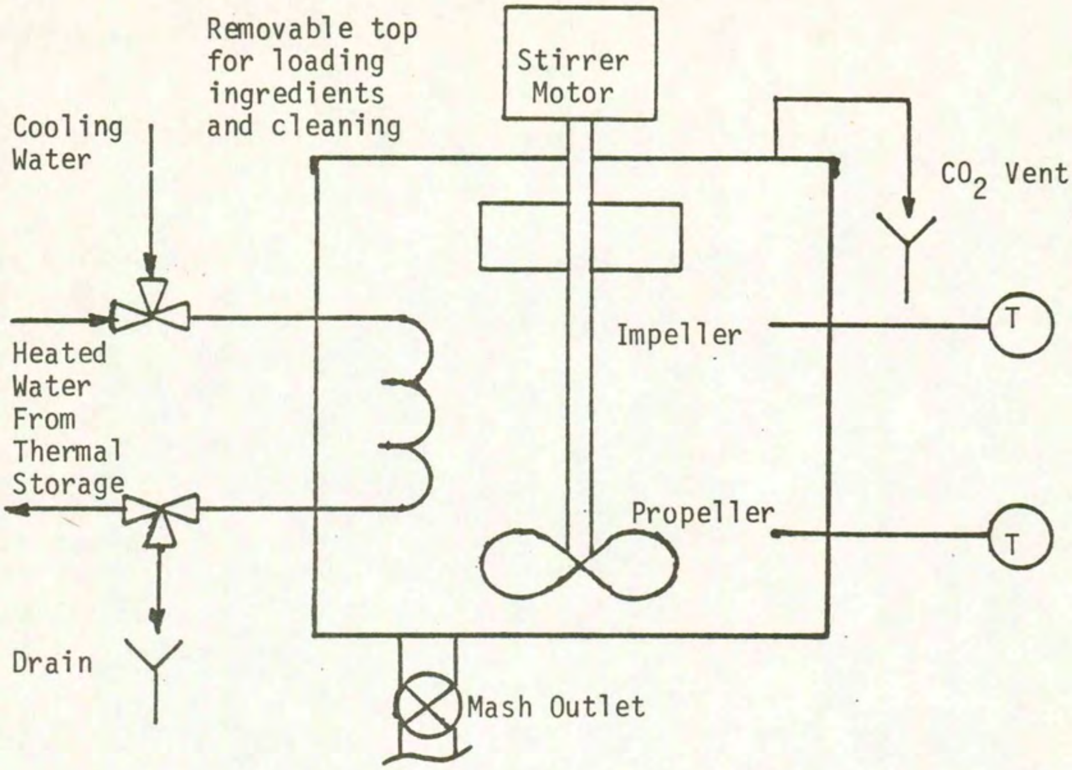

Figure 4.1 Cooker/Fermenter

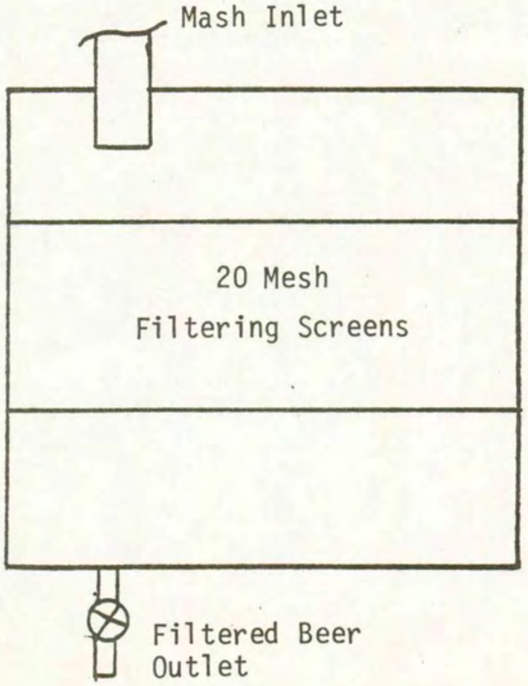

Figure 4.2 Mash Filter

It was of utmost importance to accurately determine the concentration of ethanol in the beer in finding the optimum liquefaction temperature. A simple density measurement of the beer as is commonly employed does not accurately reflect the alcohol content as dissolved proteins and unconverted sugars also alter the density. This problem was alleviated by distillating off 25 percent of the beer in the bench scale set up, which left behind the non-volatiles. The distillate was then analyzed with a gas chromatagraph. This result was then used to determine the ethanol concentration in the beer.

4.3 Process

4.3.1 Preparation

Ground corn was obtained from a local feed mill, although a more comprehensive study would have required purchase of grinding equipment and grinding the corn in the lab for greater size control. It has been suggested [1,2] that the ground corn should pass through a 16-mesh screen, a constraint which about 80 percent of the feed met. Due to the source, the quality of the feed and absence of foreign materials was assured. The first step performed was then the slurrying of the grain. The ratio of corn/water depends both on the type of cooker (for an extrusion cooker the amount of water is drastically reduced) and the enzyme used. For the present process 25 gallons of water per 56 pound bushel of corn were used, which was consistent with the enzyme manufacturer suggestion [3]. In forming the slurry, the corn was added to agitated water. This procedure prevented settling of the grain and assured proper blending of the grain with the water.

4.3.2 Liquefaction

With the slurry prepared, ALL-COHOLASE I (TM) [3] was added in the ratio of 24 grams per 56 pound bushel of corn. ALL-COHOLASE I is an enzyme of alpha-amylase activity, which is blended to work in the natural pH range of the slurry, thus eliminating pH balancing and monitoring. This was checked during the early stages of experimentation and found to be true for all the enzymes used. The slurry was then elevated in temperature by circulating heating water through the coils. Solar energy supplied the heat initially. As the slurry temperature approached that of the solar source (130-150 F), the solar source was discontinued and the additional heat was supplied by electrical heaters, as discussed in Chapter 5. As the temperature rises above 145 F gelatinization of the starch begins to occur and proceeds more rapidly until the mash reaches the holding temperature of 173 F. This gelatinization stage is the temperature limiting step of the cooking stage. While this step beings at 145 F, total gelatinization of the starch does not occur until the temperature is in excess of 300 F [4]. Therefore, total conversion of the starch is not obtained in this scheme, as it is the gelatinization step that swells open the starch molecules for attack by the enzymes. With the focus on making the system compatible with solar energy, it was desired to reduce the temperature and holding time of the gelatinization step. To this end, treatment with a protease (an enzyme which breaks down the protein structure) at 140 F was investigated. It was anticipated that breaking down the protein case around the starch, thus making the starch more available for enzymatic attack, would reduce the required intensity of gelatinization conditions. From lab testing, it was concluded that there was no significant difference in the conditions required for a given degree of conversion with or without this pre-treatment. Therefore, as this step further complicated the process, it was deleted after the initial testing. With the starch gelatinized, the enzymes then begin to break down the starch, essentially a chain of sugar molecules, into complex sugars (dextrins). It is at this point that the slurry reaches its maximum viscosity (460) cP [5]), for as the starch gelatinizes the slurry thickens and once the starch starts converting to dextrins it thins down again. Hence, it is the mixing of the gelatinized but pre-liquified starch that places the constraints on the agitation. The process utilized here reduces this, in that the gelatinizing temperature used was compatible with the liquefaction enzymes, thereby allowing concurrent gelatinization and liquefaction. If a temperature above 175 F had been used for gelatinization, the slurry would have to be cooled before addition of the enzymes and, hence, liquefaction. After 2 hr, the conversion process has essentially reached completion, and cooling is initiated to bring the mash down to the temperature for the final step, fermentation.

4.3.3 Fermentation

The cooling is continued until the mash reaches 90 F. It is important that the cooling be rapid (30 min maximum), as it gives microorganisms which compete with the yeast a head start, which results in side-products. At this point the mash is not yet fermentable, as yeast acts only on simple sugars and not dextrins. To breakdown the dextrins to a fermentable form a glucoamylase must be added. As noted before the reason for inclusion of this step under the fermentation section is that the two processes may proceed concurrently. The glucoamylaze selected, ALL-COHOLASE II (TM) [3] is active at 90 F and compatible with the natural pH of the system. Thus, by adding 12 grams of ALL-COHOLASE II and 24 grams of yeast per bushel of corn, a fermentable solution is made available for the yeast and the time necessary for an independent conversion is deleted. After agitation for 30 min to assure proper mixing of the enzyme and yeast in the slurry, the vessel was sealed and fitted with a vent for the carbon dioxide. The mash was then allowed to ferment for about 3 days. During fermentation, it was found to be advantageous to agitate the mash for about 15 min twice a day to assure that concentration gradients of enzyme, feed, or product do not occur. As the fermentation reaction is exothermic, it was not necessary to add heat to the system to maintain the desired 90 F fermentation temperature. In fact a slight excess of heat was generated, necessitating a small amount of cooling about once a day. The relative rate of fermentation was checked by monitoring the rate of CO_2 emission from the vessel. This was undertaken by counting the number of bubbles emerging from the vent for a minute. After 3 days, the bubble rate was reduced to 10 percent of the maximum and the fermentation was essentially complete. The result of the fermentation is a solution of about 10 percent alcohol by volume in water containing DG. The next step is then to concentrate the alcohol and remove the DG, as the present mixture is hardly a viable engine fuel. Two possible approaches exist for removal of the DG, namely, removal prior to distillation, or feeding the mash as is to the distillation unit and removing the solids from the bottoms product. In the latter case agitation must be supplied to the reboiler to prevent settling of the solids in the reboiler and after removal the DG may be separated from the liquid or used in its present form. As the reboiler was not equipped with agitation, the first approach was used. Several varieties of equipment might be used for the removal of the solids, such as centrifuges or filter presses. In the present study a simple gravity flow through a screen was used (see Fig. 4.2). As the corn ground to 16 mesh, a 20 mesh screen was used to filter out the corn particles. This removed all but very fine particles which were left in the beer and feed to the distillation unit. The major draw back to this approach is that the moisture retained by the solids also contains alcohol, about 10 percent by volume, whereas if the separation occurs after distillation the liquid absorbed would contain only about .005 percent by volume alcohol. Clearly this problem becomes more significant as the moisture retained by the DG increases. For the present system the DG was 75 percent liquid by weight. Obviously if the solids are to be removed prior to distillation, the moisture content of the solids must be reduced. High moisture content also makes handling and storage of the DG more difficult, therefore, drying is probably a necessity and is examined in the next section.

4.4 Distillers Grain Drying

The purpose of this study is to determine the feasibility of drying distillers grain (DG). In the production of fuel alcohol using corn as a fermentable substance, 7.5 pounds of DG ar obtained on a dry matter basis per gallon of alcohol. Analysis of laboratory produced DG revealed that the moisture content is 75 percent after the mixture is strained with a 20 mesh screen and a cheese cloth. Therefore, a batch of DG weighs 30 lb_m and contains 22 lb_m of water per gallon of alcohol. The drying of DG is required for two primary reasons, namely, handling and spoiling. For the DG to remain preserved, the moisture content should be of the order of 15 percent as is the common practice in the agricultural sector when corn is stored. Mechanical presses or centrifugal separators can be used to reduce the water content to 30 percent or 3.21 lb_m of water [6]. A further reduction in moisture content to 15 percent requires the removal of 1.89 lb_m of water. Is is, therefore, important to determine the amount of energy necessary to dry the DG.

Drying of a solid-liquid mixture is generally performed by circulating heated air through or over the wet solid. The different types of dryers are:

a) Tray Dryer: In this process, the mixture is spread in a thin layer on a tray. Heated air is then passed over the tray and the moisture is removed. Another version of this process is tunnel drying where the mixture is deposited on a conveyor belt which passes through a tunnel containing circulated heated air.

b) Modified Spray Dryer: The mixture is fed into a tower in the form of a spray. As the mixture falls through the tower, it encounters a current of upward flowing heated air. The solid is collected at the bottom of the tower and recirculated to the top for several passes.

c) Rotary Dryer: The mixture is injected into an inclined rotating cylinder and encounters a heated air current.

In an air drying process, energy from the air is transferred to the mixture increasing its temperature. However, if the mixture is at the saturation temperature, the energy which evaporates the water is referred to as the latent heat of vaporization h_{fg}. For example, at a temperature of 140 F, h_{fg} is 1014 Btu/lb_m for water [7]. The following factors affecting the rate of moisture removal in the DG must be analyzed:

a) DG temperature: The initial temperature of the DG determines the amount of sensible energy required to reach the saturation temperature at which the energy is utilized to evaporate the water.

b) Moisture content of DG: If the initial moisture content of the DG is low, less energy is necessary to dry the mixture. It is, therefore, advantageous to mechanically reduce the moisture level as much as possible.

c) Diffusion rate of the water: Water resides in the DG and must diffuse from the inside to the surface of the layer where it is removed by the air. The rate at which the moisture diffuses through the DG is called the diffusion rate. In the case of tray drying, if the thickness of the layer is large and the diffusion rate is low, moisture at the top layer is removed whereas the bottom levels remain at an intermediate moisture content. This phenomenon is called stratification.

The following properties of the air influences the rate of moisture removal from the surface:

a) Air temperature: The ambient air temperature affects the amount of energy required to raise the air to the operating temperature.

A portion of this energy could be supplied by the heated exhaust air.

b) Moisture content of air: The moisture content of air reduces the amount of water that can possibly be removed from the DG. In Iowa, the summer air has a high relative humidity and the winter air is characterized by a low relative humidity. This variation of the air humidity causes the performance of the dryer to decrease in summer and increase in winter.

c) Air velocity: The air velocity affects the rate of mass transfer between the DG and the air. Beyond an optimum air velocity at which the removal rate is maximum, the rate of diffusion is not large enough to diffuse the water to the surface which becomes dehydrated where the bottom of the layer remains moist. The rate of moisture transfer also depends on the type of air flow over the sample (laminar or turbulent).

Limited experiments were conducted where around 1.50 lb_m of DG was spread in a layer on a tray and heated air at 127 F was circulated over the sample. The thickness of the layer was approximately 0.25 inch and the area of was about 133 $inch^2$. The DG had an initial moisture content of 75 percent. The mass of the sample was recorded at regular intervals, and a water removal rate of 0.3 lb_m/hr was computed. These results indicate that 6.3 hrs are required to remove 1.89 lb_m of water per gallon of alcohol. It should be noted that these results are very limited in scope and may not be applicable under all conditions.

The minimum amount of energy required for the drying process is now examined. The actual energy is higher if the dryer efficiency is included and sensible energy is needed. The analysis is conducted for a production rate of one gallon of alcohol per hour. The energy required to dry the DG is the product of the mass of water to be removed and h_{fg}. Based on the laboratory produced DG, the energy to remove 1.89 lb_m of water is 1900 Btu/hr with the assumption that the DG is at the saturation temperature and an alcohol production rate of 1 gal/hr.

Since information on DG drying is unavailable, the energy requirement for the drying process cannot be readily supplied. This study presented the minimum energy for drying DG and this value is dependent on various factors cited previously. Other concerns related to drying DG are quality control, humidity control, and baking on the drying equipment resulting in frequent cleaning. Further studies are necessary to determine the diffussion rate of the DG and to achieve an efficient drying equipment design.

4.5 Results

As previously stated, a temperature of 173 F was found to be the optimum for the gelatinization/liquefaction cooking, and that this temperature should be held for 2 hours. This procedure results in a beer that is 9.57 percent by volume ethanol, which is a yield of 2.23 gal. of ethanol per bushel of corn.

A brief discussion on the methodology used to determine this temperature is presented. Traditionally, the emphasis in cooking conditions has been on maximum conversion of the starch to dextrins, rather than optimizing the ratio of energy output (ethanol) to energy input (cooking and distillation). Analysis of the experimental results presented in Fig. 4.3 reveals that as the cooking temperature increases the conversion to ethanol follows the law of diminishing returns, while the energy required to elevate the temperature increases drastically. Further discussion of Fig. 4.3 is presented later. Therefore, it is obvious that a temperature exists that optimizes the aforementioned energy ratio and locating that temperature is the focus of this discussion. The merit of this approach is obvious, in that it maximizes the producer's rate of energy return. The fact that all of the starch may not be utilized in this process is not of a concern for the on-farm producer. The farmer would be using excess grain for alcohol production with the residual DG utilized as livestock feed. Hence, regardless of the extent of conversion, all the starch is used, either for ethanol or feed.

The necessary information for this optimization is then, the input energy for cooking and distillation, and the output energy as useable energy in the ethanol. As discussed in Chapter 7, the intended usage of the alcohol affects this usable energy value it is subject to controversy. Therefore, the input energy is normalized on a per gallon ethanol basis, which eliminates the need to chose a usable energy value for the alcohol. The optimal value is then the temperature which requires the minimum energy input on this per gallon basis. The problem is further simplified when it is applied only to the "boughten" energy. All of the energy for distillation and cooking up to 130 F is supplied by the solar source.

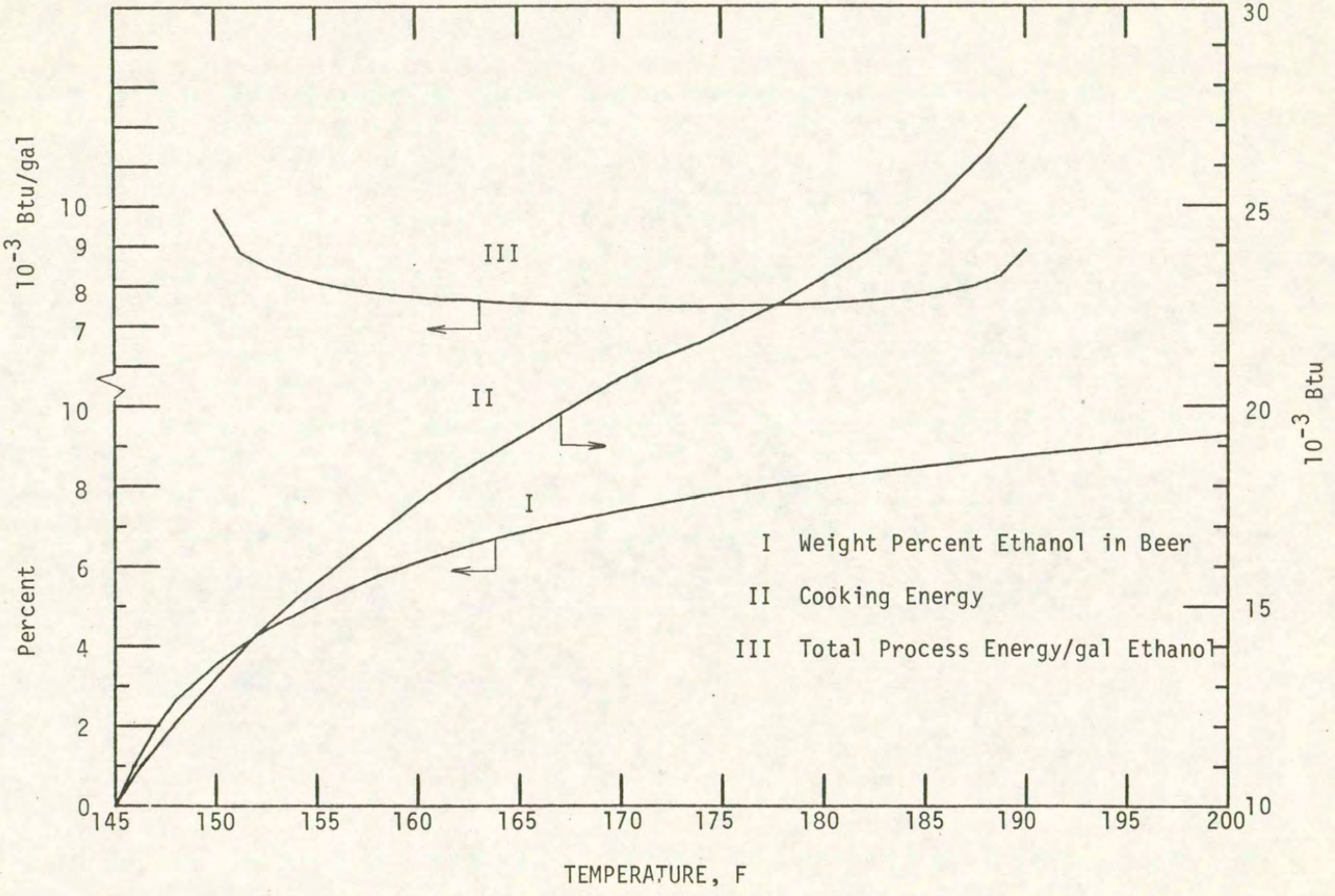

Figure 4.3 Optimization Data

This "free" energy is not included in the optimization. Hence, the energy considered in the optimization is only that necessary to raise the mash temperature above 130 F.

The optimal holding time, the cooking time necessary for maximum liquefaction, was determined at temperatures between the gelatinization point (145 F) and the maximum obtainable with the heat source (200 F). These optimum conversions, recorded as weight percent ethanol in the beer, are displayed in Fig. 4.3 as a function of the temperature at which they occurred. The upper conversion limit of 11.64 percent, was computed from the stoicheometric equations and would yield 3.38 gal/bu. The energy required during each of the optimal converions is also presented as a function of temperature in Fig. 4.3. The large increase in required energy with increasing temperature is principly due to the increasing heat loss from the cooker. The third result given in Fig. 4.3, a plot of the normalized energy input, was constructed by division of the input energy values by the yield of alcohol calculated from the conversion curve. It is from this curve that the optimum temperature of 173 F is located.

While this process of evaluation is applicable to any production system where the unconverted starch can be utilized, the temperature reported holds only for the system used in this project. A change in cooker design, utilization of "boughten" energy for distillation, a different grain to water ratio, or even different enzymes would alter the results.

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5. DISTILLATION PROCESS ANALYSIS

5.1 Introduction

Distillation is the process whereby a dilute solution of alcohol and water is enriched to an alcohol concentration suitable for fuel usage. The distillation process consumes a significant amount of energy. Typically, distillation energy requirements are 15,000 to 25,000 Btu per gallon of 90 percent alcohol - 10 percent water fuel alcohol. Since a gallon of this fuel contains 76,000 Btu, the distillation energy consumption becomes significant.

The purpose of this section is to review the theory of distillation and to present experimental results of the solar assisted vacuum distillation unit.

5.2 Distillation Theory

5.2.1 Introduction

The mixture produced by the fermentation process contains from 5 to 10 percent alcohol by volume. The most common process for raising this composition to the purity required for fuel is fractional distillation, which takes advantage of vapor-liquid equilibrium. The basic concepts related to fractional distillation are discussed here in order to provide a background for the experimental and simulation studies.

5.2.2 Equilibrium

For alcohol-water mixtures, when liquid and vapor are in equilibrium at a constant pressure, the vapor is enriched in alcohol compared with the liquid. However, for an 89 mole percent liquid at one atmosphere pressure, the equilibrium vapor composition is also 89 mole percent. This is the azeoptropic composition. Above 89 mole percent, the vapor has a lower alcohol content than the liquid. This is shown in the temperature-composition diagram for alcohol in Fig. 5.1.

In Fig. 5.1, a solution with composition x_1 at temperature A is all vapor, at temperature B it is all liquid, and at temperature C it is a mixture of liquid and vapor. The composition used are usually mole fractions, as this simplifies calculations. Sometimes a "fictitious molecular weight" of one substance is used in calculations, to make molal latent heats equal. When Liquid B, with composition x_1, is heated, the first vapor (a bubble) appears at temperature D. This is the bubble point for that composition. The composition of the vapor is found at point E. When vapor at A is cooled, the first drop of liquid (dew) appears at F. This is the dew point temperature for that composition. The composition of this liquid is found at point G. The temperatures cited in Fig. 5.1 are for a pressure of 760 mm Hg, corresponding to atmospheric conditions.

For distillation calculations, it is convenient to plot the vapor composition (y) against the liquid composition (x) as shown in Fig. 5.2 for two different pressures of 100 and 760 mm Hg. Each point on a curve is for a certain temperature, which varies from one end of the diagram to the other. The 45 degree line is drawn for reference. Since $y = x$ at the azeotrope, the curves at this composition are on the 45-degree line.

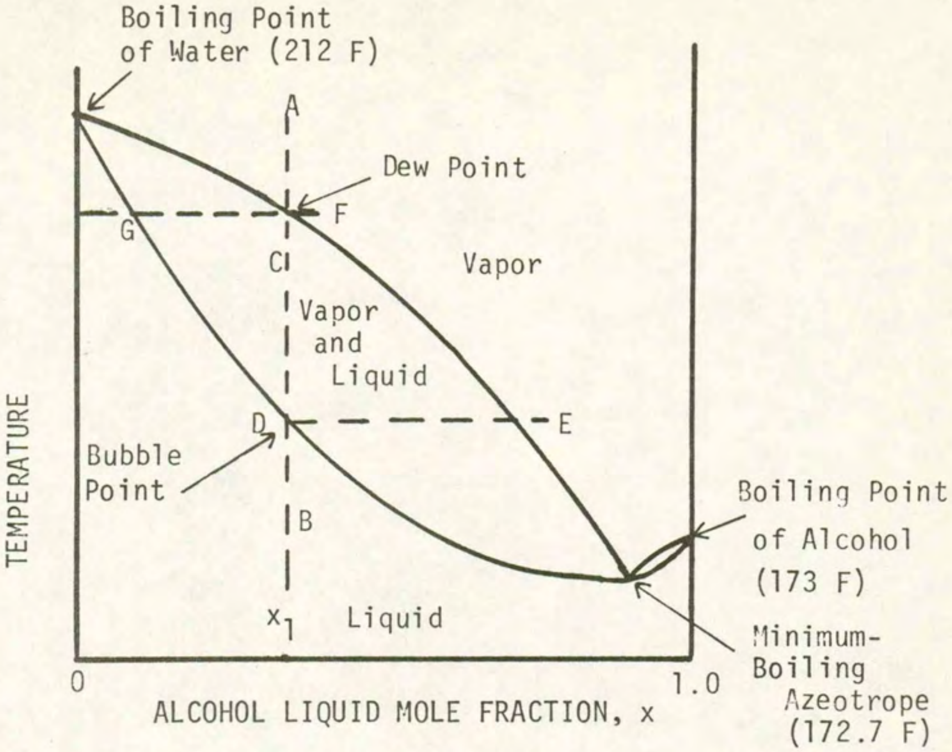


Figure 5.1 Boiling point diagram for alcohol-water

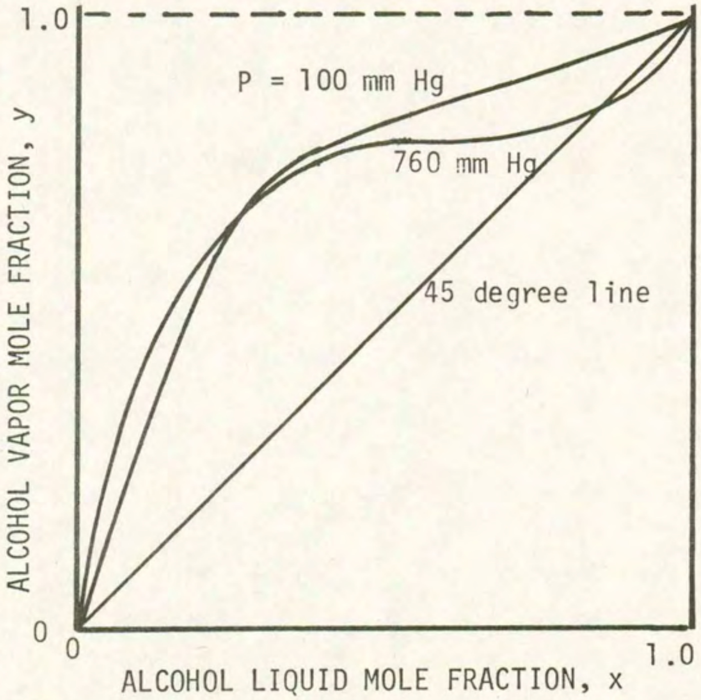


Figure 5.2 Equilibrium diagram for alcohol-water

Data are available [1] for different pressures. The azeotropic composition tends toward 100 percent as the pressure is reduced, and below about 100 mm Hg there is no azeotrope [2].

5.2.3 Continuous and Batch Distillation

Distillation may be either continuous or batch. Continuous distillation is most common, as it requires less attention than batch operation. A continuous distillation unit used to perform the fractional distillation consists of a reboiler, a column, and a condenser as shown in Fig. 5.3. Feed (F moles/hr, composition, x_F) enters the column. Liquid flows down the column, contacting vapor which is generated in the reboiler by the addition of energy Q. A portion of the liquid which reaches the reboiler is vaporized, and the remaining leaves as a bottom product (B moles/hr, composition x_B). Vapor reaching the top of the column is condensed in the condenser, and part of the liquid thus formed is returned to the column as reflux. This reflux is necessary to provide contact between the liquid and vapor so that enrichment of the vapor can take place. The remaining liquid leaves as distillate produce (D moles/hr, composition x_D). The part of the column below the feed injection point is the stripper section, and that part above is the rectifier section.

To analyze the operation of the continuous distillation process, the concept of an equilibrium stage, often called a theroetical plate, is introduced. On a theoretical plate, there is equilibrium between liquid and vapor leaving the plate. For a given separation, the number of theoretical plates is found by a step-wise procedure, called the McCabe-Thiele diagram after its originators [3].

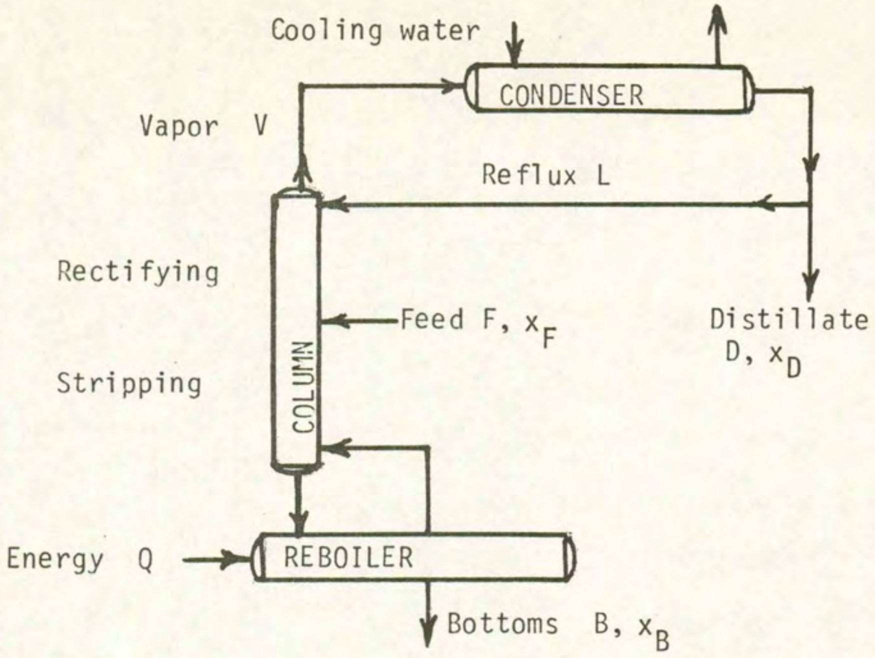


Figure 5.3 Diagram of distillation unit

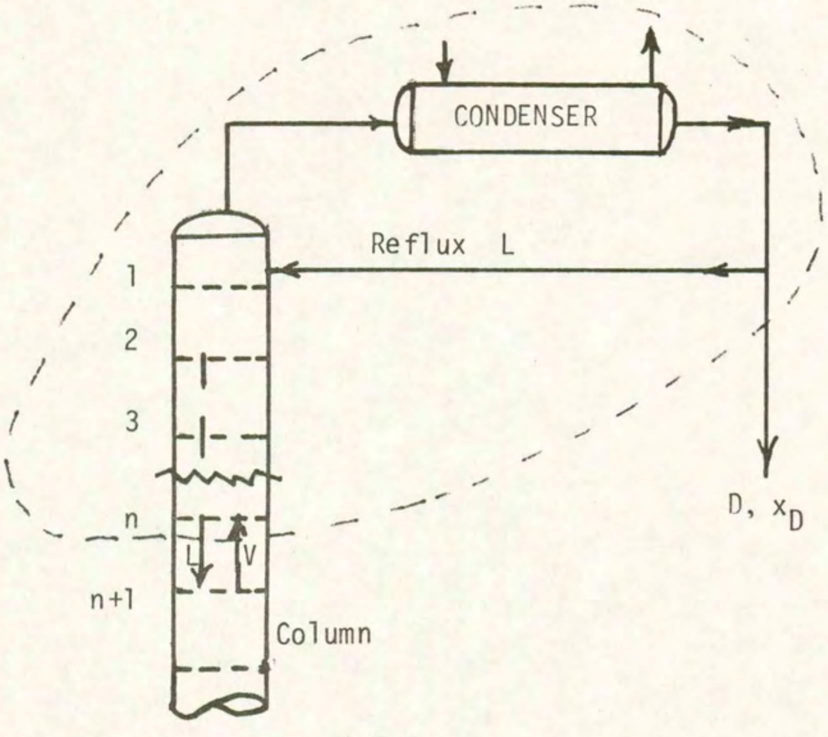


Figure 5.4 Material balance for top of column

The theoretical plates are numbered from the top, as plate 1, 2, 3, ..., n+1, ..., as shown in Fig. 5.4. A mass balance of alcohol around the first n plates yields

$$Vy_{n+1} = L\, x_n + D\, x_D \tag{5.1}$$

or

$$y_{n+1} = \frac{L}{V} x_n + \frac{D}{V} x_D \tag{5.2}$$

where L is the liquid flow rate in moles/hr, and V the moles of vapor/hr.

The McCabe-Thiele procedure is to plot this equation as the operating line so that if x_n is known, y_{n+1} can be calculated. A heat balance based on Trouton's rule leads to the conclusion that L/V and D/V (mole ratios) are constant (except as changed by the feed), so Eq. (5.2) is a straight line with a slope L/V and intercept D x_D/V. Also, when $x_n = x_D$,

$$y_{n+1} = \frac{L}{V} x_D + \frac{D}{L} x_D = \frac{(L+D)}{V} x_D = x_D \tag{5.3}$$

The McCabe-Thiele procedure as in Fig. 5.5 is outline below:

1. Draw the operating line

2. Start at y_1, which is equal to x_D by Eq. (5.3) on the 45-degree line. This is the composition of the liquid going to plate 1.

3. From the equilibrium curve, located x_1 in equilibrium with y_1.

4. From the operating line Eq. (5.2), find y_2.

5. Proceed to step off plates in this manner until the feed plate composition is reached. A new L/V is found below the feed, leading to a different operating line, which starts at the bottoms composition x_B and ends at the feed composition x_F.

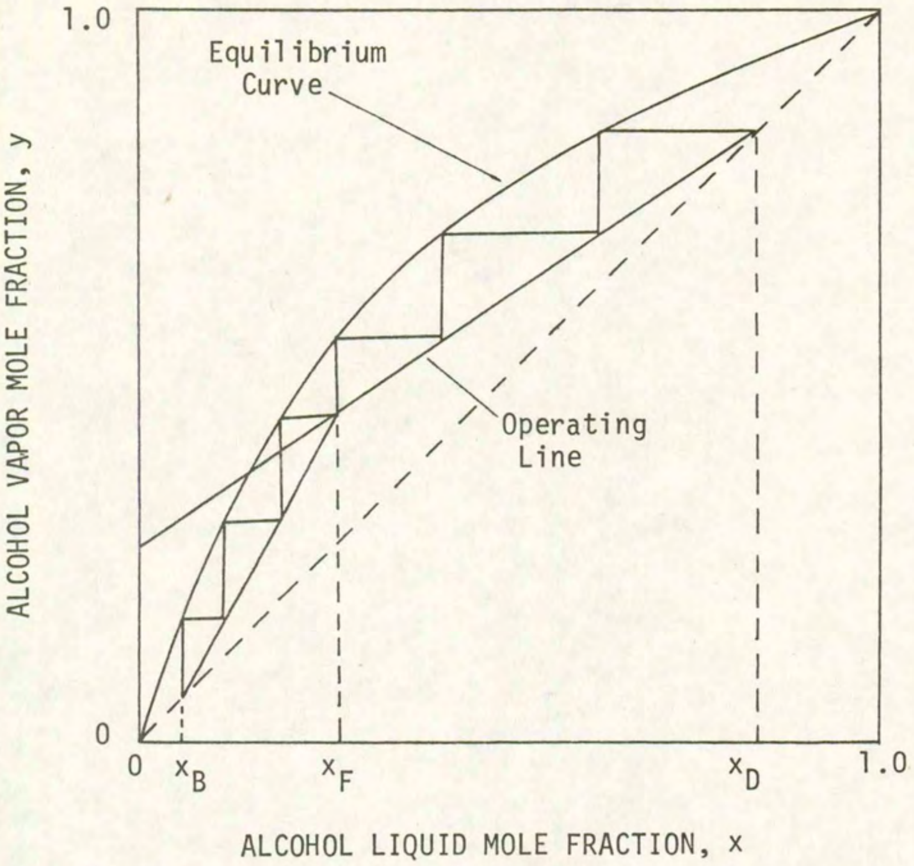


Figure 5.5 Theoretical Plates

In batch distillation, there is no feed to the column. A charge of feed solution is placed in the reboiler and heated to form a vapor. At the top of the column, vapor is condensed and the liquid returned to the column as reflux for vapor-liquid contact. The concentration in the reboiler decreases as the distillation proceeds. As the bottoms composition decreases in alcohol content, either of two different modes may be utilized: a) reflux remains constant, with resultant decrease in x_D or b) the reflux ratio increases to keep x_D constant. When the concentration in the reboiler falls to a desired value, operation is discontinued.

5.2.4 Vacuum Operation

Operation under a vacuum is frequently used in distillation, primarily to lower the operating temperature. This is a necessity when using a non-concentrating solar collector as the source of process heat, since the efficiency of a solar collector is higher at lower temperatures. Vacuum operation for separating ethanol-water mixtures also has the advantage that the azeotrope disappears at a sufficiently reduced pressure (100 mm Hg for alcohol-water), making possible a higher product concentration. There are, however, some disadvantages. These include the cost of a vacuum pump, the cost of its operation, a possible requirement of lower temperature cooling water to the condenser, and the necessity for special arrangements for removing the distillate and bottoms which are under vacuum. In continuous operation, the bottoms product and the distillate must each be pumped from the operating vacuum up to atmospheric pressure for removal while the distillation is proceeding. The column must be larger for a given rate of production, since the density of the vapor is lower at reduced pressures. Operation under a vacuum in general requires more care and control.

In batch operation, the reboiler is filled and the entire apparatus, including a receiver for the distillate product, is put under vacuum. The distillation proceeds to its conclusion without the necessity of breaking the vacuum.

5.2.5 Conventional Distillation

In conventional alcohol distillation, heating is performed by injecting steam directly into the liquid contained in the reboiler. This has two advantages, namely, it avoids the cost of heating coils and the condensed steam dilutes the bottoms stream, which may make disposal more convenient. Use of open steam would not be feasible when using a non-concentrating solar collector, since the heat transfer medium is typically water. Besides, if it is desired to recover the soluble material in the bottoms, dillution would be a disadvantage.

In the fermentation process, the starch in the corn is converted to alcohol. Some protein and dextrose go into solution, but the rest of the corn remains as solid material. Ordinarily this solid would be removed before distillation, since it would tend to plug up the column and foul up the heating surfaces. It is the practice in alcohol distillation, however, to include the solids along with the liquid feed to the reboiler. With open steam there is no heating surface to foul, but the column packing must be carefully chosen to avoid plugging. Further, if it is planned to dry the insoluble material to be used as feed for livestock, separation of the solid from the fermented solution seems desirable before the distillation process.

5.2.6 Column Height

Distillation columns may be either plate-type or packed. According to Peters [4], plate-type columns are more suitable for large diameter columns, whereas packed columns are recommended for small diameters. For plate-types, such as bubble-cap columns, the efficiency depends on the design, the properties of the materials being distilled, and the conditions of operation. The number of plates actually required is equal to the number of theoretical plates divided by the overall efficiency.

Several different types of packing are available, varying in efficiency and in pressure drop [5,6]. The efficiency is usually expressed as the height equivalent to a theoretical plate (HETP). Having calculated the number of theoretical plates the total column height is evaluated from [3]:

$$Z = N_0 \times \text{HETP} \tag{5.4}$$

where N_0 is the number of theoretical plates. The HETP is measured experimentally, although there are empirical equations for some packings.

Another method of calculation involves the concept of a transfer unit. Although the basis of this method is closer to reality, the simplicity of the HETP method has kept it in widespread use.

The required column height is influenced by the reflux ratio, which in turn affects the heat requirement and column diameter. A large reflux ratio requires fewer theoretical plates, down to a minimum number at total reflux. Reducing the reflux ratio leads to a larger number of theoretical plates but a lower heat requirement and a smaller diameter for the column.

There is, however, a minimum reflux for which the column height is infinite. Between the two limits of total reflux and minimum, there is an optimum value which balances the annual fixed charges on the column with the cost of process heat.

5.2.7 Pressure Drop

The resistance to vapor flow in a column requires a higher pressure at the bottom than at the top. This pressure drop depends on the column diameter. Operation at too high a velocity causes flooding as well as an excessive pressure drop. In flooding, vapor entrains so much liquid that the column fills with liquid and the liquid spills out the top. Pressure drop becomes particularly significant for vacuum distillation. The pressure drop over a column may be a large fraction of the total pressure. Thus, for a given vacuum at the top of the column, the vacuum in the reboiler is reduced with a resultant increase in distillation temperature. Packing characteristics are available from the manufacturer from which the pressure drop can be calculated for specified conditions of operation.

5.3 Experimental Distillation System

5.3.1 System Description

The experimental distillation system has two major components, namely, the heat source for process heat and the distillation unit. The heat source consists of a 55 gallon thermal energy storage tank which is connected to a 200 ft^2 flat plate solar collector array constructed of modules described elsewhere [7,8]. Two electric resistance heaters are immersed in the storage tank to provide a back up energy system. The electric heaters have a combined 6 kW power capacity and consist of 1 and 5 kW units. The latter heater is temperature controlled to yield a constant temperature source of heated water. The heaters provide for more flexible operation of the distillation unit.

The heat source and distillation unit are serviced by the heat source and process loops as shown in Fig. 5.6. Water is the heat transfer medium in these loops, and the loops are joined at the thermal energy storage tank. One specific advantage to the system configuration is that flow to the solar collector array can be varied for optimal operation of the array, and flow to the distillation unit can be controlled for temperature regulation. Water from the two loops is mixed in the storage tank, hence, there is no temperature drop across a heat exchanger at this point. The heated water in the process loop passes through a 165 linear feet, 5/8 inch outside diameter copper tube heat exchanger in the reboiler of the distillation unit. The reboiler is the point where thermal energy is added to the distillation unit.

The distillation unit shown schematically in Fig. 5.6 and pictorially in Fig. 5.7 consists of the following sections:

a) Reboiler - a 3 ft diameter by 3.5 ft long cylinder with heat exchanger to transfer thermal energy to the distillation unit. One end of the reboiler is removable for access to the heat exchanger.

b) Stripper Column - 15 ft high, 4 inch inside diameter column packed with 1/2 inch Norton saddle ceramic packing. This column is composed of three 5 ft sections. Feed is introduced at a distance of 5 ft from the top of the reboiler. The stripper column separates most

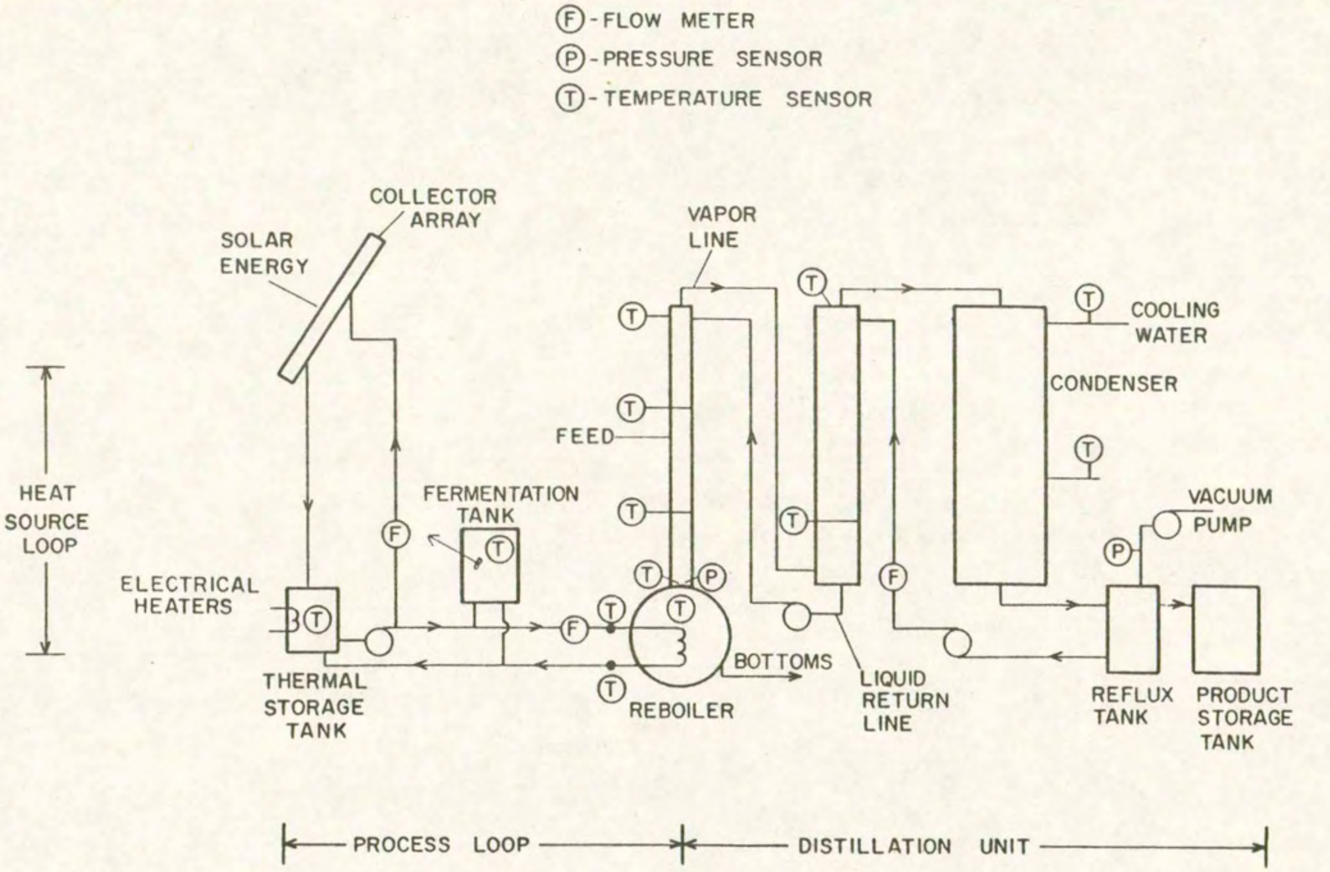
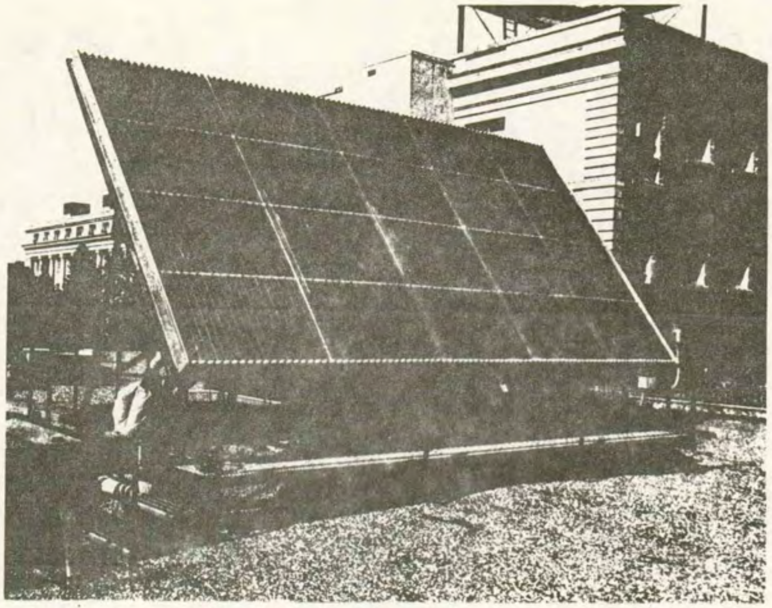
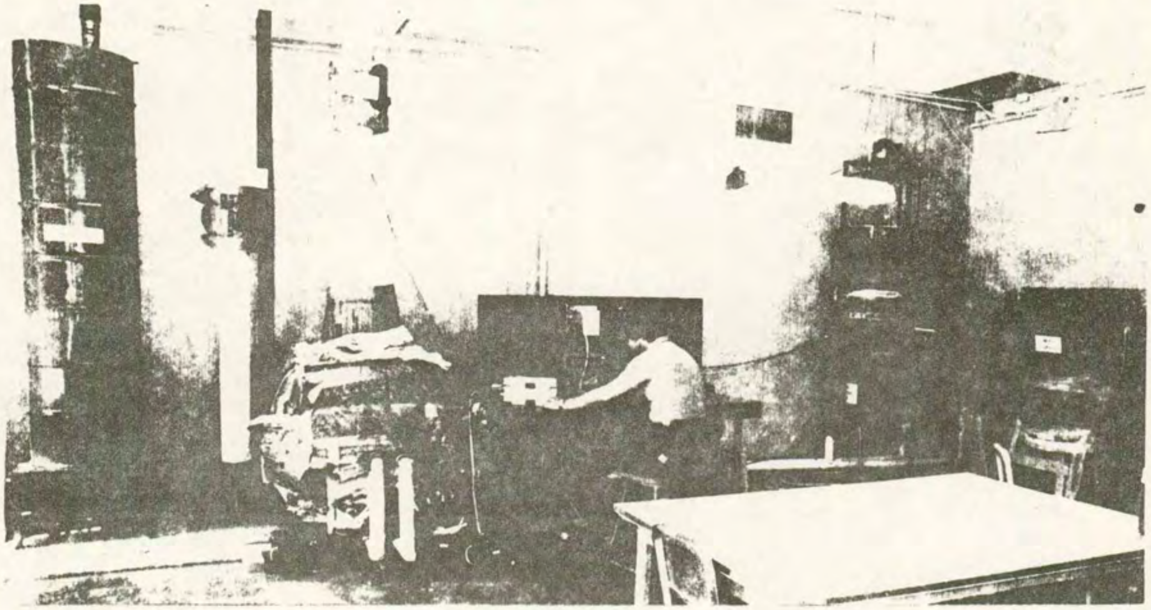


Figure 5.6 Schematic Diagram of Distillation System



(a) Solar Collector Array



(b) Distillation Unit

Figure 5.7 Solar Assisted Distillation System of the water from the feed, with the water going into the reboiler. The alcohol-water vapors from the top of the stripper column are injected at the bottom of the rectifier column.

c) Rectifier Column - 15 ft high, 4 inch inside diameter column packed with 1/2 inch saddle packing. The column consists of 5 ft and 10 ft sections. In this column, fermented corn is distilled to fuel grade concentrations. Liquid accumulated at the bottom of this column is pumped back to the top of the stripper column. The vapors from the rectifier column pass to the condenser.

d) Condenser - alcohol and a small amount of water enter the condenser and pass through 250 linear feet of copper tubing where cold tap water is circulated over the tubing. The alcohol is changed from vapor to liquid phase in the condenser. The helical coil of the condenser heat exchanger is contained within 150 gallons of continuously circulating tap water. The condensed alcohol is collected in the reflux tank.

e) Reflux tank - the liquid alcohol from the condenser empties into this one gallon tank. Part of the product is pumped to the top of the rectifier column as a reflux, and part is bled off to product storage. Reflux is employed to increase the percent alcohol in the final product.

f) Vacuum Pump - the vacuum pump connected to the reflux tank establishes and maintains a vacuum in the sections listed above. A cold trap is installed on the line between the reflux tank and vacuum pump. The cold trap is used to condense any alcohol and water vapors before they reach the vacuum pump.

In addition to the above sections of the distillation unit, miscellaneous hardware such as values and piping are installed for operation of the system and to aid in data acquisition. All sections are insulated with Fiberglas material to reduce heat loss to the surroundings.

As shown in Fig. 5.6, instrumentation of the distillation system consists of thermocouples, pressure transducers, and flow meters. Thermocouples are located throughout the distillation system including the solar collector, heat storage tank, heat exchanger inlets and outlets, reboiler, condenser, and every 5 ft in the stripper and rectifier columns, except for the 10 ft section of the latter column. Two electronic pressure transducers are utilized to measure pressure drop across the distillation columns. One electronic pressure transducer is located at the top of the reboiler and the other is at the top of the rectifier column. A third electronic pressure transducer is to be installed in the reflux tank. A dial type pressure gage is presently located on the reflux tank. The pressure transducers allow for determination of flow resistance in the distillation system. Flow resistance must be minimized in the distillation unit to facilitate vacuum operation. Flow meters are used to measure feed injection rate, reflux flow, and cooling water flow. Calibrated containers are utilized to measure production rates of fuel alcohol, bottoms product, and liquid redistribution between the two columns.

Special equipment utilized for measurement includes a gas chromatograph to measure percent alcohol present in the feed, bottoms, and product, a Wattmeter to measure power consumption of the liquid and vacuum pumps, and a pyranometer to measure solar irradiance. Sensors are also available to measure wind speed and direction and ambient air temperature.

5.3.2 Experimental Procedure

Experiments with the solar assisted distillation unit were broken into several stages. First, there is the ongoing process of determining system capabilities. Heat exchanger tests are crucial to efficient operation. The condenser heat exchanger was tested by using a gas trap on the vacuum pump line. The gas trap was immersed in liquid nitrogen to freeze all vapors that were not condensed in the condenser heat exchanger. Gas chromatograph analysis of the substances frozen in the gas trap revealed no ethanol present. This implies that the condenser heat exchanger is at least the proper size for the 1 gal/hr production rate.

The heat exchanger in the reboiler was subjected to extensive testing. If thermal energy cannot be transferred to the reboiler to support a 1 gal/hr production or to keep the temperature of the thermal energy storage tank low enough for efficient collector operation, then overall system efficiency is degraded. Preliminary experiments and heat transfer computations indicate that a high flow rate of water typically around 4 gal/min is necessary to gain both a reasonably sized heat exchanger and sufficiently large heat transfer coefficient between the reboiler heat exchanger and reboiler fluid. Based upon location of maximum temperature, the boiling in the reboiler should be initiated on the heat exchanger surface. If the liquid cannot gain enough contact with the heat exchanger surface due to rapid boiling, where a vapor film surrounds the heat exchanger tube, then the heat exchanger efficiency is reduced. Proper rate of heat input to the heat exchanger is essential for optimal heat transfer. This facet of the experimental investigation continues to receive attention.

Gas leak tests were performed on the components of the distillation unit. The entire distillation unit was evacuated to a vacuum of 27 inch Hg, and the vacuum pump was disconnected. Negligible losses (0.5 inch Hg/hr) were found when the entire system except for the reflux and product storage tank were tested. The reflux and product storage tanks do have leaks (the tanks will lose 27 inch Hg vacuum in 30 min). However, these leaks are small in view of the combined 2 gallon capacities of these tanks. Overall, the system has an excellent seal when the unit size and number of fittings are considered.

Specific problems with the system found during experimentation deal primarily with the liquid and vacuum pumps. Liquid pumps with the minimal pumping capacity required for this application are not readily available. Inexpensive chemical metering gear pumps with a plastic housing were located. These pumps, however, could not handle the liquid under vacuum for the plastic housing deflected inwards ruining the pumping gears and seals. Pumps with variable speed motors in which the gears are housed in a metallic enclosure now replace the inexpensive plastic pumps.

Water condensing out in the vacuum pump oil presents another concern. Either a gas trap using ice as a chilling medium or a liquid ring vacuum pump with either water or ethanol comprising the working fluid is needed to prevent water contamination of the working fluid. Water in the vacuum pump may cause corrosion and lubrication problems and may flood the pump, thus decreasing the pumping capability.

Start-up procedure of the distillation unit is reasonably straight forward, though it demands close attention. The procedure follows:

1) Heat reboiler bottoms product to 120 F. This heating takes approximately 90 minutes with an initial reboiler temperature of 110 F, an inlet heat exchanger temperature of 140 F and a heat exchanger flow rate of 4 gal/min.

2) In conjunction with step 1 fill condenser with tap water and adjust water flow to maintain a fixed water level.

3) Turn on vacuum pump. Vacuum takes around 10 min to reach 25-28 inch Hg vacuum. The unit is typically run at 26.5 inch Hg vacuum.

4) Allow the feed to flow into the column. The feed is drawn into the stripper column by the pressure differential, provided the feed is not at a large hydrostatic head below the feed inlet.

5) Based upon percent alcohol in feed and feed rate, production rate can be estimated, and from this, the reflux rate can be calculated. The reflux rate is set at this calculated value once the product reaches the reflux tank. It takes approximately 10 min for alcohol to reach the reflux after initial feed injection. After 20 minutes the column is completely heated as indicated by the top of the rectifier column reaching 85-95 F.

The above procedure may appear simple, however, two people are required for start up. One person is needed to record data and observations while the other person adjusts and fine tunes the flow rates and makes sure everything is in order. Once the unit is at steady rate, an operator is needed to record data periodically, make minor adjustments, and be present in the event of any problems.

5.3.3 Experimental Results

Experiments with fuel alcohol distillation had three main phases, namely, distillation using an electric resistance heater and a mixture of grain alcohol and water, distillation using solar energy and a mixture of grain alcohol and water, and distillation using solar energy and a fermented alcohol solution. The additional and considerable effort required to ferment alcohol was necessary for several reasons. First, the dissovled CO_2 in a fermented solution may cause some foaming in the distillation process and the liberated CO_2 may create a greater load on the vacuum pump. Secondly, the dissolved solids in a fermented solution may produce clogging in the distillation unit. Finally, to give an accurate analysis of fuel alcohol production, an examination of fermentation is necessary.

Experimental results of the distillation unit are not completed. However, preliminary results are generally encouraging. Mechanical problems associated with the vacuum pump, liquid pumps, container seals, and flow meters developed and are now corrected. These problems are typical of those experienced for any experimental apparatus of the type under development.

The distillation unit has operated for approximately 30 hours, utilizing electric heat or solar energy. All experiments were run at a reboiler vacuum of near 26 inch Hg. Based upon the electric heat experiments, temperatures of 118 F in the reboiler and 85 F at the top of the column yielded the best results as measured in terms of an alcohol production rate of about 1.5 gal/hr. The unit temperatures and pressures under these conditions are illustrated in Fig. 5.8. The fuel alcohol

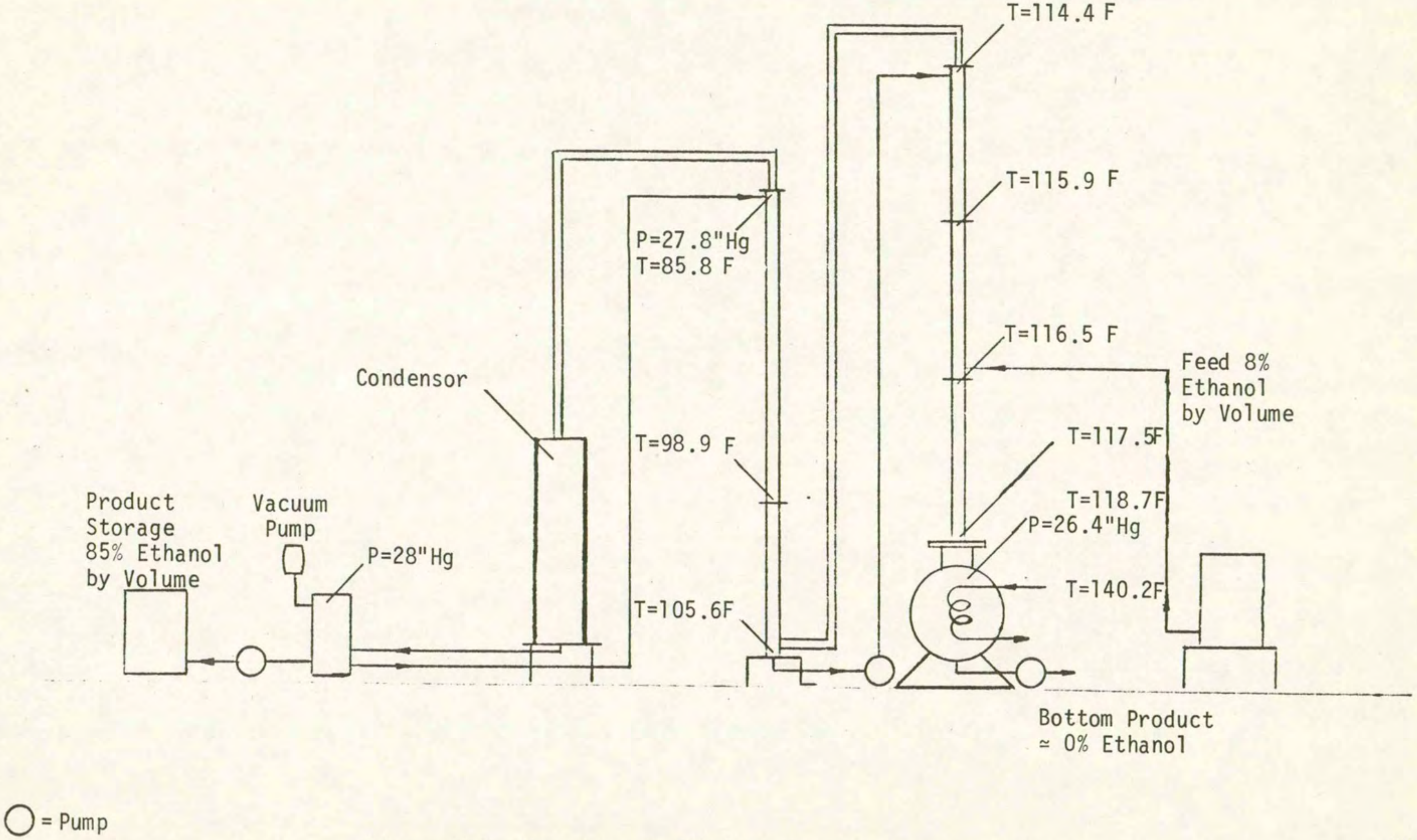


Figure 5.8 Operating Conditions for Distillation Unit

produced at the above condition ranged between 60 to 70 mole percent ethanol or 168 to 178 proof for a feed concentration of 8 volume percent and bottoms composition of $\approx$ 0 volume percent ethanol. Higher ethanol contents can be obtained by adjusting reflux and feed flow rates, which will be part of the on-going experimentation. The pressure drop across the packed column of 1.4 inch Hg remained fairly constant for all of the experiments. Pressure drop is not expected to pose any problems with establishing a sufficient vacuum in the reboiler.

These optimal conditions have yet to be repeated using solar energy. This is due to the difficulty in manually controlling the process with a variable temperature heat source. Electronic controls could keep the reboiler at a constant temperature and provide a constant quantity of energy. The need for electronic controls is perhaps the most important result of this aspect of the experiment. Another important result is buffering of temperature fluctuations on cloudy days by the thermal energy storage tank and the liquid in the reboiler. Time-temperature results for a partly cloudy day are shown in Fig. 5.9 and the corresponding solar energy is shown in Fig. 5.10. The top of the column remained at essentially a constant temperature of 130 F when the heat storage tank varied in temperature of about 10 F due to intermittent clouds. During this experiment the heat storage tank contained 50 gallons of water and the reboiler contained 180 gallons of bottoms product. The unit was running almost 20 F too hot at the column top, but the time-temperature results are still illustrative of the buffering offered by the thermal mass of the heat storage tank and reboiler.

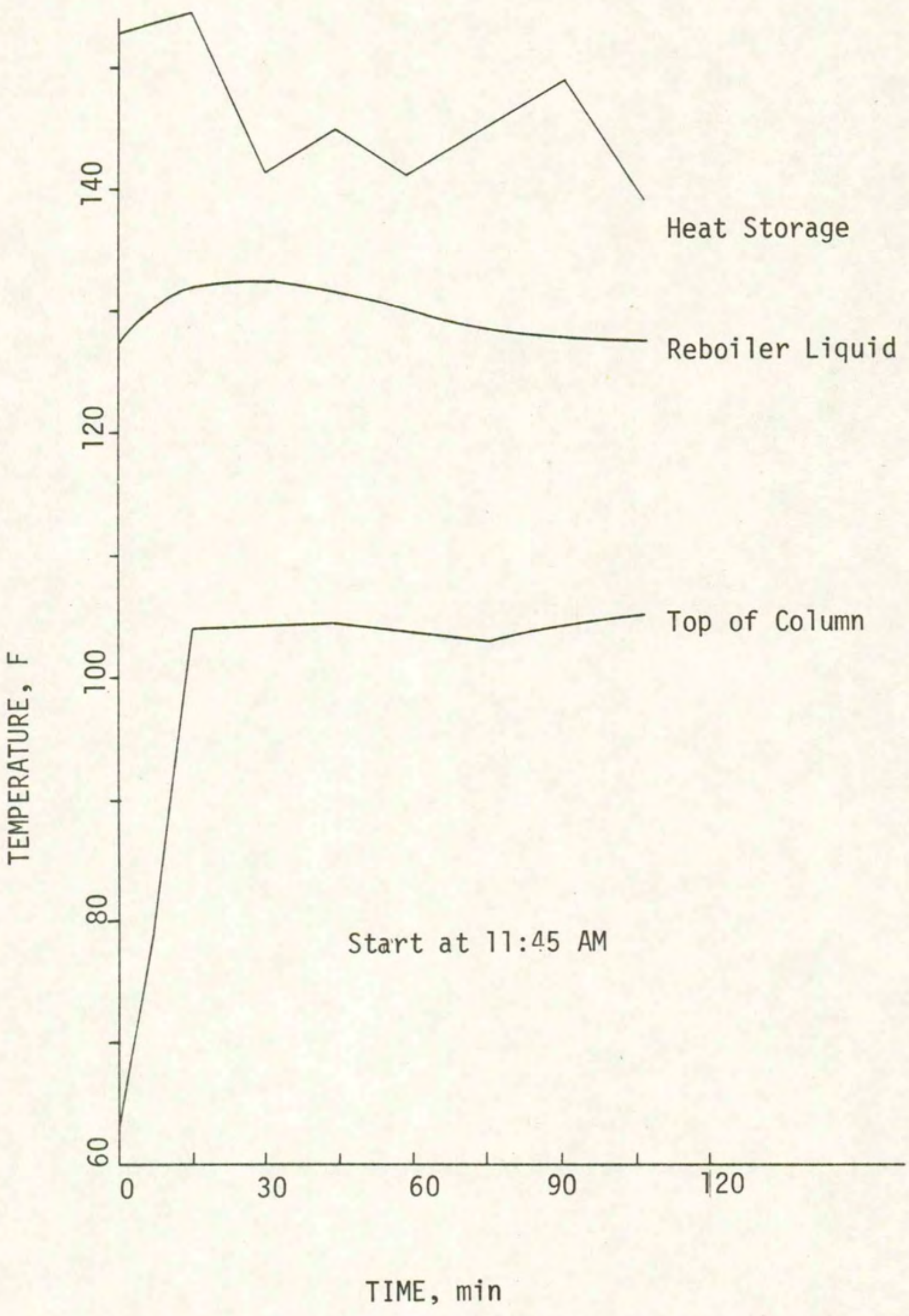


Figure 5.9 Distillation Response

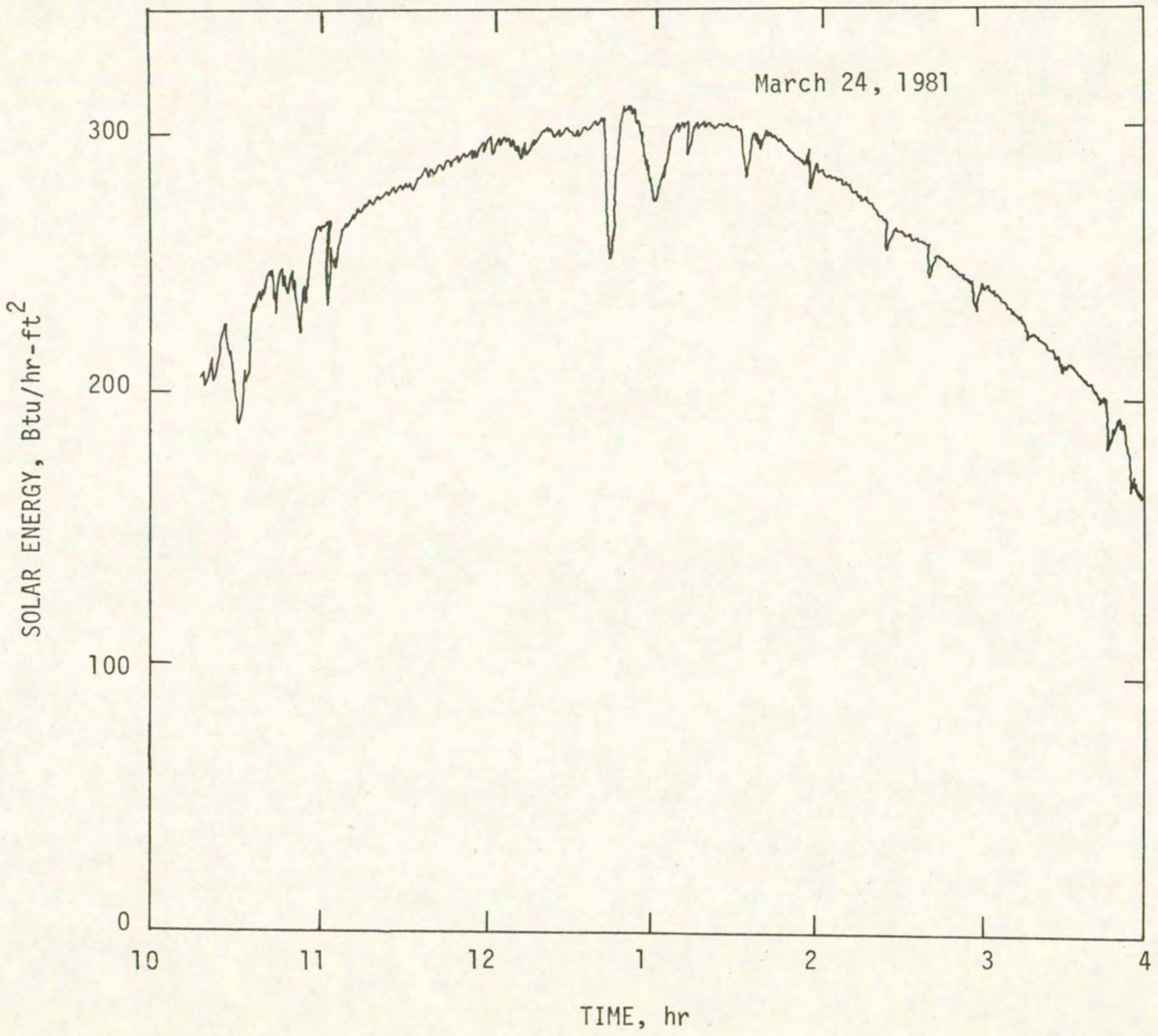


Figure 5.10 Solar Energy

Distillation with a fermented feed solution found no difference in column performance. The distillers grain was separated from the liquid using a 20 mesh screen as described in Chapter 4. Before entering the column the feed solution is passed through a final filter of 100 mesh, which clogs after 3 hours of operation. Either a finer screen can used in the initial separation process or a dual feed system to the column (where one filter is cleaned while the other filters) or no filter at all could prevent filter clogging. Based upon preliminary experimental results it is doubtful that the feed, after passing through a 20 mesh screen, could cause any clogging problem with the column. Also no foaming or extra vacuum pump load due to liberated CO_2 was detected during the experiments.

Experimental electrical energy consumption values were measured with a Wattmeter, and are tabulated below.

Collector Water Pump	440 Watt
Circulating Water Pump	270
Vacuum Pump	615
Liquid Redistribution Pump	80
Reflux Pump	80
Total	1485

If 1.5 gal of 90-10 ethanol-water fuel is produced per hr, then 1485 Watt-hr of electricity are consumed to produce this fuel. Multiplying the electrical energy consumption by 3 yields the "true" energy input by accounting for the efficiency of a power plant. These values yield a ratio of 1 gal of alcohol/10,136 Btu. A more favorable ratio could be obtained by use of a properly sized pumps. The energy content of fuel alcohol is discussed in Chapter 7, and from these values an energy

in/energy out ratio can be obtained. Experimental measurement of energy provided by the electrical heater or solar collector thermal energy sources will be performed in future experiments. This experimental energy value is compared to the value of 21,400 Btu/gal distilled obtained from the model described in Chapter 6.

5.3.4 Conclusions

Overall the experiments proved the technical feasibility of solar assisted alcohol distillation, although some aspects of the technology remain to be investigated (ex. controls). The experiments also showed the need for further data collection.

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6. SYSTEM SIMULATION

6.1 Introduction

Research and experimentation are synonymous in connection with the operation of a fuel alcohol system, but of necessity, the scope of actual experimentation is limited by constraints on equipment, time, and monetary resources. Consequently, experiments have to be supplemented by mathematical or theoretical simulation models in order that the performance of the system by fully understood. This discussion is devoted to an examination of two such models. The distillation model determines the design parameters of the distillation unit for specified operating conditions. The system model predicts the performance of the entire system for several different operating conditions, equipment specifications, as well as site and environmental conditions. In addition, both models project the size and performance of the systems for different alcohol production rates.

6.2 Distillation Simulation

6.2.1 System Description

A schematic diagram of a continuous distillation unit is depicted in Fig. 6.1 along with the appropriate nomenclature. Distillation energy Q is supplied by the reboiler which has bottoms at temperature T_B. The bottoms product contains mostly water with an alcohol liquid mole fraction composition x_B and is removed at a volumetric flow rate $\dot{V}_B$. The alcohol and water vapors inside the column have a velocity v. The packed column

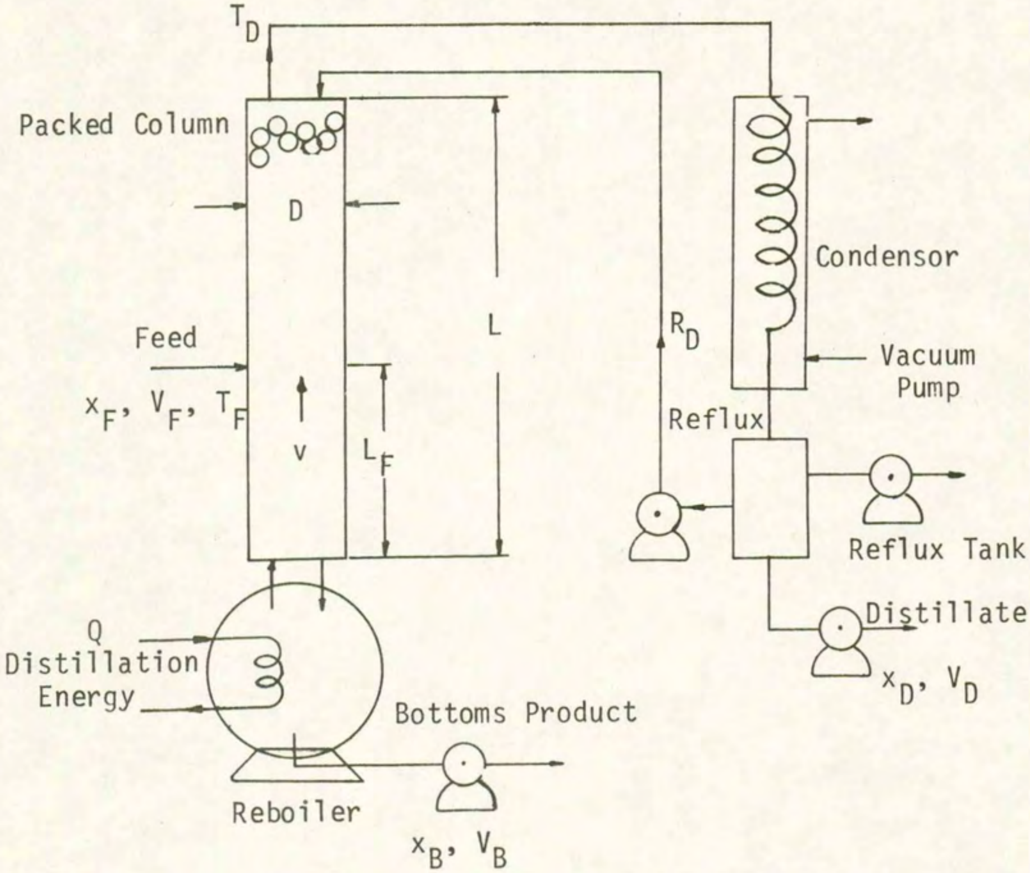


Figure 6.1 Schematic Diagram of Distillation Unit

has a height L and diameter D. Feed at composition x_F, temperature T_F, and rate $\dot{V}_F$ is injected in the column at a height L_F above the reboiler. Alcohol vapor leaves the top of the column at temperature T_D and passes to the condenser where it is condensed to liquid. The liquid alcohol with some water is collected in the reflux tank. A portion of the liquid is injected at the top of the column at a reflux ratio R_D. The remainder is withdrawn at a composition x_D and flow rate $\dot{V}_D$. The temperature T_D determines the cooling fluid temperature for the condenser.

6.2.2 System Analysis

The amount of energy required to perform the distillation is one of the first quantities of interest. The minimum energy, as presented here, excludes heat losses to the environment and is composed of the energy required to raise the feed from T_F to T_B and to T_D and the latent heat of vaporization including that associated with the reflux. In this analysis, it is assumed that the distillate leaves at T_D which implies no subcooling in the condenser. The feed energy is evaluated as follows

$$\begin{aligned} Q_1 = {} & [(\dot{m}_{F,ETOH} - \dot{m}_{D,ETOH})c_{P,ETOH} + (\dot{m}_{F,H_2O} - \dot{m}_{D,H_2O})c_{P,H_2O}] \\ & \cdot (T_B - T_F) + (\dot{m}_{D,ETOH}c_{P,ETOH} + \dot{m}_{D,H_2O}c_{P,H_2O})(T_D - T_F) \qquad (6.1) \end{aligned}$$

and the vaporization energy is

$$Q_2 = (\dot{m}_{D,ETOH}h_{fg,ETOH} + \dot{m}_{D,H_2O}h_{fg,H_2O})(R_D + 1) \qquad (6.2)$$

where $\dot{m}_F$ and $\dot{m}_D$ denote the mass flow rates of feed and distillate, respectively. c_p is the specific heat, h_{fg} is the latent heat of varporization, and R_D is the ratio of reflux to distillate flow rates. Subscripts "ETOH" and "H_2O" refer to ethanol and water, respectively. Thus the minimum energy is

$$Q = Q_1 + Q_2 \tag{6.3}$$

As noted in Chapter 5, the equilibrium properties inside a column must be evaluated in order to design the column. Liquid-vapor equilibrium data for alcohol-water systems at various pressures are given by Chu [1]. The McCabe-Thiele method [2] is employed to compute the number of ideal plates required to accomplish a specified composition difference in either the stripper or rectifier column. As shown in Fig. 6.2 with given equilibrium information, bottoms, feed, and distillate compositions as well as reflux ratio a step-by-step distillation diagram can be constructed. The feed line at x_F is considered first and is given as [2]

$$y = \frac{-q}{1-q} x + \frac{x_F}{1-q} \tag{6.4}$$

where for cold feed, that is when the feed temperature is below the boiling point,

$$q = 1 + c_{p,F}(T_b - T_F)/h_{fg,F} \tag{6.5}$$

T_b is the bubble point temperature of the feed. For the present distillation column q is approximately unity. Thus, the feed line can be considered as a vertical line in Fig. 6.2 at composition x_F. The operating

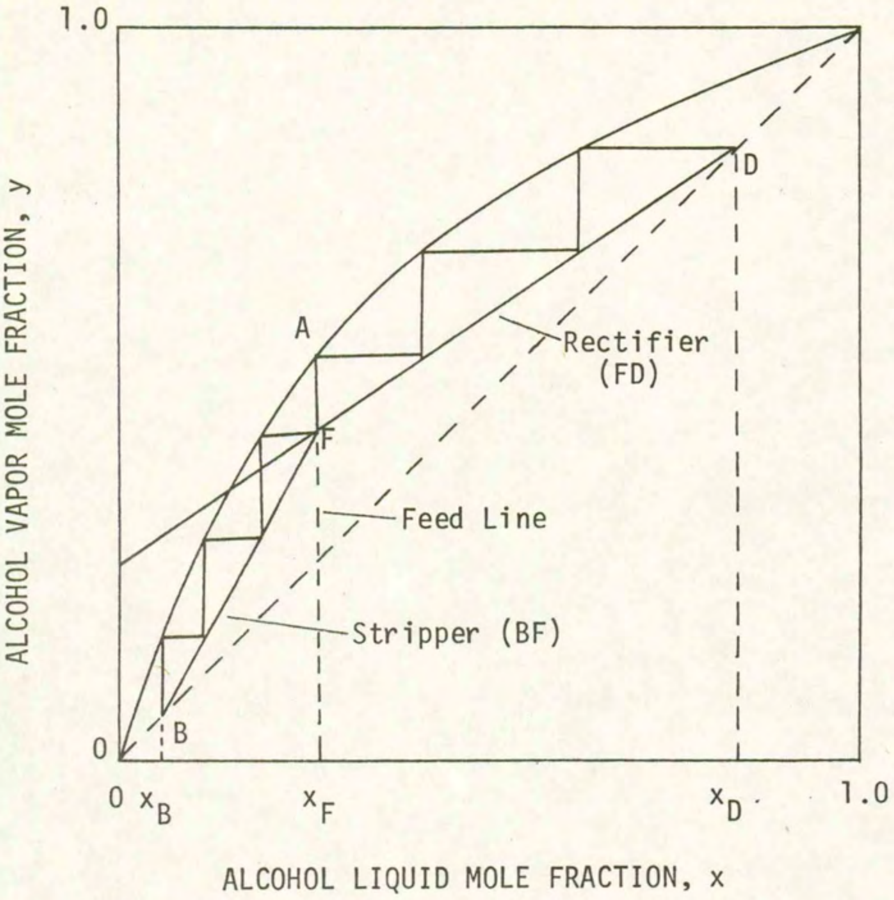


Figure 6.2 Theoretical Plates

line intersects the 45 degree line at x_D and the y axis at

$$y = x_D/(R_D + 1) \tag{6.6}$$

The operating line FD from the intersection with the feed line to the distillate line is the rectifier column. A line connecting the intersection of x_B with the 45 degree line and the rectifier line at x_F is the operating line for the stripper column. The ideal plates can then be constructed by a step-by-step operation and the number of plates N_p determined. The height of the column and location of the feed can also be evaluated. The height equivalent to a theoretical plate (HETP) for a packed column equals that for an ideal plate. HETP is given by [3]

$$\text{HETP} = 28\ D_p\ M_a\ (R_D + 1)/R_D \tag{6.7}$$

where D_p is the packing size. M_a is the average slope of the equilibrium curve. The column height is expressed as

$$L = N_p \quad \text{HETP} \tag{6.8}$$

The column diameter D expressed in terms of R_D is

$$D = \left[\frac{4\ V_D\ \dfrac{\dot{m}_D}{\bar{M}_D}\ (R_D + 1)}{\pi\ v}\right]^{1/2} \tag{6.9}$$

where $\bar{M}_D$ and V_D are the molecular weight and molecular volume of the distillate, and $\dot{m}_D$ is the mass rate of flow of distillate. The vapor velocity v is taken to be 11 ft/sec [4] which is optimal for a packed column for the most efficient vacuum operation. The pressure drop through the column per unit column length with units of lb_f/ft^2-ft is [5]

$$\Delta P = 24\ f_F\ \rho\ v^2/g_c\ D_p \tag{6.10}$$

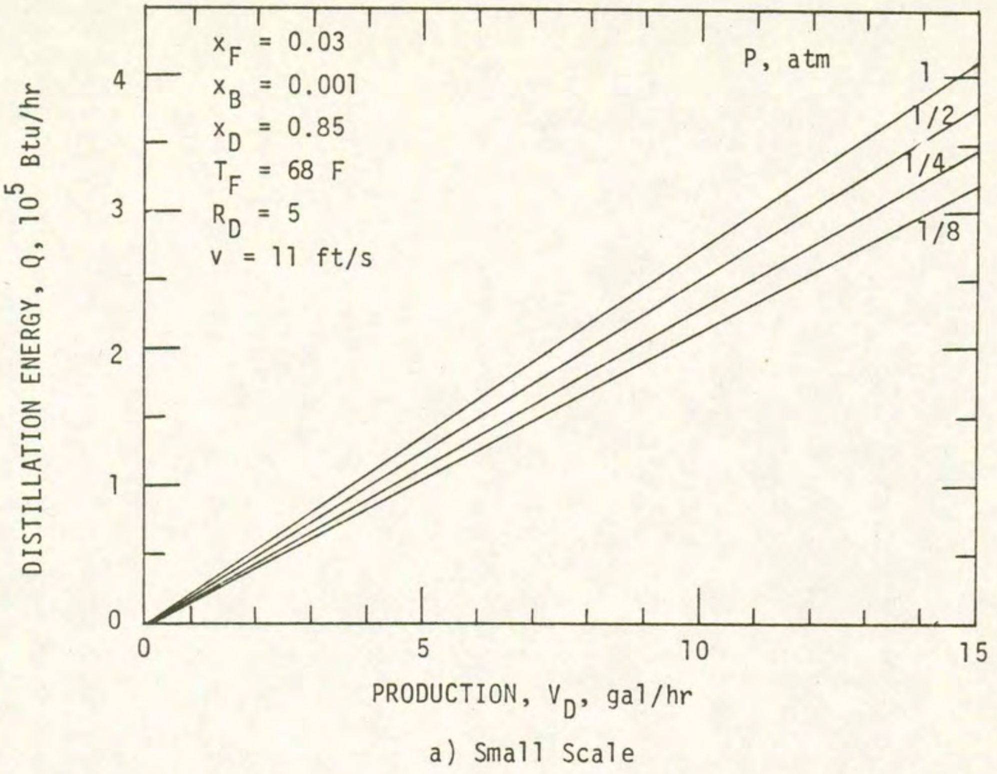
where g_c is the universal gravitational constant (32.2 ft-lb_m/lb_f-sec^2), f_F is the Fanning friction factor [5], and ρ is the vapor density.

Also of interest is the minimum reflux ratio R_{min}, for which an infinite number of ideal plates would be required. This ratio is computed by selecting the larger of the two values from a) the slope of a line which is tangent to the equilibrium curve and passing through the point D in Fig. 6.2 and b) the slope of a line connecting points A and D in Fig. 6.2.

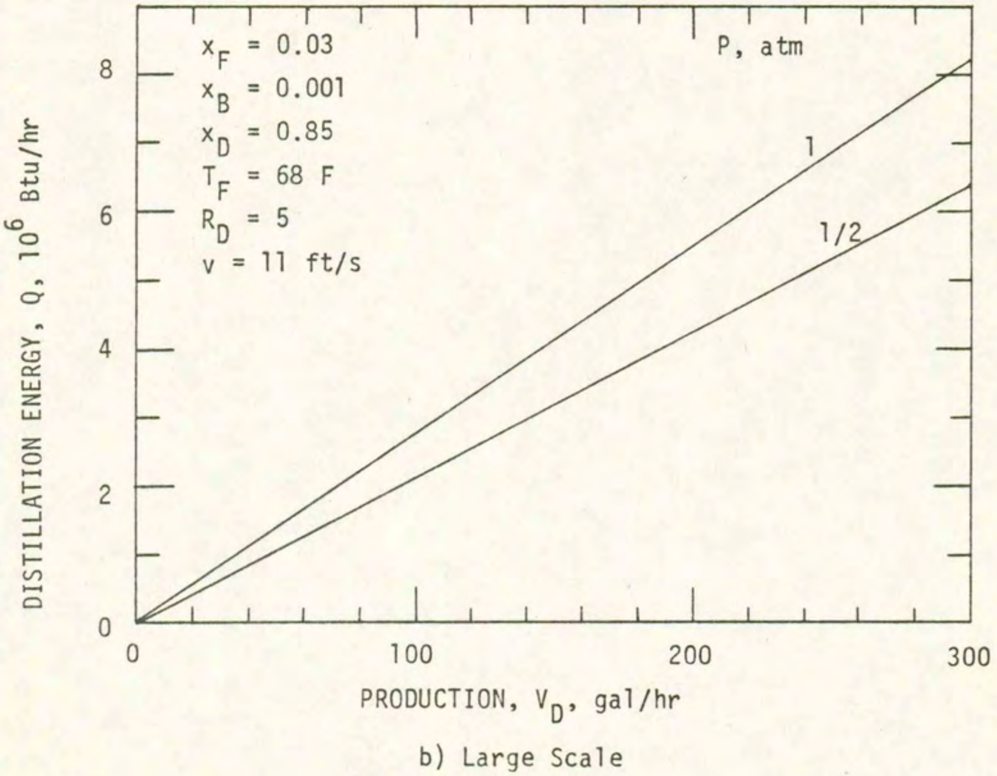
6.2.3 Results and Discussion

Examination of the design and performance of a continuous distillation unit was performed by studying the effects of the various parameters introduced in the model. Based on the number of parameters as well as the intended application, certain parameters were fixed and others were varied. The fixed parameters were the feed temperature at 68 F, the bottoms composition at 0.001 mole fraction, vapor velocity at 11 ft/sec, and packing size at 0.5 inch. The value for the bottoms composition was selected to insure an acceptable extraction of the alcohol from the feed. It should be noted that the packing size is recommended to be one-eighth of the column diameter [2]. For the present results, however, the packing size is held fixed at the stated value. In addition, the feed composition is taken as 0.03 mole fraction, although the influence of this parameter on the minimum reflux ratio is examined. The other input parameters which were studied were the pressure, distillate composition, reflux ratio, and production rate. The effect of the parameters on the minimum distillation energy, minimum reflux ratio, column diameter and height, as well as feed location is examined. Results for both small- and large-scale production rates of 1 and 300 gal/hr of alcohol, respectively, are reported. In view of the number of parameters and extensiveness of the results, only representative results are presented.

The distillation energy as a function of production rates based on small-scale and large-scale distillation units is displayed in Fig. 6.3 for distillation pressures ranging from 1/8 to 1 atm, a reflux ratio of 5, and a distillate composition of 0.85 mole fraction. Although not stated in this as well as succeeding graphs, it is understood that the compositions are expressed in terms of alcohol liquid mole fraction. As observed in Fig. 6.3, the distillation energy increases linearly with production as reflected by Eqs. (6.1) and (6.2). As the pressure decreases implying vacuum distillation, the energy decreases. This trend is attributed to a decrease in the energy required to raise the feed to the distillation temperature even though the vaporization energy increases due to the increase in the latent heat of vaporization. The boiling point temperature and latent heat of vaporization for the bottoms composition (essentially water) at pressures of 1/8 and 1 atm are 123 F and 8500 Btu/gal as 2.2 F and 8093 Btu/gal, respectively. The saturation temperatures for 0.85 mole fraction, typical of the distillate composition, are 97 and 173 F for these pressures [11]. The required temperature of the condenser



a) Small Scale



b) Large Scale

Figure 6.3 Distillation Energy vs. Production cooling water is governed by the saturation temperature of the distillate.

The influence of the reflux ratio on the distillation energy is demonstrated in Fig. 6.4 for a small rate of production. The linear behavior is related to the amount of reflux which must be vaporized as indicated by Eq. (6.2). The minimum reflux values as shown by symbols in this graph are only a function of x_F, x_D, T_F, v, and P. The dependency of the minimum reflux ratio on feed composition for various pressures is presented in Fig. 6.5. As the feed composition increases, the minimum reflux decreases to maintain the same distillate composition for all pressures shown. The behavior of the minimum reflux ratio with pressure for a fixed feed composition is more complex and is attributed to the shape of the equilibrium curves which varies with pressure. For $x_F = 0.03$, typical of a fermented solution, the minimum reflux ratio decreases with decreasing pressure until about 1/2 atm and then increases as the pressure is decreases further. The minimum reflux ratio as noted in Chapter 5 corresponds to an infinitely long column. Thus, in view of practical considerations, the actual reflux ratios are higher than the minimum values. From operational experiences [2,6], it is recommended that the actual reflux ratio be approximately 1.5 times higher than the minimum reflux ratio.

The influence of the reflux ratio on the column and feed heights is shown in Figs. 6.6 and 6.7, respectively, at pressures of 1/8 and 1 atm and for distillate compositions ranging from 0.70 to 0.85 mole fraction. These heights are independent of the production rate since the packing size is held constant and not allowed to vary with the column diameter, which depends on the production rate. The column and feed heights decrease

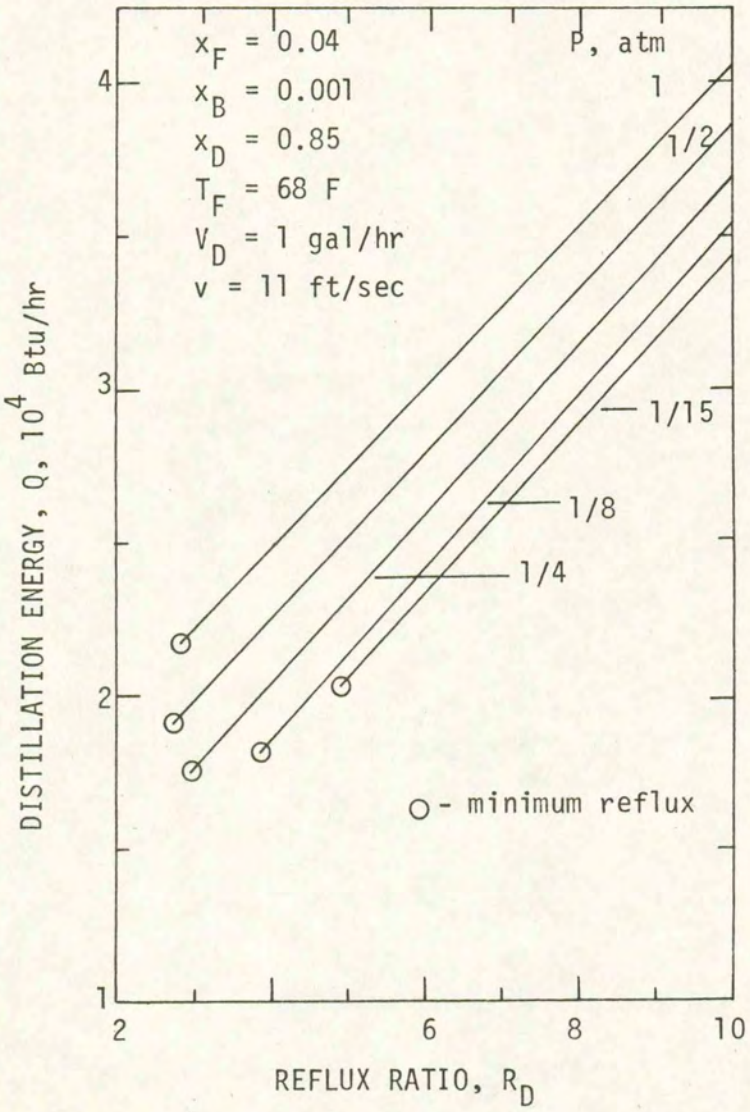


Figure 6.4 Distillation Energy vs Reflux Ratio

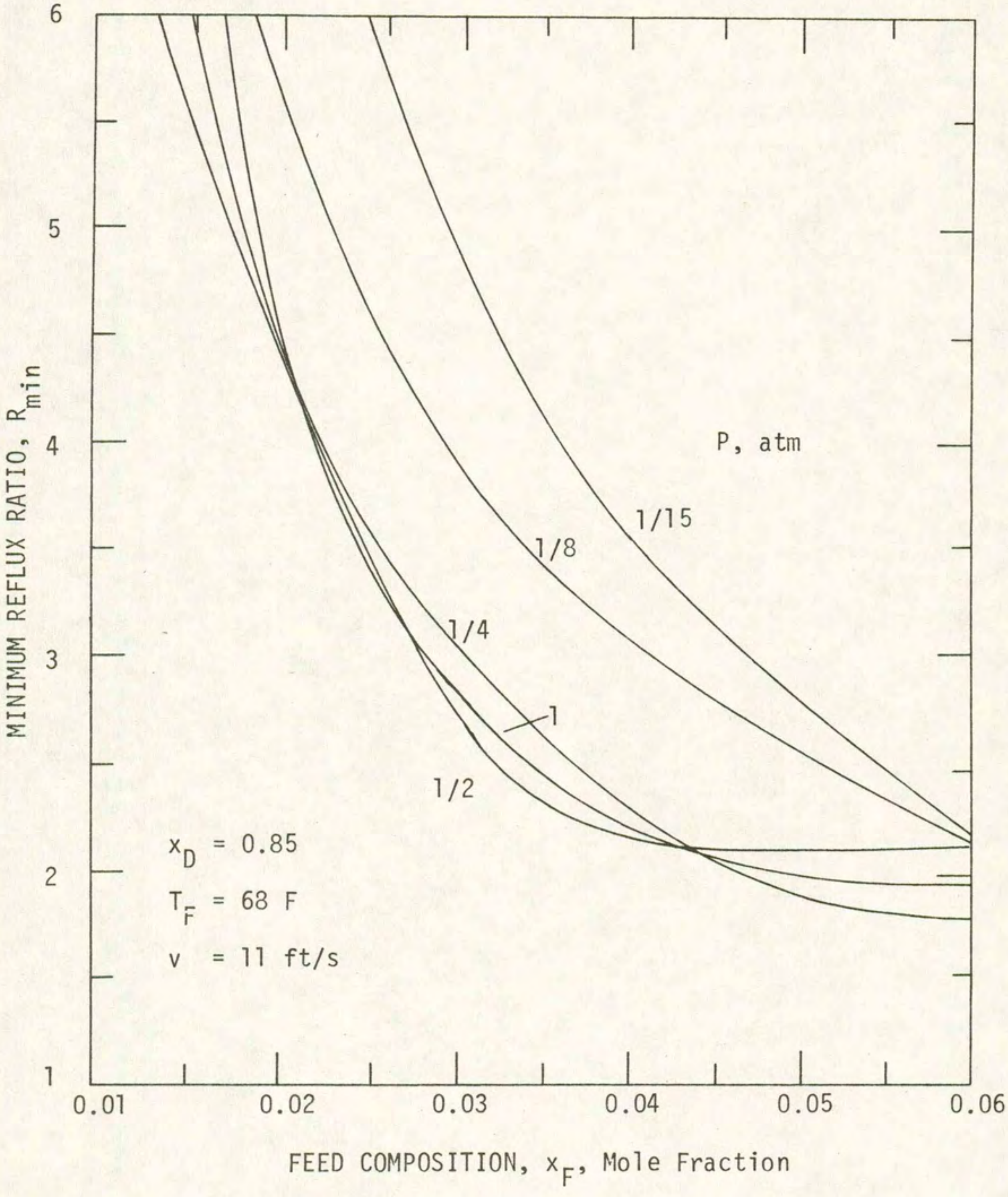


Figure 6.5 Minimum Reflux Ratio vs Feed Composition

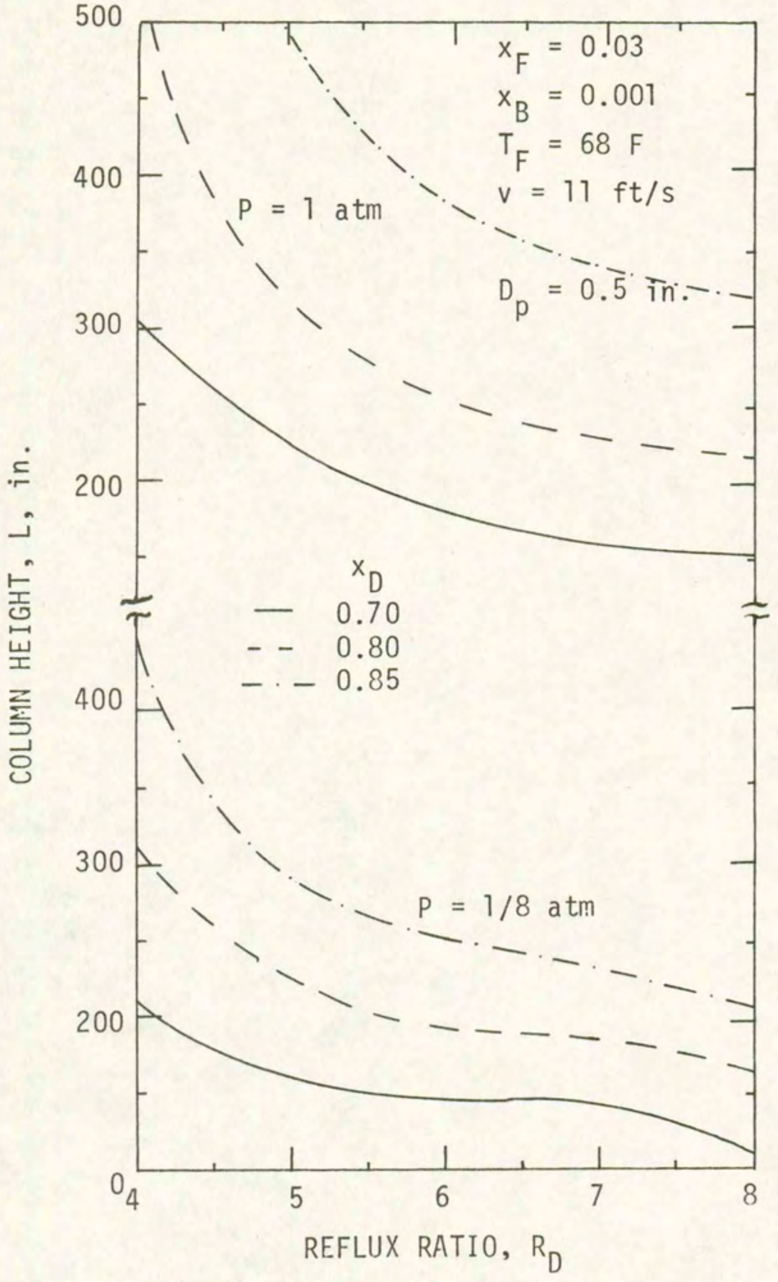


Figure 6.6 Column Height vs Reflux Ratio

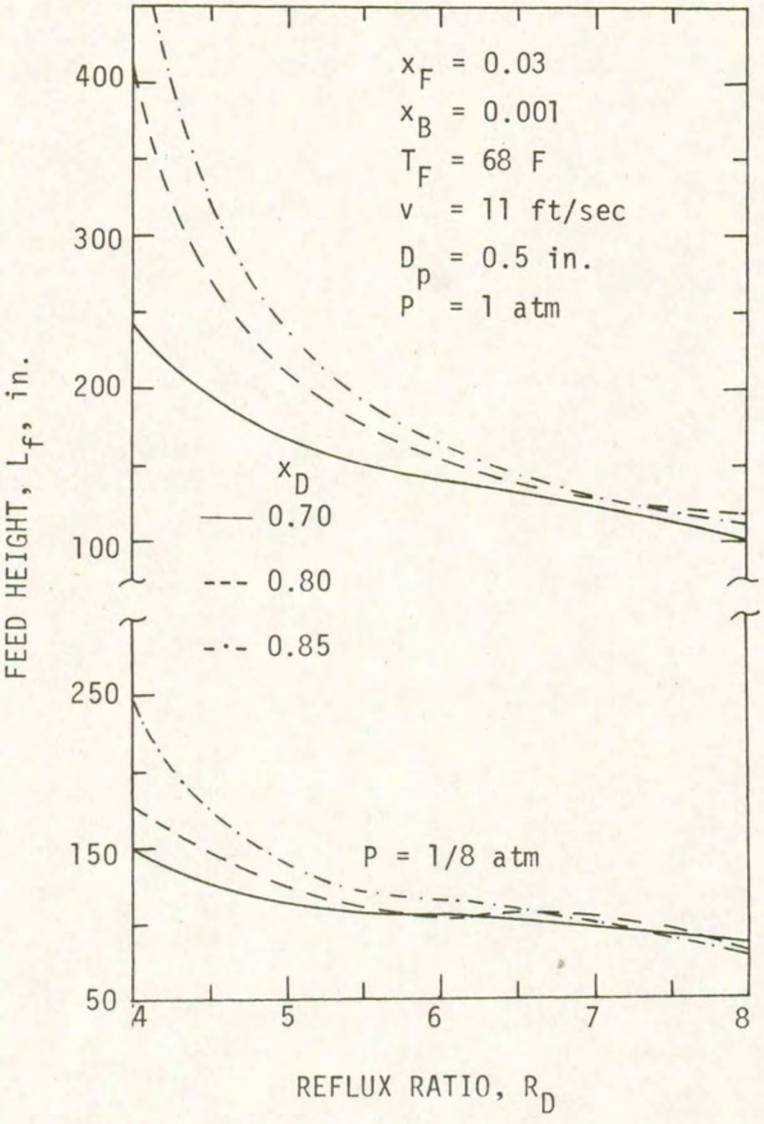


Figure 6.7 Feed Height vs Reflux Ratio

as the reflux ratio increases and are higher for increasing distillate composition. A lower pressure decreases these heights. For example, with $R_D = 5$ and $x_D = 0.85$, the column heights are 290 and 490 inch for 1/8 and 1 atm respectively. In addition to the column height, the column diameter is a design requirement and depends on the reflux ratio.

Column diameter as a function of the reflux ratio is presented in Fig. 6.8 for small and large scale production rates with pressures of 1/8 and 1 atm. The effects of the distillate composition are illustrated for each production rate and pressure. As the reflux ratio increases, the column diameter must increase to prevent flooding. The column diameter increases as the pressure is decreased since the vapor volume expands as the pressure is lowered. As expected, a larger column diameter is required as the production rate is increased.

6.2.4 Conclusions

Analysis and results have been presented to illustrate the influence of column size and performance on design parameters of feed, bottoms, and distillate compositions, feed temperature, reflux ratio, production rate, packing size, and pressure. Bottoms composition, feed temperature, and packing size were held constant. The influence of these parameters on the distillate energy, minimum reflux ratio, as well as column height and diameter was examined.

The results indicated that for prescribed feed and distillate compositions, pressure, and production, a higher column requires a smaller reflux ratio which requires a lower distillation energy. This illustrates the trade-off between initial equipment investment and operating energy expenses.

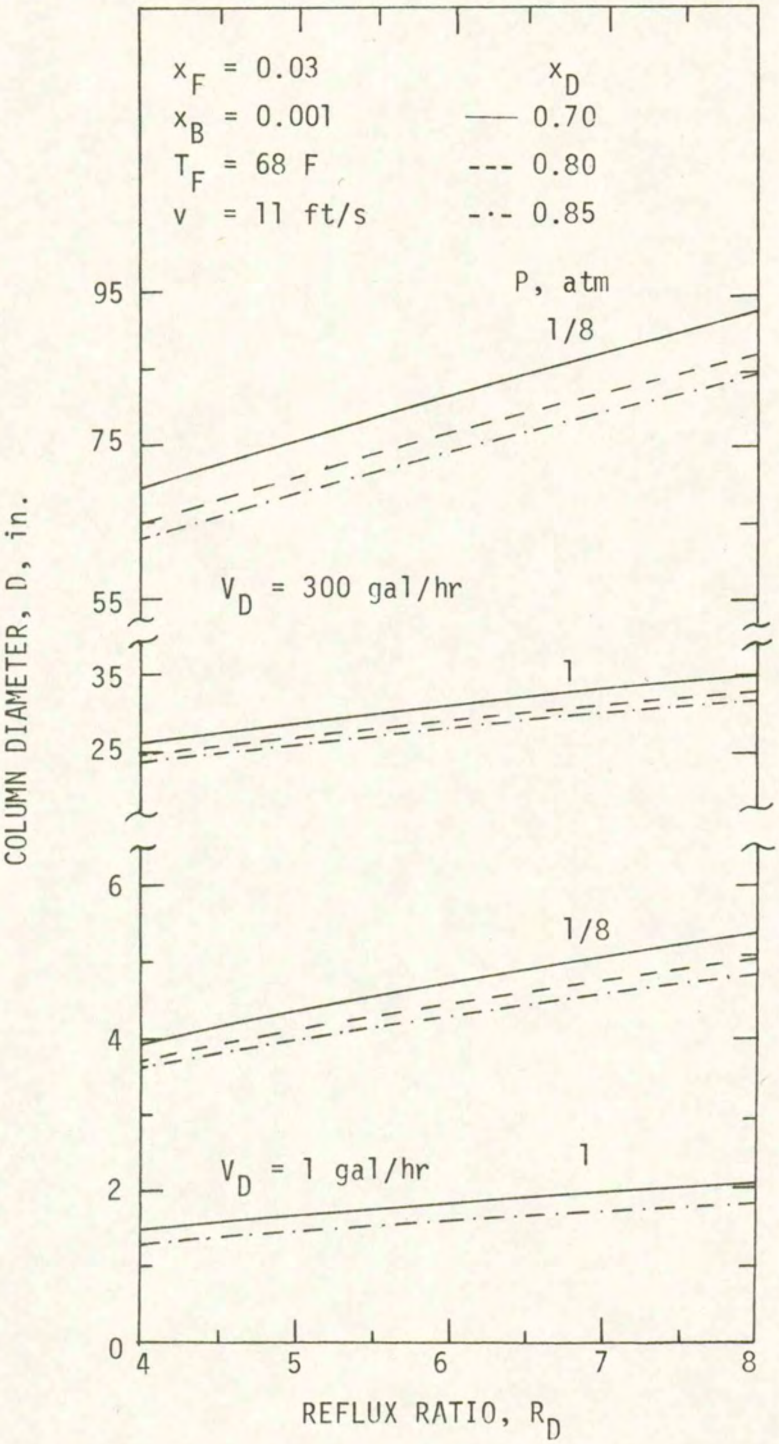


Figure 6.8 Column Diameter vs Reflux Ratio

As the pressure is lowered, the column diameter increases but the column height and distillation energy decrease for the same reflux ratio and other parameters fixed. Thus, for vacuum distillation, the trade-off between investment due to a large column diameter but a smaller column height and lower energy requirements must be examined. The question of whether solar energy can supply a significant portion of the distillation energy is addressed in the following section.

6.3 System Simulation

6.3.1 System Description

The solar assisted ethanol distillation system is simulated by an analysis that seeks to duplicate its performance on the basis of physical and empirical formulations. The system components include the sun, collector, thermal energy storage tank, distillation unit, and environment. The analysis is limited to these components of the system, but fermentation may be included in if necessary. All components are simulated by mathematical modesl which balance the energy and mass interactions between the components. In view of the number of equations involved in the analysis, the equations are not presented and only brief descriptions of the models are provided. These models are converted to a computer code consisting of a series of routines. The function and purpose of the code and routines are summarized in the following section.

6.3.2 Model Description

A schematic block diagram of the major routines in the program is shown in Fig. 6.9. The MAIN routine basically accepts input data related to the system parameters which include production rates, operating patterns, control indices, and empirical constants, and determines the operating options from them. The distillation model VACUUM is interfaced with the system model in MAIN. VACUUM estimates the distillation energy requirement and the operating temperature of the distillation unit which are needed to operate the system model. After the operating options have been partially sorted out, control is transferred to SIMUL.

SIMUL is the receptor of the input data for thermal performance evaluation. Based on the options determined in MAIN, relevant items from the input data are selected for analysis, and SIMUL proceeds to call other routines to estimate collector area, tilt angle, and storage size. For a given production rate, operating temperature, and time of the year, these operating parameters can be optimized. In addition, SIMUL has the capability to function on fixed input values of these parameters. It has allowance for the variation of collector, operating, site, and environmental parameters, as well as collector type, thermal storage type, and equipment capacity. After the operating conditions are fixed, SOLAR is called from SIMUL.

SOLAR is the principal routine in the model. As apparent from Fig. 6.9, thermal performance is evaluated in this routine by calling several other component simulating routines. SOLAR operates on a daily basis, and continuous simulation is obtained by changing control indices

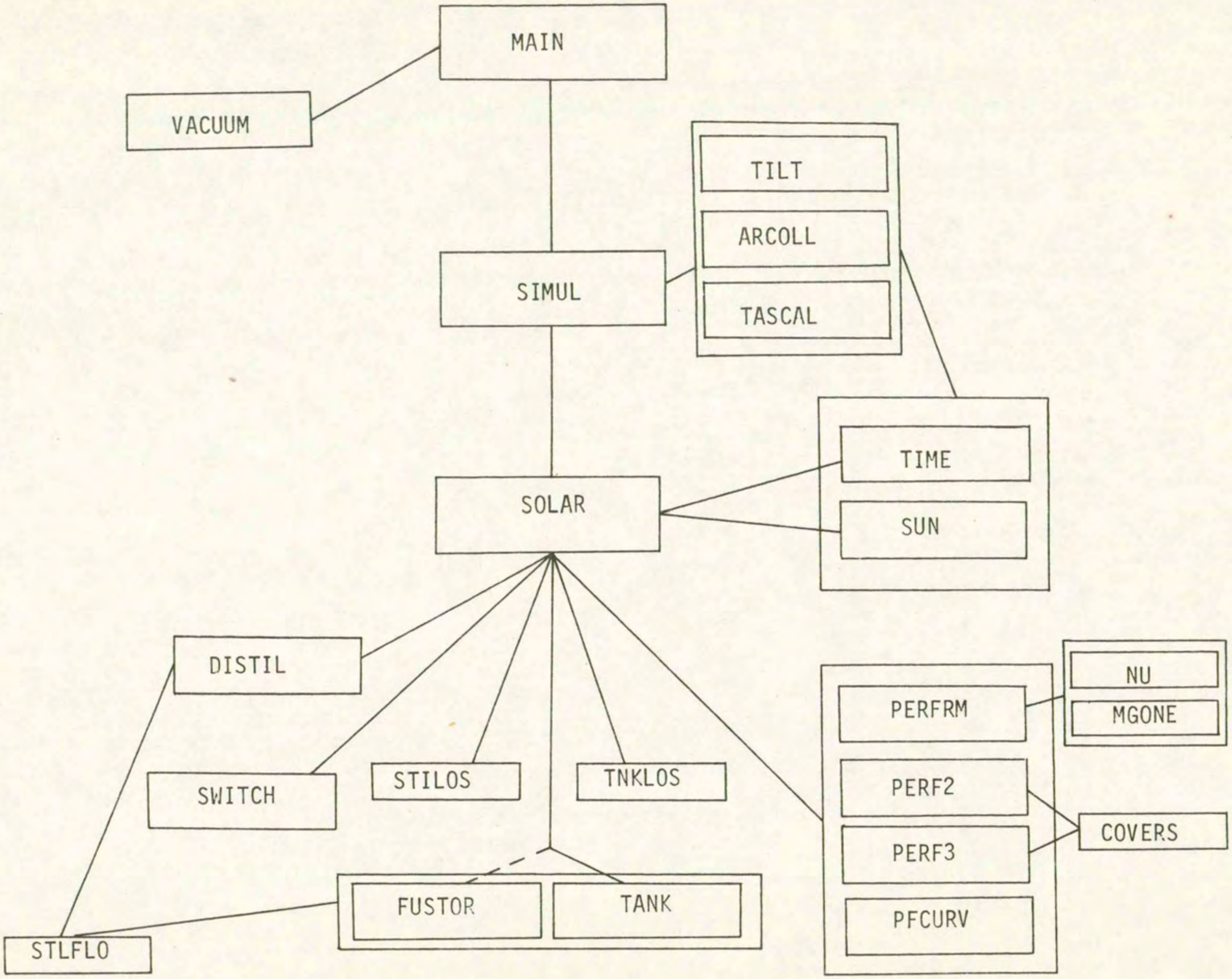


Figure 6.9 Block Diagram of Major Routines

in MAIN or SIMUL. The routines that SOLAR employs are discussed in their order of occurrence.

TIME determines the solar equation of time for a specified day of the year through trigonometric and geometric manipulations. It also evaluates the solar constant, as well as sunrise and sunset times. At this point in the program, a time counter is started, and all the succeeding routines are activated once for every time step. With a time step of 300 seconds, good approximation to instantaneous performance is obtained. Following this routine, SUN is accessed to estimate the terrestrial solar energy at any given time of the day, based on the results from TIME. TIME and SUN routines are based on the solar energy model mentioned in Chapter 3.

Then, depending on the collector type option, either a collector thermal performance model (PERFRM, PERF2 or PERF3), or curve (PFCURV) is accessed. Table 6.1 summarizes the capabilities of these routines as well as several other supplemental routines. In these routines, the inputs include, ambient air and inlet fluid temperatures, collector dimensions, absorber characteristics, and solar energy, and the outputs consist of collector efficiency, useful energy gain, and outlet fluid temperature.

At a given time step, therefore, the useful energy from the collector is known, and this is conveyed to a thermal energy storage simulated by TANK, which uses a liquid, commonly water, as the storage medium. The useful energy gained by the collector is added to the fluid in the tank to increase its temperature. Phase change storage is considered potentially superior to a fluid-thermal or sensible heat storage because it functions as a constant temperature heat sink for the collector and as a

Table 6.1

Characteristics of Collector Performance Routines

Routine	Features
PERFRM	Simulates distributed flow flat-plate collector. Uses nearly exact heat transfer analysis. Evaluates heat loss coefficient by extended iteration. Limited to single cover collectors. [7,8]
PERF2	Simulates flat-plate collector. Approximate heat transfer analysis. Estimates heat loss coefficient by a semi-empirical formulation. Can handle up to 5 covers with good accuracy. [8,9]
PERF3	Simulates performance of fin-and-tube collectors. Uses approximate heat transfer analysis. Loss coefficient determined by semi-empirical formula. [9]
PFCURV	Contains performance curves for some commercial collectors - flat plate, fin-and-tube, and concentrating types. Useful in comparison of preceding routines with commercial collectors. [10]
NU	Peripheral routine to evaluate Nusselt number for PERFRM. [7]
MGONE	Assists in iterative method in PERFRM.
COVERS	Determines heat loss coefficient for a variable number of collector covers. Used in PERF2 and PERF3. [9]

constant temperature heat sink for the collector and as a constant temperature heat source for the distillation system. Though this means a simplification in the heat transfer analysis in the model, several peripheral physical and modeling problems arise. Two more heat exchangers need to be introduced into the flow circuit. FUSTOR models the phase change storage and is used in a partial-storage direct-flow operating situation as well as in a full storage situation.

The control for the distillation unit is actuated by SWITCH which turns the unit on or off depending on the operating preferences and from the empirical formulations mentioned before. SWITCH attempts to run the distillation system on a continuous basis determined by the available and projected energy storage. The heat transfer characteristics of the distillation system are simulated in DISTIL. The reboiler heat exchanger flow rates are directly influenced by the transient effects of the system, and are evaluated in a peripheral subroutine. The operating features of the distillation process can typically be fixed input data, or they can be estimated from the distillation model. The heat loss from the reboiler and heat storage tank are evaluated at the present time step from STILOS and TNKLOS, respectively.

At this point, the entire system has traversed one time step, and performance parameters such as solar energy, useful collector energy, storage temperature, flow rates, and distillation energy are computed. The time is then advanced by one time step, and the process is repeated until the end of the day or termination time. All performance characteristics are summed over the day, and operating difficulties such as excessive storage temperatures, excess collector area, inadequate storage capacity, or extreme changes in heat exchanger flow rates, are listed as warning messages. SOLAR then returns these values to SIMUL, and this may be repeated for several representative days in any operating period. SIMUL then integrates these results to give the overall performance results. If any of the numerical results indicates a divergent trend, or if the input data are inconsistent, SOLAR and SIMUL cause the program to abort.

Empirical correlations are used to suppress any erratic numerical behavior caused by the transient response of the collector, thermal storage, or reboiler. The flow rate routine STLFLO is accessed more than once in one time step to help maintain dynamic equilibrium in FUSTOR, SWITCH and DISTIL.

There are three other subroutines that are related to system scale-up options, and are accessed directly from SIMUL to estimate the collector area, storage capacity, and collector tilt. ARCOLL calls TIME and SUN to find the effective insolation on a given day, and with a knowledge of energy requirement for distillation, determines the collector area based on some empirical approximation. TASCAL assumes linear variations in net energy gains and estimates storage size. Empirical relations again modify the estimate by safety factors. TILT uses the declination of the sun on the operating day to estimate the collector tilt.

The simulation of the system is fairly comprehensive, but the following additions could make it more versatile and complete:

(1) A detailed analysis of a concentrating collector,

(2) A probabilistic climate simulator,

(3) An analysis of a tracking solar collector,

(4) A more detailed simulation of phase change characteristics.

6.3.3 Results

The performance parameters sought from the model are the collector efficiency, total alcohol production, and the continuity of operation. These parameters depend on the collector area, thermal storage tank size, production rate, distillation temperature, type of collector, number of collector covers, and the collector tilt angle. In addition, site and environmental conditions affect the parameters, but for the current results, it is assumed that the collector site is in Iowa City (Lat 41.5 N, Long 77.0 W, altitude above mean sea level 600 ft.) Furthermore, unless otherwise stated, it is assumed that the collector is a flat-plate distributed-flow type and is tracked in the altitude plane to ensure normal incidence of solar radiation at solar noon, ambient air temperature varies sinusoidally over the day, distillation is at one-eighth of an atmosphere, and the results are based on environmental conditions for June 15 of the year.

The size of the sensible thermal storage tank is important for the operation of the system because its thermal capacity directly influences its temperature response. The temperature should be low enought to derive maximum performance from the collector, yet high enough to sustain the distillation process without interruption. The temperature response of the sensible heat storage tank for different tank sizes, at a production rate of 1 gal/hr, with water as the medium, is shown in Fig. 6.10. The dip in the tank temperature at about 7 a.m. is due to the fact that the

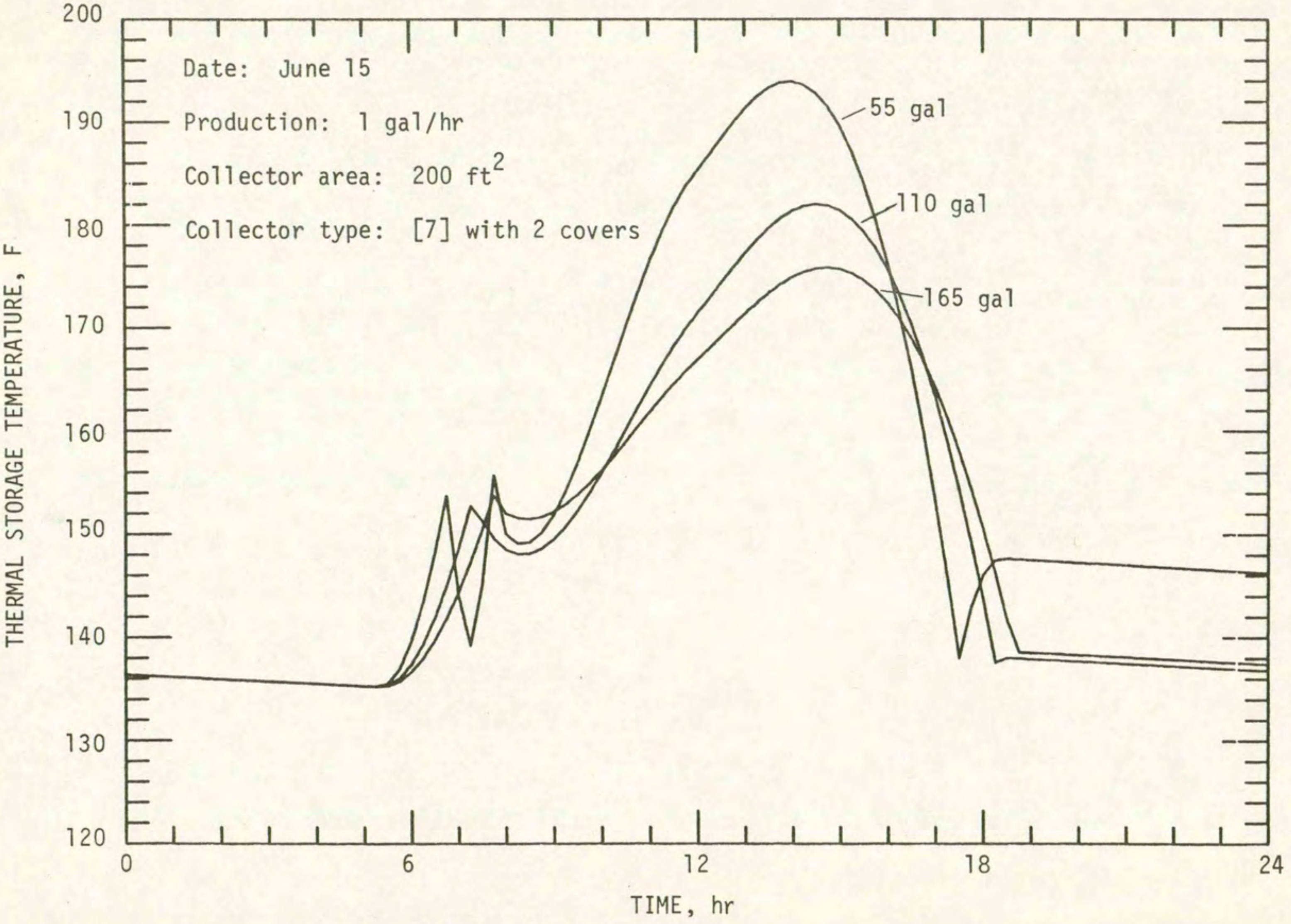


Figure 6.10 Temperature Response of Thermal Storage

solar energy available from the collector at this hour is insufficient to sustain the process, and energy stored in the tank previously has to be utilized for distillation. The 55 gal tank shows a rise in temperature after distillation is stopped at 5:30 p.m. because sunset is only at 6 p.m. Since the size of the tank is inversely related to its temperature gain, it is important that the tank be properly sized to get optimum performance from the collector.

The variation of the daily alcohol production for daytime operation with the volume of the storage tank where both quantities are normalized by the collector area, is illustrated in Fig. 6.11. The distillation unit is assumed to operate only during periods of available solar energy. Distillation temperature is 125 F and the initial tank temperature is 135 F. In is seen that production reaches a maximum of 0.068 gal/ft^2 at a storage volume of 0.95 gal/ft^2. For an area of 200 ft^2, as applicable to the University of Iowa collector array, this translates to 13.6 gal of ethanol and 190 gal of water storage. Collector efficiency varies in a similar manner, with a maximum of 56 percent at a storage volume of 190 gal. Beyond this storage volume, the temperature rise of the tank is inadequate to sustain distillation, causing the production to decrease. Continuous operation (24 hr) requires a water storage volume of 4.5 gal/ft^2. The corresponding efficiency and total production are respectively, 54 percent and 0.066 gal/ft^2.

With phase change storage, the inlet temperature to the collector is nearly constant at about 140 F. Consequently, the collector efficiency and total production are invariant with storage volume, since a constant

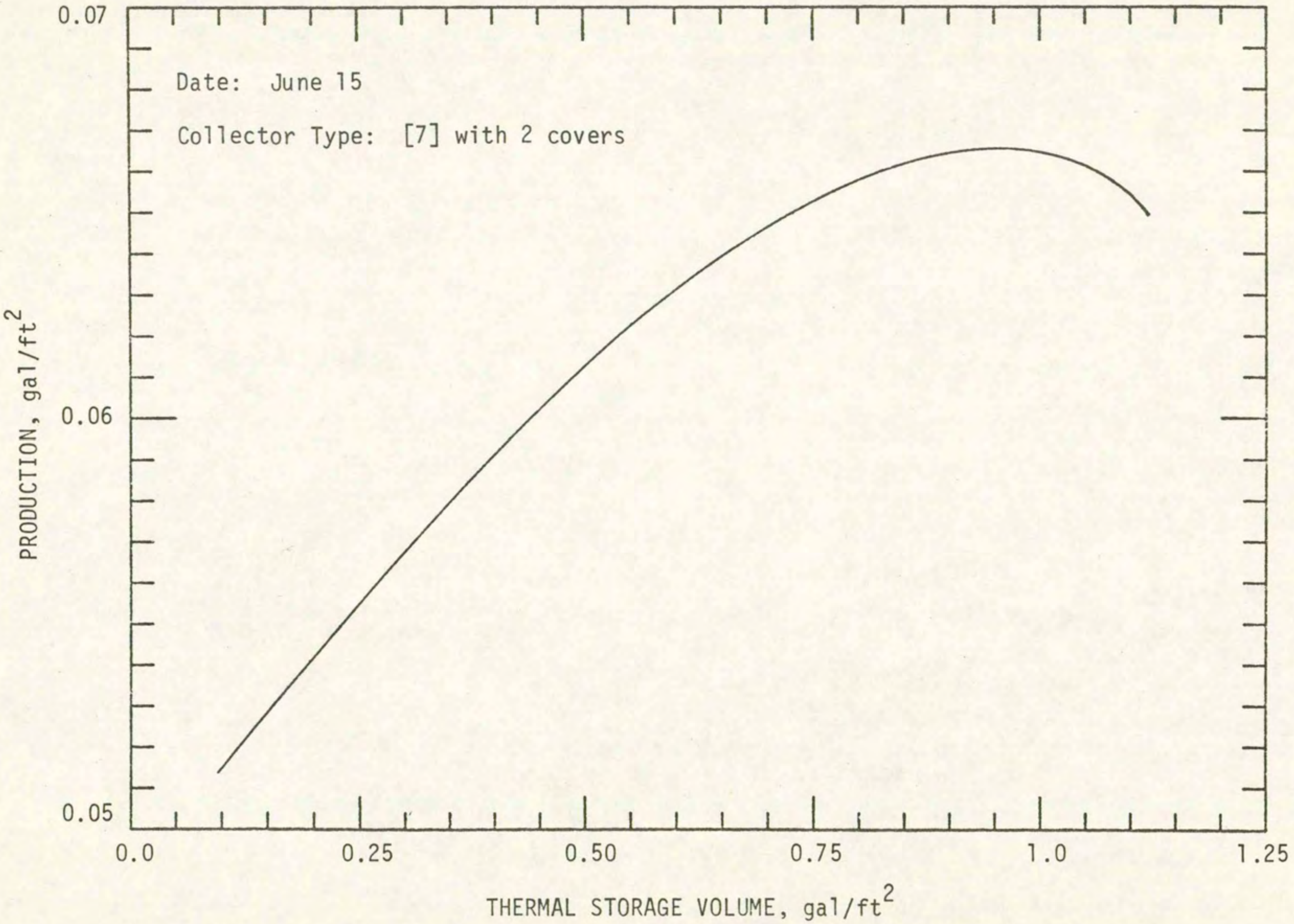


Figure 6.11 Production

temperature storage is assumed. For a distillation temperature of 125 F, collector efficiency reached 60 percent and ethanol production was 0.072 gal/ft^2 for a production rate of 1 gal/hr and a production time of 14 hr 25 min.

Daily production is a function of the hourly production rate when collector area and sensible storage volume are constant. These results are shown in Fig. 6.12. Small production rates result in poor collector efficiencies and total output, due to excessive tank temperatures, while large production rates have a similar result because of interrupted operation. There is an optimum production rate of 1.5 gal/hr where both daily production and collector efficiency are maximum, for a storage volume of 55 gal, collector area of 200 ft^2 and a single collector cover. Maximum daily production and efficiency are, respectively, 11.9 gal and 38 percent. The distillation unit operates for 7 hr and 55 min. under these conditions. Continuous operation can be achieved only with a sub-optimum production rate, and consequently the daily production is also sub-optimum.

With phase change storage, production and efficiency do not depend on the production rate. Daily production is a function of collector area only, and uninterrupted operation is ensured by small production rates.

All other parameters being fixed, collector efficiency and daily production increase significantly when the number of collector covers is increased from one to two or three. This is due to the reduced heat loss from the top of the collector. Typical values are given in the following table:

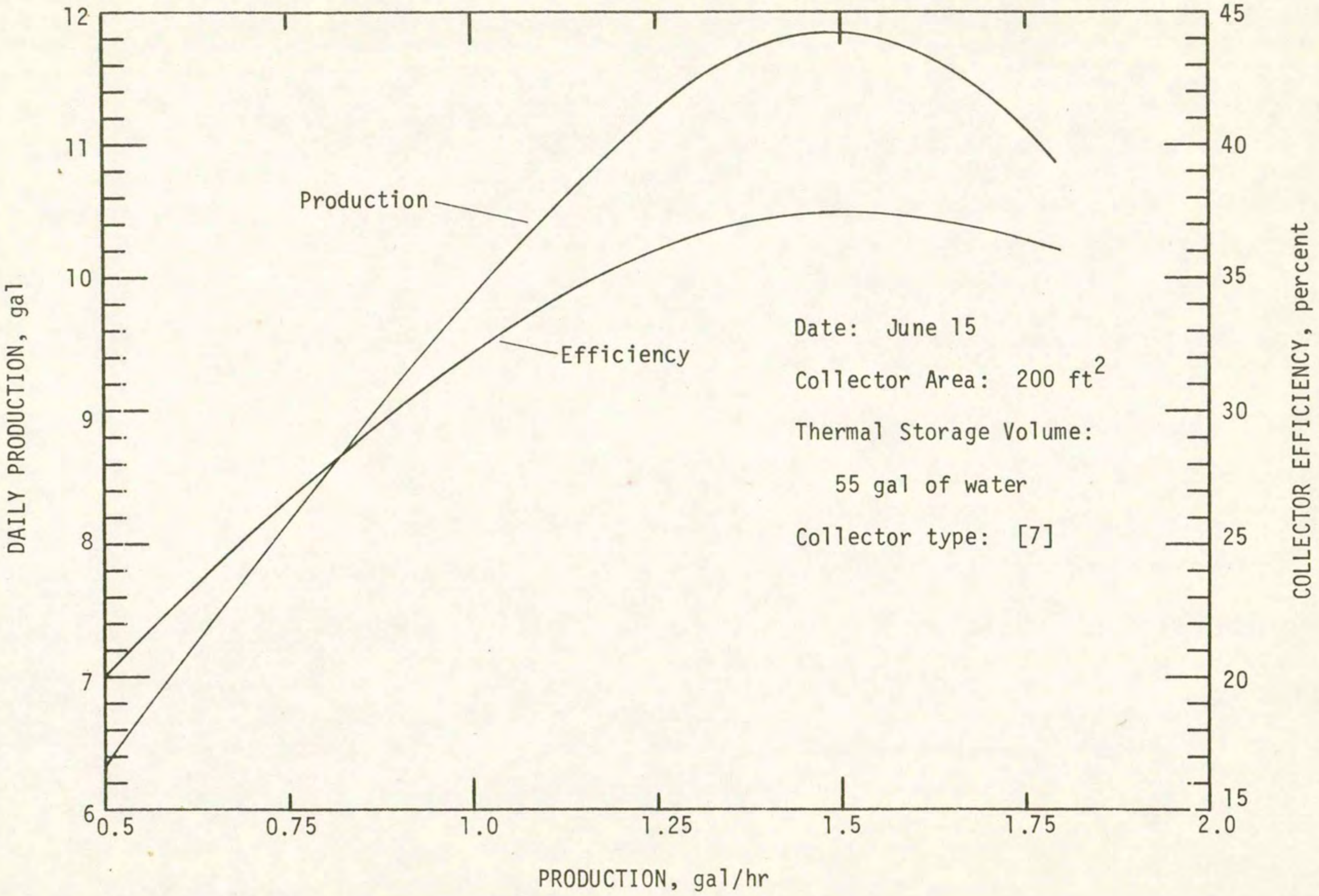


Figure 6.12 Production and Efficiency

Storage volume: 165 gal. Collector area: 200 ft^2

Production rate: 1 gal/hr. June 15, daytime operation.

No. of Covers	Efficiency (percent)	Production (gal)
1	33.4	9.42
2	44.8	12.67
3	52.9	13.75

From these results, it is seen that by increasing the number of covers from one to two, an increase in production of about 35 percent occurs. However, a third cover results in a marginal production increase of only 9 percent. This means that a trade off has to be made between the cost of additional covers and the increased production resulting from them. It would seem that two covers are optimum.

For the same operating conditions, the performance of the system depends on the type of the collector. Typically, a distributed flow collector exhibits a 3 to 5 percent higher efficiency than a fin-and-tube collector. Commercial collector performance curves indicate efficiencies that are about 5 percent below the efficiency of the distributed flow collector.

Variation of the production, collector efficiency and operating time with the distillation temperature is shown in the following table. It is seen that all of these quantities decrease as distillation temperature increases.

Storage volume: 165 gal		Collector area: 200 ft^2

Production rate: 1 gal/hr		June 15, daytime operation

Distillation Temp, (F)	Efficiency (percent)	Production (gal)	Operating Time (hr: min)
115	45.8	14.58	14:35
120	44.4	13.67	13:40
125	43.5	12.92	12:55
130	42.9	12.25	12:15

Performance simulation for several other operating conditions is possible, but the possibilities are too numerous to be considered here. Only the most important results have been discussed.

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7. ENERGY BALANCE

7.1 Introduction

Ever since alcohol fuels were introduced as an alternative to gasoline to alleviate the problem of the United States' dependence on imported oil, a considerable amount of discussion has been made and a lot of controversy generated on the question of the energy balance and efficiency of energy utilization in the production of ethanol from corn. The energy balance for a grain alcohol process is obviously of great importance because it directly determines the feasibility of the process, that is, whether or not it is worth producing ethanol from corn. Several individuals and organizations have analyzed the process for an energy balance, but most of these studies are characterized by rather extreme differences in their results and conclusions [1]. It seems that an energy balance for a particular system depends largely on the specific process characteristics, the priorities of the different forms of energy used in the process, and on the end use of the product.

Early research on grain alcohol production processes yielded only negative energy balances, thereby questioning the advocation of ethanol as a substitute automotive fuel. Presumably, these studies were based on antiquated data, because recent advances in process technology and new studies based on them indicate a favorable energy balance for the process [2].

In this discussion, an integrated energy balance scheme that incorporates the features of most previous and recent studies is presented, with particular attention to solar energy-assisted ethanol production.

7.2 Approach Analysis

The energy and material input-output features of the grain alcohol process are schematically represented in Fig. 7.1. This diagram includes all the inputs and outputs for the process, but for purposes of analysis, a judicious system boundary must be chosen to include or exclude some of them, depending on the specific requirements of the energy balance scheme.

With reference to the diagram, three main nodes of energy and material interaction are cited, namely, on-farm, transportation, and the plant process. Farm inputs include different forms of energy for farming operations plus material inputs such as seeds and fertilizers. Labor is an estimated energy equivalent of manual effort in farming operations. Investment is a measure of the energy consumed in manufacturing the farm equipment (or process equipment). Energy spent in operation and upkeep of machinery on a day-to-day basis and not accounted for in the fuel inputs is entered under machinery in the input-output diagram. In the quantitative energy balance approach that follows, the transportation node is assumed to have been integrated with the farm node. This can be interpreted as meaning that whatever transportation occurs is accounted for in one of the farm inputs.

Process energy inputs include energy for grinding the corn, cooking, fermentation, distillation, refining or dehydration (if pertinent), drying and separating the distillers' dried grain (DDG), which is a high protein feed material, and miscellaneous electrical inputs such as for pumps and stirrers. The outputs from the process are ethanol, DDG, carbon dioxide, and small quantities of fusel oil (a mixture of organic acids, aldehydes and ketones).

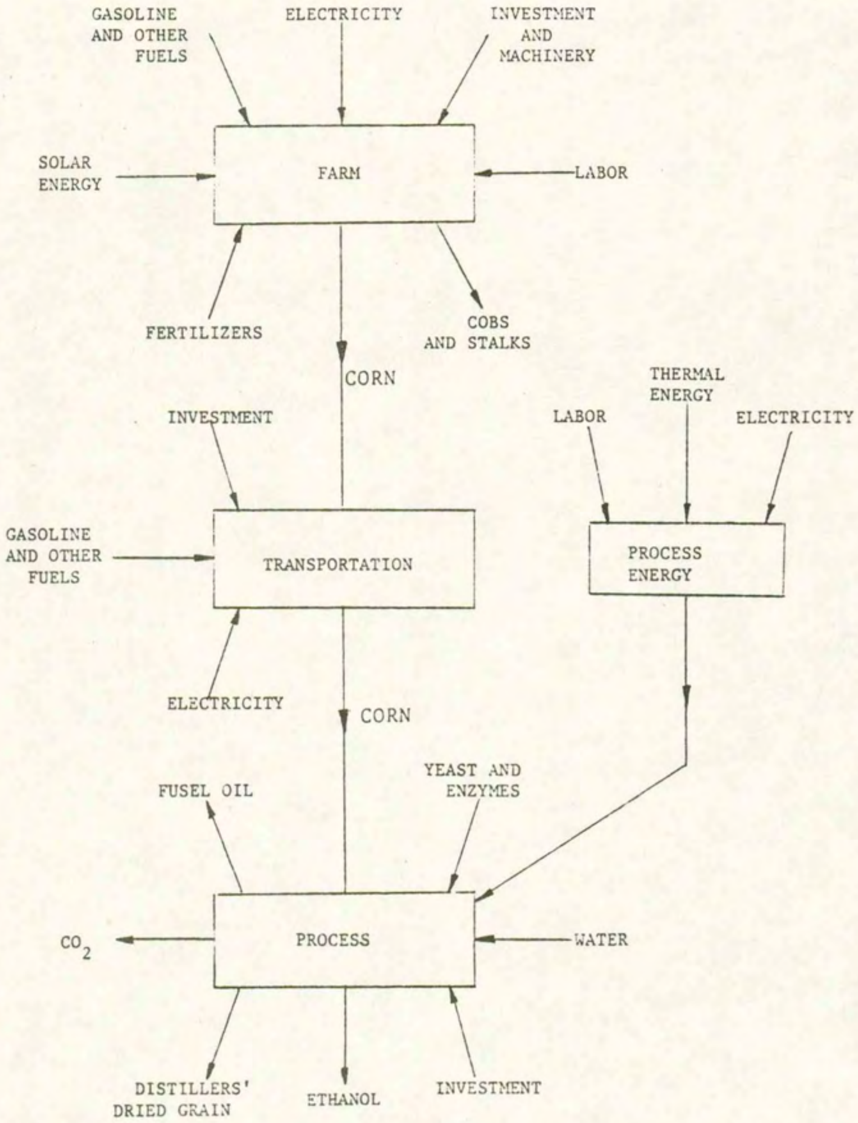

Figure 7.1 Material and Energy Interactions

From a scientific standpoint, it would be reasonable to exclude the capital-invested energy and material on the farm and in the process, as this component will not contribute to the steady state energy balance of the system. It should, however, be borne in mind that a large investment of money and materials can reduce steady state inputs, and tilt the energy balance to the favorable side, and vice versa. But a large amount of energy for construction and materials means that a long payback period results, in other words, if it takes 100 Btu to build a plant which produces 5 Btu/year, 20 years must elapse before the plant generates positive energy. For example, an elaborate waste heat recovery system may reduce energy inputs into the process, but will obviously mean a higher initial monetary outlay. The exclusion of the capital-invested energy and material, therefore, has to be treated as a limitation of the scheme. Still, one can compare two energy balances with this exclusion if the processes involved do not differ widely in sophistication of materials and construction techniques. This is applicable to The University of Iowa solar-assisted ethanol plant versus fossil fuel powered units.

Again from a practical viewpoint, energy inputs that are not paid for, that are "free", are excluded from the energy balance in the same way that rainfall is not treated as a material input in farming. For example, solar energy used in the process or absorbed naturally by photosynthesis, is a free input. Instead of farm energy inputs, some studies have employed the heat content of corn as a substitute, but this approach does not reflect the energy actually expended in farming as it includes free, natural inputs like photosynthetic energy. As before, the exclusion of free inputs is a limitation because solar energy used for processing will require an initial investment in equipment, and this is ignored in the energy balance scheme.

DDG, the secondary output from the process is often a controversial element in the energy input-output relationships. Different sources view its use and quantify its energy content differently. According to the National Research Council [3], one pound of corn has a metabolizable energy content of 5930 Btu, while one pound of DDG has 5731 Btu of the same - a 4 percent difference. A Kentucky study [4] shows that cattle fed with DDG as a supplement to corn gained 12.9 percent more weight than cattle fed with corn alone, on an equal weight basis, presumably because of the higher protein content of DDG. Another source [5] notes that if all the DDG from a fermented batch were fed to cattle, then the DDG would have a feed value that is 0.41 times that of all the corn that was used in the fermentation. Since 56 lbs of corn produce 18.5 lbs of DDG, and 0.41 times 56 is 22.96 lbs of corn feed, this means that DDG has a 24 percent higher feed value than corn on a unit mass basis.

If DDG is assumed to be equivalent to corn for cattle feed purposes - a conservative assumption based on the above - the energy balance scheme is vastly simplified. The energy contribution from DDG can now be proportional to the farm input energy for corn. This approach is not used in most previous studies, their value for the energy contribution of DDG being its heat content. This is obviously an inconsistency, for DDG must be treated just the same as corn, since like corn, it is not normally used as a combustible fuel, and its energy credit must be related directly to that of corn as above. Cobs and stalks figure prominently in some studies as controversial input-output contributors. It is assumed for purpose of simplicity in this report, as is also common farming practice, that the cobs and stalks are left back in the field and will not be involved in the energy balance.

Of the outputs, carbon dioxide is assumed to be vented to the atmosphere, while fusel oil is assumed to have a negligible effect on the energy balance (production of industrial grade ethanol requires fusel oil to be extracted out of the distillate, but for automotive purposes, fusel oil need not be separated out as it is a good fuel) [4].

The only contributors to the energy balance are, thus, the farm energy, process energy, the energy equivalent of ethanol, and the farm energy equivalent of DDG (treating DDG as corn). On this basis, a scheme that gives a consistent representation of all the input-output components may be drawn up.

7.3 Thermodynamic Efficiency Considerations

Several energy balance studies made on alcohol plants in the recent past have failed to take into consideration the influence of thermodynamic efficiencies of various inputs and the end use of alcohol, on the final energy balance [1,3]. This section is an attempt to include this factor in the analysis.

For the purpose of this discussion, a premium energy source is defined as one that has a high energy density, is versatile in its utility, and is highly transportable. Gasoline is considered a premium fuel, whereas coal is not a premium fuel.

Electricity is even more of a premium energy source than liquid fuels, and should not be considered equivalently with such inputs in the energy balance as diesel oil or gasoline, for it takes approximately 3 Btu of thermal energy from a petro-fuel to produce a 1 Btu of electrical energy in a power plant [6]. For uniformity, therefore, actual electrical inputs in the energy balance will be tripled where applicable. This procedure is necessary if the comparison of energy interactions in the production of ethanol is to be valid and consistent.

Thermodynamic efficiency also influences the energy credit given to the primary output of the process, namely ethanol, in the following manner. A two million mile road test conducted in Nebraska [4] over a 34-month period to compare the fuel economy of gasohol and unleaded gasoline showed that gasohol powered cars obtained on the average 6.7 percent more miles per gallon (mpg) than cars powered by pure gasoline. Other investigators [3,4] quote a 3 to 5 percent increase in mpg with gasohol. As a simplification, this analysis assumes that the ethanol produced from corn will fuel an internal combustion engine, and that there is no change in the mpg with gasohol over gasoline. This assumption is reasonably conservative, as the foregoing arguments show that gasohol has performed better than gasoline in road tests. Thus, one gallon of ethanol is thermodynamically equivalent to at least one gallon of gasoline when mixed in a 9 to 1 gasoline to ethanol ratio. If, therefore, gasoline is treated as 100 percent efficient and given an energy credit of 121,000 Btu/gal, alcohol should also be given a credit of 121,000 Btu/gal.

The improved thermodynamic performance of gasohol that enables it to function better than gasoline despite a smaller heat content is due to the superior combustion characteristics of ethanol. Ethanol has a high oxygen content and keeps the combustion mixture lean. It has in addition the benefits of higher octane rating and lower toxic exhaust emissions [3,4].

Another aspect of the end use of ethanol is its 10 percent blend with diesel oil, called diesohol, but this is considered impractical as the fuel efficiency of a diesel engine decreases if it is fueled by diesohol. This is because of the low energy content and very low octane rating of the blending ethanol [7,8].

Dual fueling diesel and ethanol, however, seems promising, especially in turbocharged diesel engines, but this requires major engine modifications. It is claimed that in a test with a 125 hp tractor engine, diesel fuel consumption dropped from 8.5 to 6.0 gal/hour with the injection of 2 gal/hour of 100 proof ethanol [7,9]. This implies that 1 gallon of anhydrous ethanol is equivalent to 2.5 gallons of diesel fuel for purposes of energy credit, and will, therefore, raise the output energy credit for ethanol substantially. Correspondingly, the net energy gain will also be higher.

The foregoing argument cannot be invoked in order to give alcohol a higher energy credit than its heat content if it is to be put to uses other than that as a fuel in a motor vehicle engine. In that event, it would be difficult to draw up a consistent energy balance scheme. For instance, if ethanol functioned as a space heating fuel, it would burn only about as efficiently as natural gas or other liquid fuels, and on this assumption, its energy credit would be just its heat content of 84,600 Btu/gal. No reliable data are available for such applications, and it can only be said that in this case the energy balance for the process will be less favorable, but could still be positive.

7.4 Energy Input-Output Relationships

7.4.1 Farm Energy

Farm energy inputs vary widely depending on location, climatic condition, and the specific requirements of the individual farming regions [4]. The values for Iowa differ widely from those for other states and also from the national average [5,6]. The largest farm input is the fertilizer energy equivalent, consuming 3.88 million Btu/acre annually [5,6]. Gasoline, diesel, electricity, and other fuels take up 3.0 million Btu/acre/year. The total farm energy for Iowa is 6.96 million Btu/acre, compared to the national average of 7.66 million Btu/acre (other sources [3,10] quote an even higher figure). Iowa's farm energy inputs are characterized by a low electrical fraction, as irrigated farming is very isolated. A study by Bunger [3] and two farm energy reports [6,11] are the basis for the farm energy input values in Table 7.1. In this analysis, a corn crop yield of 101.2 bu/acre silo weight (the US average for 1979) and an ethanol yield of 2.5 gal/bu are assumed. Silo weight is the weight of the corn before it is put in storage, and includes a 14.5 percent moisture content.

Various figures between 36,000 and 40,000 Btu/gal are usually quoted for farm energy inputs in Iowa. US averages are generally between 44,000 and 47,000 Btu/gal. States which require extensive irrigation use much more farming energy, e.g., Nebraska at 76,000 Btu/gal. This increase is mainly due to larger consumption of electricity and diesel fuel.

The annual energy requirements for farm operations listed before are for 1974-1975, but no significant change is expected for the 1980-81 values.

Table 7.1

Energy Requirements for Corn Production in Iowa [3,6,10,11]

		Btu/gal of Ethanol
Labor		80
Machinery		6,320
Gasoline and other fuels		11,860
Fertilizer		15,330
Nitrogenous	13,270	
Phosphatic	1,220	
Potash based	840	
Seed		990
Insecticides, etc.		340
Drying		1,880
Transportation and other misc.		1,190
Correction for electrical input eff.		800
Total		38,790

7.4.2 Process Energy

Process energy values for an alcohol plant show a downward trend with time, presumably because the values used in the past were those from energy-inefficient brewery stills. Modern technology has reduced these values, and the fact that automotive grade alcohol need not be purified as thoroughly as brewery grade product, reduces them even further.

Ofoli and Stout [2,12,13] have demonstrated a positive energy balance based on recent data. Their data show greatly reduced values for process energy. From 1973 to 1979, process energy has decreased from 170,000 Btu/gal to 57,000 Btu/gal [4]. A process energy table based on these recent advances is presented in Table 7.2, assuming that one bushel of corn produces 2.5 gallons of ethanol and 18.6 lbs of DDG [3] (1 bushel of corn = 56 lbs).

It can be seen that distillation and DDG separation (centrifuging and drying) are the major components of the process energy, taking up about 32 percent and 24 percent, respectively.

About 80 percent of the thermal energy requirements for cooking, fermentation, and distillation can be supplied by solar energy. Thus, out of the 59,640 Btu/gal energy requirement, approximately 22,300 Btu/gal or 37 percent can be supplied by solar energy. The balance can be made up with conventional heat sources. With investment in air heating solar collectors and dehumidifying equipment, it is possible to utilize solar energy to dry the DDG by-product, but this possibility is excluded here, since the drying of DDG is discussed elsewhere in this report.

The outputs from the process are 2.5 gal/bu of ethanol and 18.6 lbs/bu of DDG. Thus, for every gallon of ethanol produced, 7.45 lbs of DDG result. Also, one gallon of ethanol is obtained from 22.4 lbs of corn. As has been

Table 7.2

Energy Requirements for Plant Operation [5,13,15]

	Btu/gal
Grinding	2,500
Cooking (two steps)	6,000
Fermentation	840
Distillation	21,000
Evaporators	8,200
Dryers	7,500
Centrifuges or other separators	5,600
Misc. power for motors, pumps, lights, etc.	8,000
Total	59,640

Note: (1) Shaft power and electricity are assumed to have the conversion 10,000 Btu/kwh [6].

(2) This energy balance is for anhydrous ethanol production.

discussed before, DDG is equivalent to or better than corn for use as cattle feed. The energy credit given to it, therefore, will be proportional to the farm input energy for corn, that is, (7.45/22.4) times the farm input energy of 38,789 Btu/gal, or 12,900 Btu/gal.

Alcohol, as also discussed before, if used as a blend in gasohol, functions more efficiently than gasoline, and earns an energy credit of 121,000 Btu/gal, equivalent to the energy content of pure gasoline. The final energy balance for the process is given in Table 7.3(a).

For the case when ethanol is not used to make gasohol, but is burned straight in an engine, it cannot be assumed that it will deliver as much power as an equal mass of gasoline. The efficiency of alcohol combustion is better than that of gasoline for proofs around 180, but cannot match the heat content difference of 36,400 Btu/gal between them. A comparative study of the efficiencies of ethanol and gasoline combustion in an internal combustion engine has been made in [7]. For engine speeds ranging from 1300 to 1800 rpm, the study shows that the mean efficiency for gasoline combustion is 31.7 percent, and that for ethanol over the same range is 32.2 percent. Thus, ethanol gets an energy credit (32.2/31.7) times its heat content of 84,600 Btu/gal, or 85,930 Btu/gal. The energy balance for this case is given in Table 7.3 (b). Again, a positive energy balance is shown. It may be noted that the process energy input has been reduced by 8,200 Btu/gal. This is because, hydrous alcohol can be combusted directly, and there is no need to evaporate all of the water from it.

Table 7.3

Energy Balance for Ethanol Produced From Corn

(a) Used as Gasohol

		Btu/gal
Output:		
Ethanol (gasoline equivalent)		121,000
DDG		12,900
	Total	133,900
Input:		
Farm input		38,790
Process input		59,640
	Total	98,430
Net energy gain:		35,470

(b) Used directly in engines

Output:		
Ethanol		85,930
DDG		12,900
	Total	98,830
Input:		
Farm input		38,790
Process input		51,440
	Total	90,230
Net energy gain:		8,600

7.5 Interpretations and Conclusions

The energy balance for grain ethanol production has been shown to be positive, even with stringent assumptions regarding the end use of the alcohol, and the utility of the DDG. In actual cases, the net energy gain can be even higher for the following reasons:

(1) Alcohol distinctly improves the mpg when used as a blend in gasohol, and this will give an upward boost to its equivalent energy credit.

(2) No significance has been given to the fact that ethanol raises the octane rating of gasohol. This means that the gasoline used in the blend can have a lower octane rating than at present for the gasohol to perform as well as gasoline does now. Gasoline should then cost less, since it does not have to be manufactured with as much purity as it is now, and octane-boosting additives such as tetra-ethyl lead are not necessary. This point cannot be directly incorporated into the energy balance, but is nevertheless a plus point.

(3) In the past, it has been common to treat the output energy as merely the sum of the heat contents of the products, and not as done in this report. For the followers of this traditional method of energy balancing, ethanol gives an even higher net energy gain, as shown in the table that follows.

		Btu/gal
Output:		
Ethanol		84,600
DDG [5]		65,000
	Total	149,600

Input:	98,430
Net energy gain:	51,170

(4) The energy gain given in Table 7.3(b) does not represent the true potentialities of alcohol as a straight fuel in internal combustion engines. It has been shown [7] that in an engine built specifically to utilize the unique properties of ethanol, where combustion occurs by the so-called Brandt system [14], the thermal efficiency is about 42 percent, compared to about 30 percent for gasoline. This means that the energy credit given to ethanol would be much higher, and, hence, also the net energy gain.

(5) The energy balance in Table 7.3(a) assumes no free energy inputs. If, for instance, solar energy were used to assist in the distillation and cooking, contributions corresponding to them would be reduced from the energy balance, thus resulting in a higher net energy gain. With an 80 percent solar assisted cooking and distillation, the net energy gain would increase to about 57,000 Btu/gal.

The location of the alcohol plant can influence the energy balance to a considerable extent. For instance, if the plant were located on the farm, transportation energy inputs would decrease. Energy consumed for drying the corn would be reduced in the balance if the corn were fed to the ethanol plant directly. Similarly, if the DDG were being consumed on the farm itself, there would no need to dry it and the energy input corresponding to it would be zero. In this case, the energy balance of Table 7.3(a) would yield a net gain of about 50,000 Btu/gal.

The source of the corn can be another influence on the energy balance. In other states, the farming energy is somewhat higher for reasons listed before, and this can reduce the net energy gain.

As has been discussed before, modern technology has helped to reduce the distillation energy significantly, and fresh innovations can reduce it and other inputs even more. The University of Iowa ethanol plant has been constructed on the basis of modern design concepts. Vacuum distillation enables the maximum temperature of the reboiler vessel to be less than 120 F. The distillation pressure is one-eighth of an atmosphere. The beer is a 10 percent solution of ethanol, and the process is operated on a reflux ratio of 5:1. Heat is transported from the solar collectors to a storage tank by a water circuit, and water is drawn out from this tank for distillation. The capacity of the plant is up to 12 gal/day of 180 proof ethanol. The distillation energy for this process has been estimated as 20,300 Btu/gal.

For this ethanol plant, a major portion of the distillation energy is expected to come from solar energy absorbed by a 200 square foot collector array. Since this energy is "free", as discussed before, the contribution corresponding to it in the energy balance will be zero. Additional electrical or shaft power has to be put in to run the circulating pumps, hold the vacuum on the system, etc., but this increase is only of the order of 3,800 Btu/gal (based on 1.65 kw. pumps and 1.5 gal/hr production rate), and in any case, it is expected that it would be offset by the reduction in energy for fuel handling equipment (coal conveyors, oil pumps) in conventional plants. Thus, the net energy gain can be expected to increase by about 21,000 Btu/gal.

All the fuel inputs into the energy balance so far have been treated as premium fuels, not low grade ones like coal. If, as some investigators view it, a good portion of the inputs can be made non-premium, the premium fuel energy gain would be considerable, since alcohol is obviously a premium fuel. For example, if all petroleum fuel heat sources for drying, distillation or cooking were substituted by coal, wood, or combustible waste material burners, the process would be a net premium fuel generator.

From all considerations, therefore, the production of ethanol from corn utilizing modern technology shows a net positive energy balance, and, hence, the replacement of gasoline by gasohol or pure ethanol for automotive applications will result in a net reduction in fossil fuel consumption and could lead to more stable petroleum prices and a reduction in the trade deficit.

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8. CONCEPTUAL DESIGNS

8.1 Introduction

The purpose of this section is to examine and discuss the different means of utilizing solar energy in the production of fuel alcohol. Solar preheating for cooking corn, solar drying of DG, and solar assisted fuel alcohol distillation processes are discussed.

8.2 Cooking Preheating

Solar thermal energy can be used in the process of converting starchy grains (corn) into fermentable sugars. As reported in the discussion on fermentation, a minimum temperature of 160 F is necessary to hydrolize the starches in preparation for fermentation. For analysis purposes a batch fermentation process is assumed, with a new batch to be cooked each day. This allows for a solar collector to run each day energy is available and to make an energy contribution to the cooking process. The make up water is assumed to be at 60 F and this water is mixed with distillation column bottoms product at a ratio of 2 parts water to 1 part bottoms product. This process is technically feasible and boosts the make-up cooking water to 80 or 98 F for vacuum or atmospheric distillation, respectively [1]. At this temperature, the water is then fed into the solar collector. Table 8.1 shows useful energy gain for four different collector types, namely, fixed flat plate (FFP), tracking flat plate (TFP), fixed compound parabolic (FCPC), and tracking parabolic collector

Table 8.1

Comparison of Collector Performances

		Winter	Summer	Fall
S_o	normal	2267	3056	2430
S_o	(β)[3]	1995 (60°)	2393 (20°)	2022 (40°)
T_a	[2]	25	76	55
		$T_i = 80$		
FFP [4]	η	0.678	0.692	0.690
	Q_u	1353	1656	1395
TFP [4]	η	0.688	0.698	0.692
	Q_u	1560	2131	1682
FCPC [5]	η	0.6871	0.690	0.683
	Q_u	1371	1650	1380
TPC [6]	η	0.734	0.744	0.740
	Q_u	1665	2274	1799
		$T_i = 98$		
FFP	η	0.672	0.692	0.670
	Q_u	1341	1656	1355
TFP	η	0.675	0.694	0.686
	Q_u	1530	2119	1667
CPC	η	0.686	0.689	0.677
	Q_u	1369	1649	1369
TPC	η	0.731	0.742	0.737
	Q_u	1657	2265	1791

Key:

S_o - Ave Solar energy, Btu/day-ft^2

T_a - Ambient air temperature, F

η - Collector efficiency

β - Collector tilt

T_i - Collector fluid inlet temperature, F

Q_u - Useful energy, Btu/hr-ft^2

(TPC). There is some variation in useful energy gain between collector types, but based upon initial cost and maintenance simplicity, the stationary flat plate collector is probably most appropriate. Also, there is little difference in collector efficiency between an inlet temperature of 80 or 98 F. The results for spring are similar to those for fall.

Table 8.1 does not present the outlet temperature of the solar collectors. Outlet temperature can be calculated based upon useful energy gain and flow rate. Collector outlet temperature can be adjusted through the collector flow rate. A lower flow rate and, consequently, higher outlet temperature decreases collector efficiency. Thus, for a higher outlet temperature more collector area is required, even for the same amount of useful energy.

Another factor to be considered is that the dissolved solids in the bottoms product may cause solar collector clogging problems. If clogging poses a site specific problem (depending on exact fermentation, distillation processes, and collector type) the bottoms product can be added after make up water passes through the collector.

In conclusion, cooking preheating is a technically feasible application of solar energy. Site specifics and economics, as discussed in Section 9, determine the extent of solar energy usage for this process.

8.3 Solar Distillers Grain Drying

The purpose of this study is to determine the feasibility of drying DG using solar energy. The specifications of solar collectors that are required for the drying process are energy for drying and collector area. Two types of solar collectors that can be used in this process are examined.

In order to determine the collector area, the thermal efficiency curves for air and water collectors are needed. Representative curves are given as follows

Air collector [7]: $\eta = 0.55 - 0.94\ X$

Water collector [4]: $\eta = 0.699 - 0.71\ X - 5.74\ X^2$

where $X = (T_i - T_a)/S_o$. T_i and T_a denote the collector inlet fluid and ambient air temperatures, respectively. S_o is the solar energy incident on the collector, and η is the collector efficiency.

For values of T_a, T_i, and S_o of 70 F, 80 F, and 250 Btu/hr-ft^2, respectively, the air and water collectors exhibit efficiencies of 0.51 and 0.66, respectively. From these values, it is possible to calculate the collector area needed for drying as

$$A = Q_u/(\eta\ S_o)$$

where Q_u represents the energy to dry the DG which, is estimated in Chapter 4, to be 1900 Btu/hr. In the case of the water collector, a water-air heat exchanger is necessary. The effectiveness of that heat exchanger is assumed to be unity for simplicity of the analysis. The resultant air and water collector areas necessary to dry DG obtained from the production of one gallon of alcohol are 14.9 and 11.5 ft^2, respectively. These values represent the minimum areas with actual requirements being higher depending on the design of the drying apparatus. These areas are not excessive and could be accommodated.

Since information on DG drying is lacking the question of using solar energy as the source supplying the energy needed cannot be answered entirely, although these results indicate that it is feasible. The DG obtained from the production of one gallon of alcohol requires a collector area of around 13 ft^2. A problem raised by solar DG drying is the necessity of a back up heat source in the case of cloudy days.

8.4 Designs of Solar Assisted Distillation Units

8.4.1 Introduction

There are several ways to utilize solar energy in fuel alcohol distillation. It should be noted that regardless of the system configuration there is a set amount of solar energy available as discussed in Chapter 3. Collection of this solar energy as efficiently and economically possible is the variable. Different solar collectors and distillation units govern which design is best for a given site and design constraints of that site. Figure 8.1 shows the overall distillation possibilities with fuel alcohol, which include atmospheric and vacuum distillation, batch and continuous processes, and wet and anhydrous ethanol production. Atmospheric and vacuum distillation, as well as batch and continuous processes are discussed in Chapter 5. This report only addresses wet alcohol production due to the multiplicity of fuel alcohol dewatering techniques and the fact that solar energy has minimal effect on the application of these techniques. Dewatering techniques need

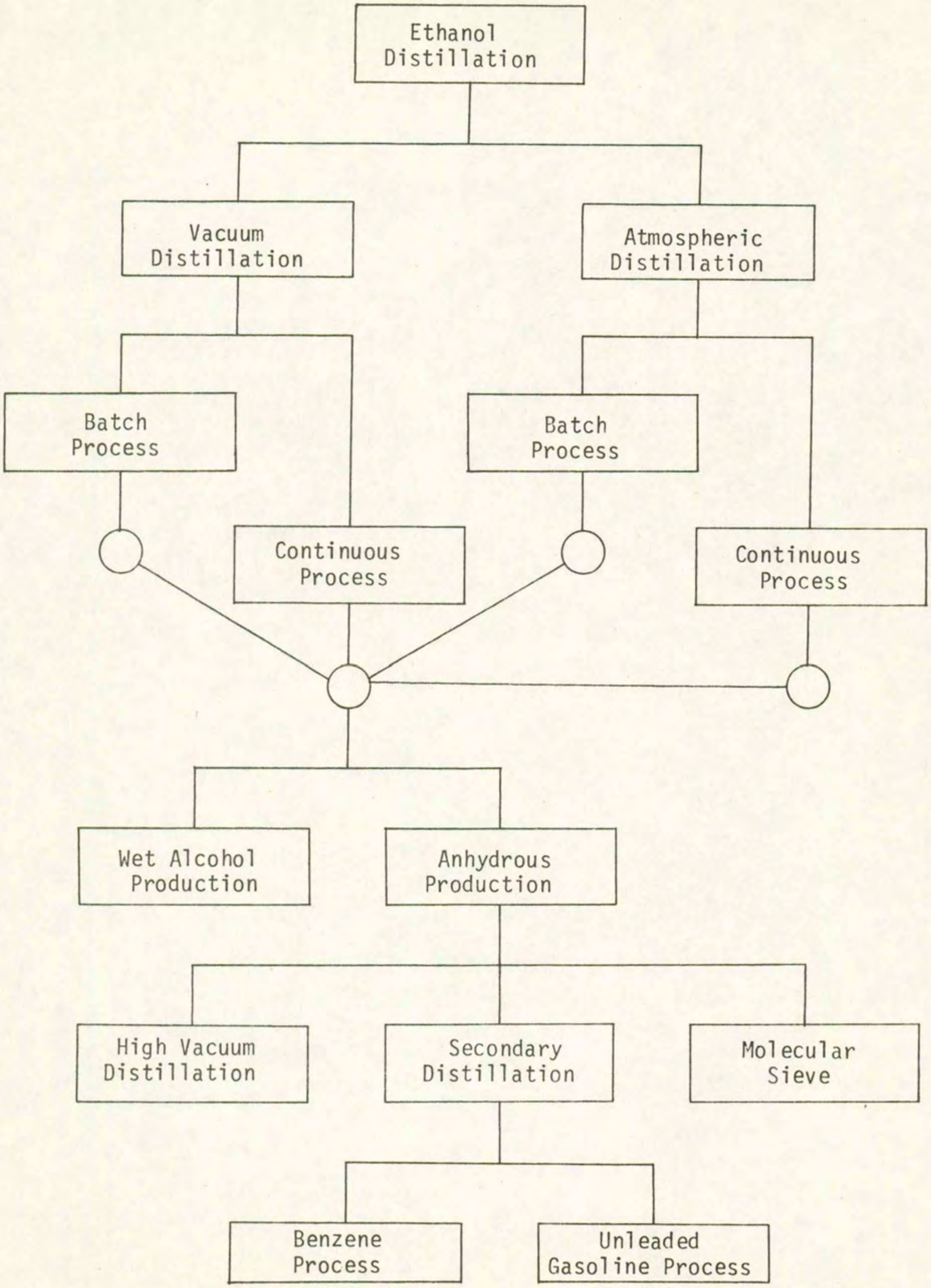


Figure 8.1 Ethanol Distillation Possibilities

an input of, say 90 percent alcohol and 10 percent water in either vapor or liquid phase. Generating this vapor or liquid with a fossil fuel or solar energy heat source has minimal impact on the dewatering technique. Some dewatering techniques are listed in Fig. 8.1 for sake of completeness.

8.4.2 Large Scale Production

Figure 8.2 displays solar energy applications for large scale fuel alcohol production with yearly production rates of 3 million gallon. The solar collectors to power a 3 million gallon per year plant could be assembled on an area of one acre, which is not unreasonably large. However, with large scale production, solar energy is believed to have a role in preheating due mostly to the vast thermal energy storage requirements or the need for a complete back up energy system for operation in the absence of solar energy. Consequently, solar energy usage on a large scale has application to preheating with or without thermal energy storage. As shown in Fig. 8.3, the advantage to storage is the fixed energy required from a non solar energy source. That is, no extensive back up energy source must sit idle eight hours a day and then suffer the thermal shock of start up and shut down (boiler manufacturers prefer to operate their units continuously).

The disadvantage of thermal energy storage is cost, volume required, and the eventual breakdown of most energy storage material. Phase change thermal energy storage is the most promising storage system. Sodium acetate ($NaC_2H_3O_2 \cdot 3H_2O$) which changes hydration-dehydration phase at 136 F appears well matched for vacuum distillation temperatures, and efficient operational temperatures for a solar collector. The technical

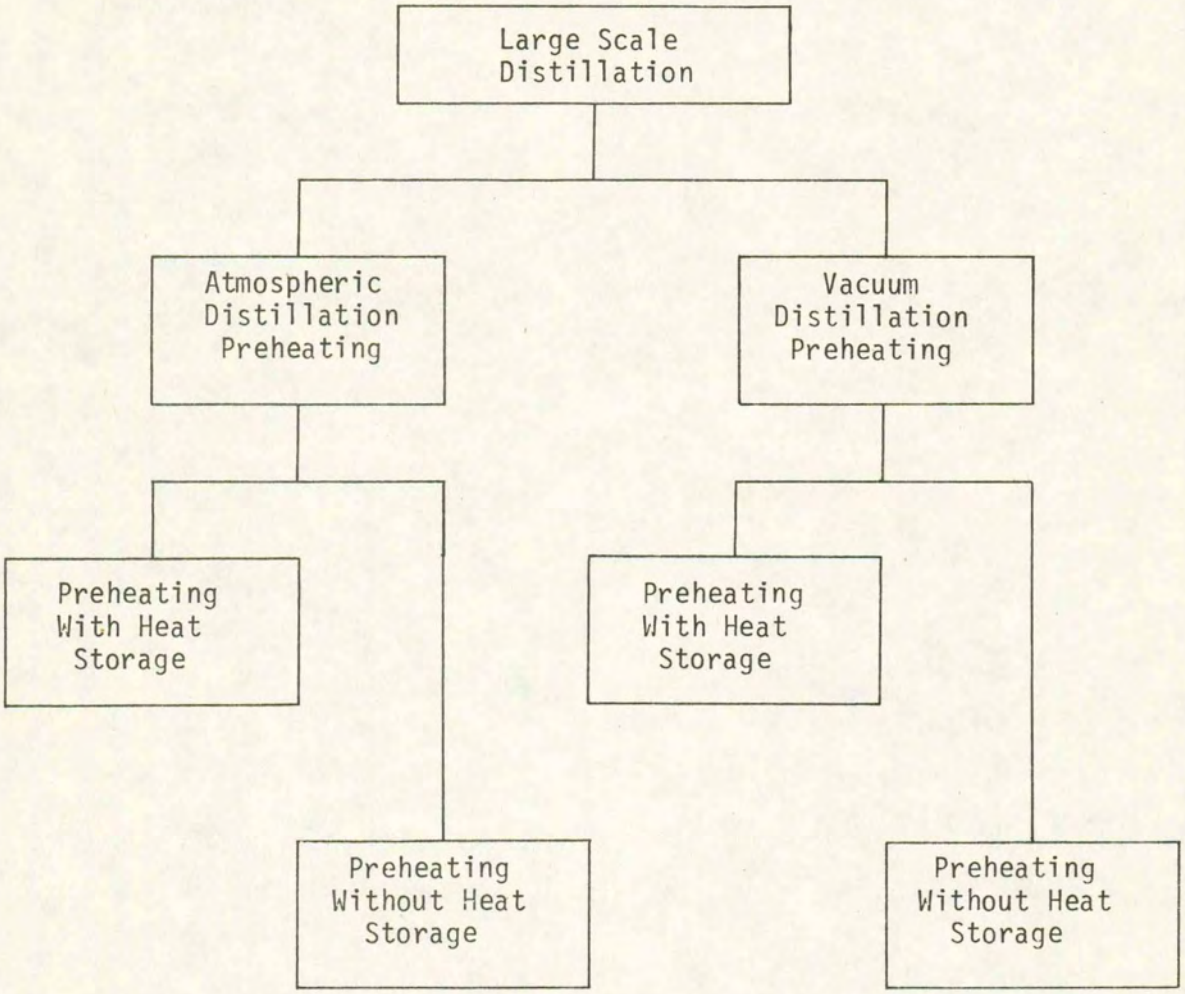


Figure 8.2 Large Scale ($3x10^6$ gal/yr) Ethanol Distillation Using Solar Energy

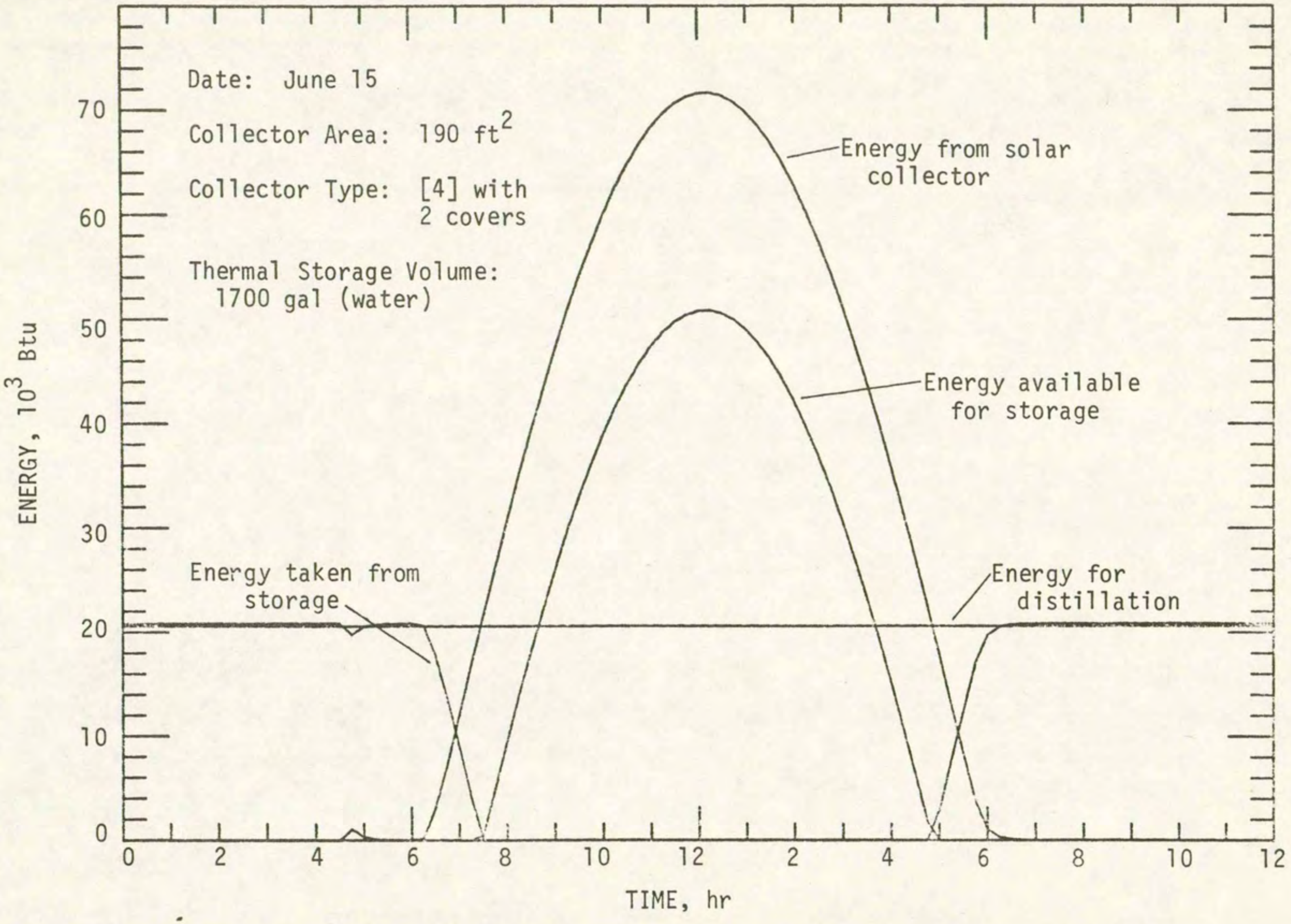


Figure 8.3 Useful, Stored, and Distillation Energy

feasibility for most phase change storage above 90 F including sodium acetate has yet to be proven. Consequently, the economics of such storage media are unknown. In addition to the cost of the energy storage media, the cost of a container, heat exchanger, and any additional collector area must also be included. The total cost of thermal energy storage must be compared to the capital and long term costs of a fossil fuel energy source for back up energy systems.

8.4.3 Small Scale Production

Figure 8.4 illustrates several feasible systems for small scale wet alcohol distillation using solar energy. Design criteria for small scale systems which produce 10,000 gal/yr include overall costs (capital and maintenance), labor intensiveness, quality control, and energy contribution from solar.

The first design decision is whether to use flat plate collectors or concentrating collectors of either the compound parabolic (CPC) [8] or tracking collector type. The decision to use a flat plate collector more than likely requires vacuum distillation. Use of CPC or tracking collectors should lead to atmospheric distillation for the "best" utilization of the solar equipment. In either case the decision of back up energy systems versus thermal energy storage and shut down must be made.

The factor of utilization of the distillation unit determines the need for either back up energy or thermal energy storage. For a fixed amount of yearly production, a two thirds to three fourths larger distillation unit is necessary for daylight distillation versus continuous operation. Cost of distillation equipment, thermal energy storage, back

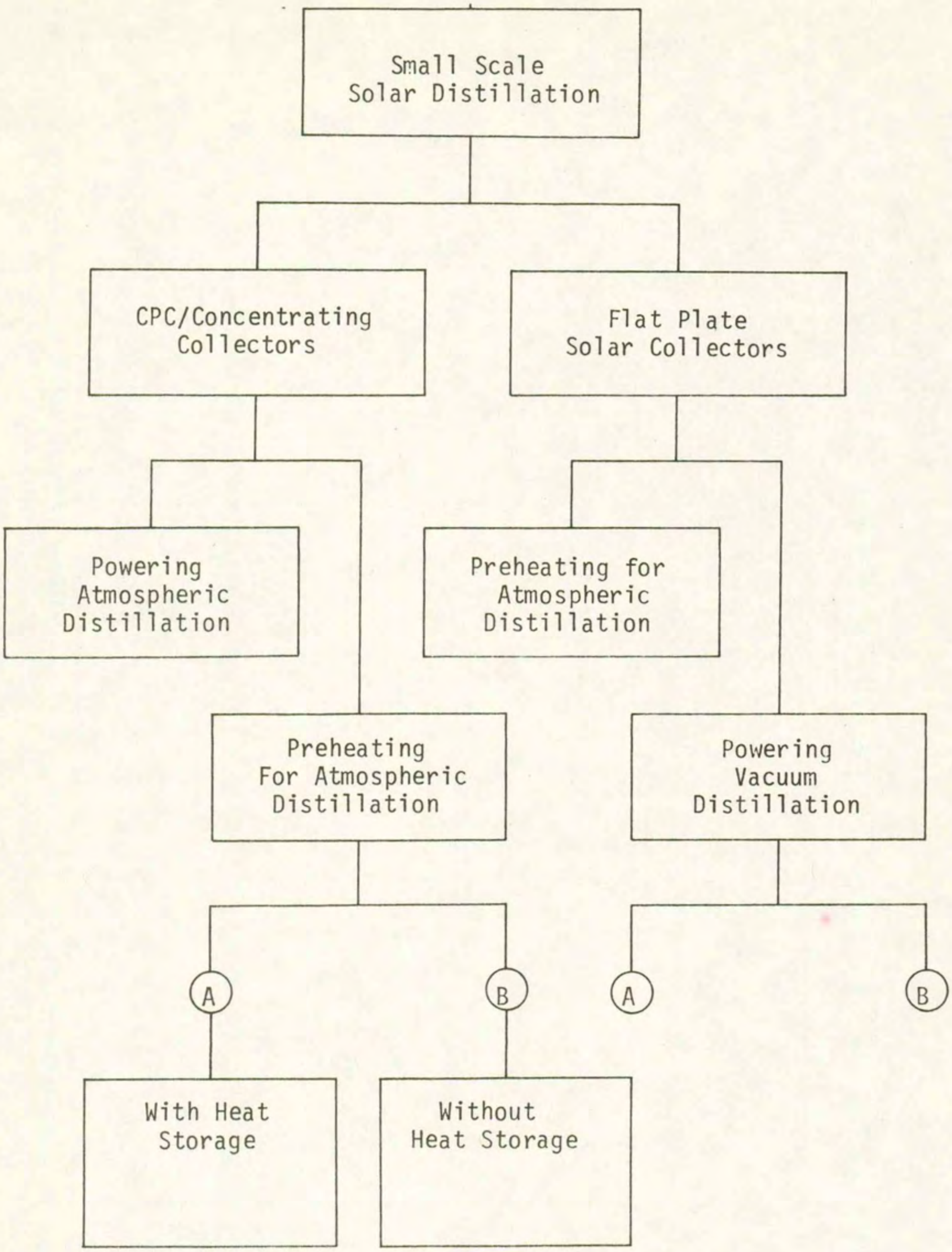


Figure 8.4 Feasible Systems for Small Scale (10,000 gal/yr) Wet Ethanol Distillation Using Solar Energy

up energy systems, and labor for start up and shut down determines the feasibility of continuous operation. Thermal energy storage allows for more "free" solar energy input for distillation at the cost of a storage system.

Atmospheric and vacuum distillations for small scale production were modeled using the models described in Chapter 6, and results are presented in Tables 8.2 and 8.3. It is interesting to note the difference in column height, diameter, volume, and distillation energy consumption which are tabulated below:

Distillation Type	Column Height inch	Column Diameter inch	Column Volume $inch^3$	Distill Energy Btu/gal
Vacuum	291	8.1	14,995	21,400
Atmospheric	492	3.1	3,713	27,400

These results specifically illustrate the advantages and disadvantages of vacuum distillation for the small scale producer of 10,000 gal/yr over a three month period. A three month period of January, June, and October is used to give both an idea of system performance over a year, and so that a farmer can still grow crops when producing his fuel.

There is a significant amount of latitude in the design of solar assisted fuel alcohol distillation units. Certainly on site variables play an important role in design engineering. Examples of on site variables are methane generation or corn cobs for a back up distillation energy source, crops grown, amount of livestock feed, amount of labor available for distillation operation, availability and temperature of make up and cooling water, and investment capital available.

Table 8.2

Atmospheric Distillation Modeling Results

```
CASE : 10,000 GAL/YR OVER 3 MONTHS


        ATMOSPHERIC PRESSURE DISTILLATION SIMULATION
        ETHANOL WATER SYSTEM
        INPUTS
         NPR   :PRESSURE                                =      1
               (1=760, 2=380, 3=190, 4=95, 5=50 MM HG)
         CF    :FEED CONCENTRATION, MOLE FRACTION =   0.03000
         CB    :BOTTOM PRODUCT,     MOLE FRACTION =   0.00100
         CD    :TOP PRODUCT,        MOLE FRACTION =   0.85000
         RD    :REFLUX RATIO                      =   5.00000
         PRATE:PRODUCTION RATE,            GAL/HR =   4.20000
         TF    :FEED TEMPERATURE,               C =  20.00000
         DP    :PACKING SIZE,                  IN =   0.50000
         COLDT:TOP PRODUCT TEMPERATURE,         C =  30.00000
         V     :VAPOR VELOCITY,            FT/SEC =  11.00000
         DT    :DELTA TEMPERATURE OF CONDENSER, C =   2.00000

        TOP PLATE BOILING POINT,                C =            78.30
        BOILING POINT OF BOTTOM PRODUCT.        C =            97.00

        FEED FLOW RATE,         CM**3/HR, GAL/HR =     176011.81             46.50
        BOTTOM FLOW RATE,       CM**3/HR, GAL/HR =     160214.38             42.33

        MINI HEAT REQUIREMENT,     CAL/HR, BTU/HR =   29059195.62         115314.27
        HEAT UP TOP PRODUCT,       CAL/HR, BTU/HR =     564547.69           2240.27
        HEAT UP BOTTOM PRODUCT,    CAL/HR, BTU/HR =   11822634.59          46915.21
        HEAT OF VAPORIZATION,      CAL/HR, BTU/HR =   16672013.34          66158.78

        LOCATION OF FEED PLATE =14
        NUMBER OF IDEAL STAGES =29

                                          LIQUID        VAPOR MOLE %
        CONCENTRATION AT STAGE = 1      0.0010000      0.0060000
        CONCENTRATION AT STAGE = 2      0.0018753      0.0112515
        CONCENTRATION AT STAGE = 3      0.0027945      0.0167672
        CONCENTRATION AT STAGE = 4      0.0037600      0.0225603
        CONCENTRATION AT STAGE = 5      0.0047741      0.0286443
        CONCENTRATION AT STAGE = 6      0.0058392      0.0350354
        CONCENTRATION AT STAGE = 7      0.0069579      0.0417474
        CONCENTRATION AT STAGE = 8      0.0081329      0.0487971
        CONCENTRATION AT STAGE = 9      0.0093669      0.0562014
        CONCENTRATION AT STAGE =10      0.0106630      0.0676247
        CONCENTRATION AT STAGE =11      0.0126627      0.0906208
        CONCENTRATION AT STAGE =12      0.0166881      0.1369137
        CONCENTRATION AT STAGE =13      0.0247917      0.2085421
        CONCENTRATION AT STAGE =14      0.0902505      0.4055009
        CONCENTRATION AT STAGE =15      0.3166012      0.5796404
        CONCENTRATION AT STAGE =16      0.5255685      0.6612273
        CONCENTRATION AT STAGE =17      0.6234728      0.7070836
        CONCENTRATION AT STAGE =18      0.6785003      0.7392499
        CONCENTRATION AT STAGE =19      0.7170999      0.7632599
        CONCENTRATION AT STAGE =20      0.7459118      0.7821382
        CONCENTRATION AT STAGE =21      0.7685659      0.7959961
        CONCENTRATION AT STAGE =22      0.7851954      0.8066367
        CONCENTRATION AT STAGE =23      0.7979641      0.8155748
        CONCENTRATION AT STAGE =24      0.8086897      0.8239516
        CONCENTRATION AT STAGE =25      0.8187419      0.8302450


        CONCENTRATION AT STAGE =26      0.8262941      0.8366646
        CONCENTRATION AT STAGE =27      0.8339975      0.8431978
        CONCENTRATION AT STAGE =28      0.8418374      0.8494693
        CONCENTRATION AT STAGE =29      0.8493638      0.8554909

        COLUMN DIAMETER,                   CM, IN =        7.82          3.08

        MINIMUN REFLUX FOR THE GIVEN PRESSURE   =        2.81

        HEIGHT OF THEORETICAL PLATE,       CM, IN =       43.08         16.96

        TOTAL HEIGHT OF VACUUM COLUMN,     CM, IN =     1249.27        491.84
        STRIPPING COLUMN HEIGHT,           CM, IN =      603.09        237.44
        RECTIFYING COLUMN HEIGHT.          CM, IN =      646.17        254.40

        AREA OF CONDENSER,         CM**2, FT**2 =   259112.22        278.91

        PRESSURE DROP PER FOOT OF PACKING, MMHG =        1.40
```

Table 8.3

Vacuum Distillation Modeling Results

```
CASE : 10.000 GAL/YR OVER 3 MONTHS


     VACUUM DISTILLATION SIMULATION
     ETHANOL WATER SYSTEM
     INPUTS
      NPR   :PRESSURE                                    =     4
             (1=760, 2=380, 3=190, 4=95, 5=50 MM HG)
      CF    :FEED CONCENTRATION, MOLE FRACTION =   0.33000
      CB    :BOTTOM PRODUCT,     MOLE FRACTION =   0.00100
      CD    :TOP PRODUCT,        MOLE FRACTION =   0.85000
      RD    :REFLUX RATIO                      =   5.00000
      PRATE:PRODUCTION RATE,             GAL/HR =   4.20000
      TF    :FEED TEMPERATURE,                C =  20.00000
      DP    :PACKING SIZE,                   IN =   0.50000
      COLDT:TOP PRODUCT TEMPERATURE,          C =  30.00000
      V     :VAPOR VELOCITY,             FT/SEC =  11.00000
      DT    :DELTA TEMPERATURE OF CONDENSER, C =   2.00000

     TOP PLATE BOILING POINT,                 C =          36.20
     BOILING POINT OF BOTTOM PRODUCT,         C =          50.00

     FEED FLOW RATE,          CM**3/HR, GAL/HR =      176011.81              46.50
     BOTTOM FLOW RATE,        CM**3/HR, GAL/HR =      155871.03              41.18

     MINI HEAT REQUIREMENT,     CAL/HR, BTU/HR =    22700334.70           90080.69
     HEAT UP TOP PRODUCT,       CAL/HR, BTU/HR =      131093.57             520.21
     HEAT UP BOTTOM PRODUCT,    CAL/HR, BTU/HR =     4604370.91           18271.31
     HEAT OF VAPORIZATION,      CAL/HR, BTU/HR =    17964870.22           71289.16

     LOCATION OF FEED PLATE = 8
     NUMBER OF IDEAL STAGES =17

                                        LIQUID       VAPOR MOLE %
     CONCENTRATION AT STAGE = 1       0.0010000     0.0090000
     CONCENTRATION AT STAGE = 2       0.0024004     0.0216036
     CONCENTRATION AT STAGE = 3       0.0046067     0.0414600
     CONCENTRATION AT STAGE = 4       0.0080825     0.0727428
     CONCENTRATION AT STAGE = 5       0.0135586     0.1106399
     CONCENTRATION AT STAGE = 6       0.0201925     0.1499624
     CONCENTRATION AT STAGE = 7       0.0269009     0.1825043
     CONCENTRATION AT STAGE = 8       0.0490052     0.2715182
     CONCENTRATION AT STAGE = 9       0.1558218     0.3084037
     CONCENTRATION AT STAGE =10       0.4400847     0.6350332
     CONCENTRATION AT STAGE =11       0.5920407     0.7040203
     CONCENTRATION AT STAGE =12       0.6748244     0.7474121
     CONCENTRATION AT STAGE =13       0.7268945     0.7798260
     CONCENTRATION AT STAGE =14       0.7657913     0.8050534
     CONCENTRATION AT STAGE =15       0.7960646     0.8256387
     CONCENTRATION AT STAGE =16       0.8207664     0.8425363
     CONCENTRATION AT STAGE =17       0.8410436     0.8557304

     COLUMN DIAMETER,                   CM, IN =        20.65            8.13

     MINIMUN REFLUX FOR THE GIVEN PRESSURE    =         3.88

     HEIGHT OF THEORETICAL PLATE,       CM, IN =        43.43           17.10

     TOTAL HEIGHT OF VACUUM COLUMN,     CM, IN =       738.37          290.70


     STRIPPING COLUMN HEIGHT,           CM, IN =       347.47          136.80
     RECTIFYING COLUMN HEIGHT,          CM, IN =       390.90          153.90

     AREA OF CONDENSER,         CM**2, FT**2 =     261586.59          281.57

     PRESSURE DROP PER FOOT OF PACKING, MMHG =          0.27
```

8.4.4 Conceptual Designs

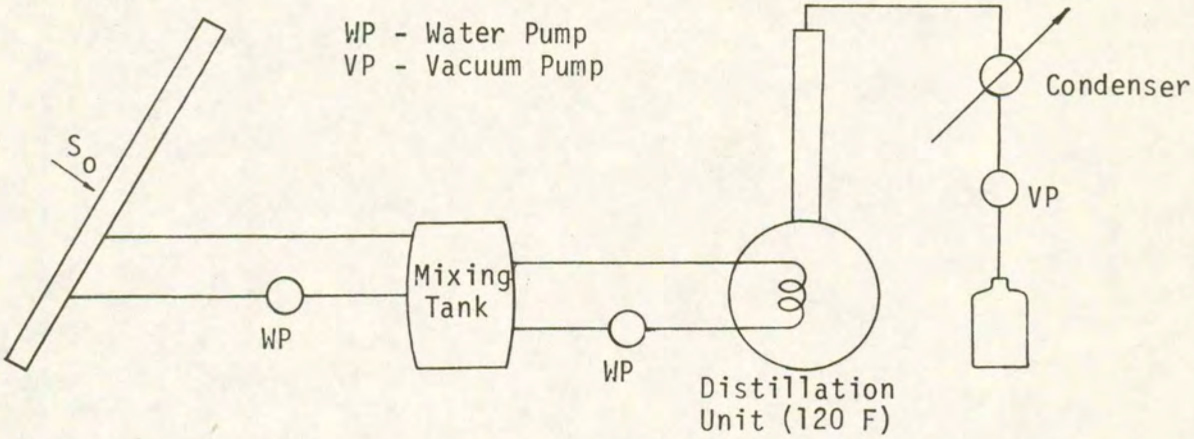
Some possible designs of distillation units are shown in Fig. 8.5. Designs 1-3 utilize flat plate solar collectors as the energy source, and all three operate at vacuum pressure. Vacuum operation matches energy demands of the distillation unit with the energy that can be efficiently supplied by the solar collector.

There are three important variables in designs 1-3, namely, operating temperature of the distillation unit (controlled by the level of vacuum), type of back up energy if any, and efficiency of the flat plate collector which is a function of the absorber paint and the number of covers for a fixed inlet temperature. The effect of these variables have been simulated, and results are presented in Tables 8.4-8.5.

Calculations for Tables 8.4-8.6 assume a fixed collector area and vary the thermal storage mass to "optimaize" collector efficiency. Increasing the storage mass prevents the fluid inlet temperature to the collector from reaching a value that would significantly degrade the collector performance. For phase change storage, flow rate and heat exchanger area in the reboiler increase as the reboiler operating temperature approaches the temperature of the phase change material (136 F). The flow rate and heat exchanger area vary between 13 gal/min and 134 ft^2 to 54 gal/min and 554 ft^2 for reboiler temperatures from 110 F to 130 F, respectively. Table 8.4 illustrates that utilizing solar energy just during the day reduces the collector area significantly. The major advantage of phase change storage is the reduction in storage mass it affords, as shown in Table 8.4. Collector efficiency is a function of the number of collector covers, especially during the winter. Results for the number of covers versus

Design 1

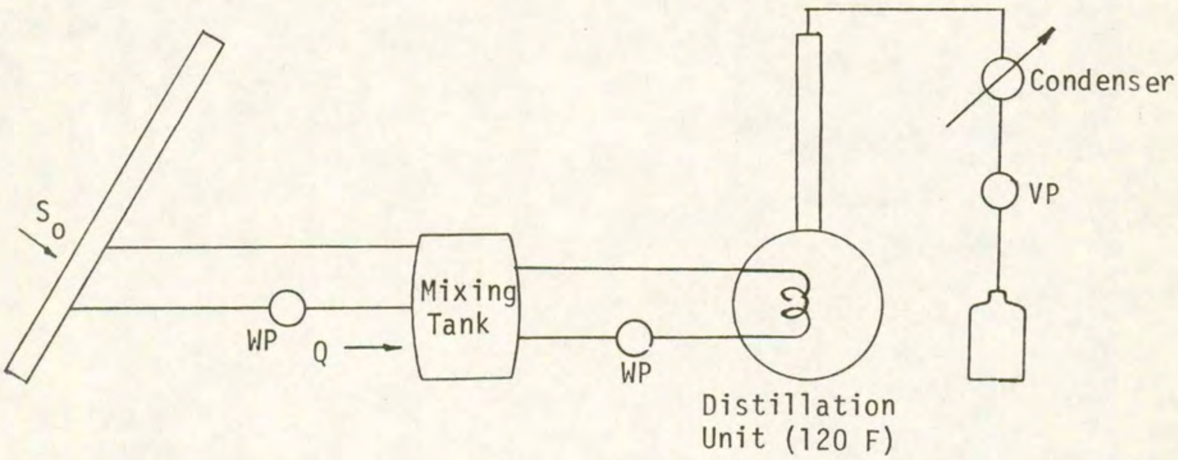
Flat Plate Collector, Vacuum Distillation, No Back Up Energy Source



mixing tank buffers temperature fluctuations due to clouds

Design 2

Flat Plate Collector, Vacuum Distillation, Continuous Operation, Combustion Back Up Energy Source

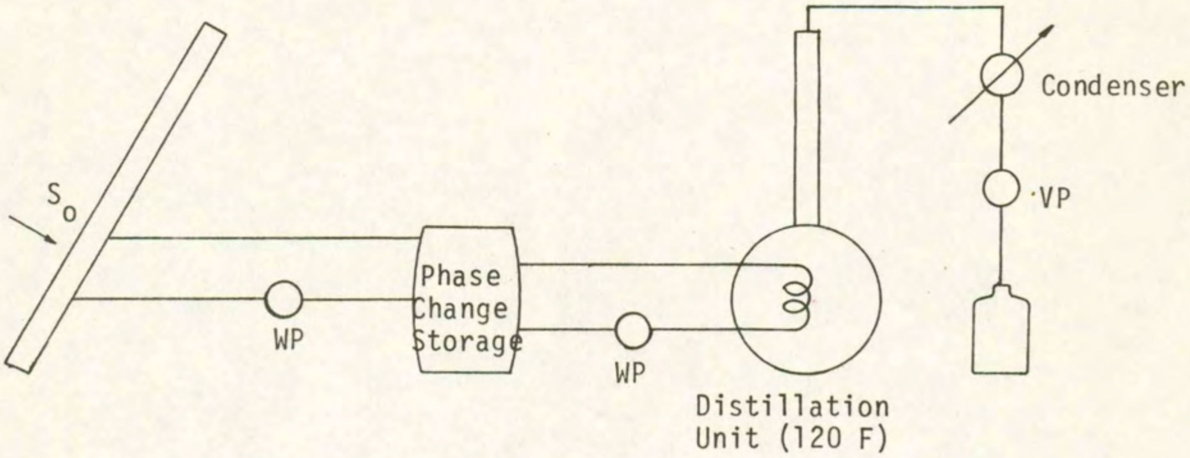


Q = burner of cobs, stover, methane, propane, wood chips, etc.

Figure 8.5 Conceptual Designs

Design 3

Flat Plate Collector, Vacuum Distillation, Continuous Operation, Phase Change Thermal Energy Storage



Design 4

Tracking Concentrating Collector or CPC, No Back Up Energy Source

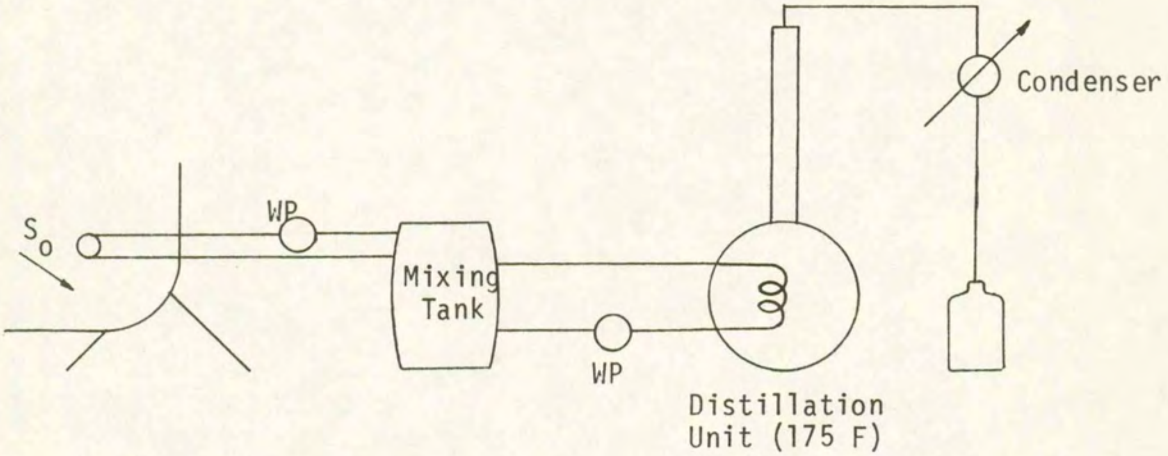
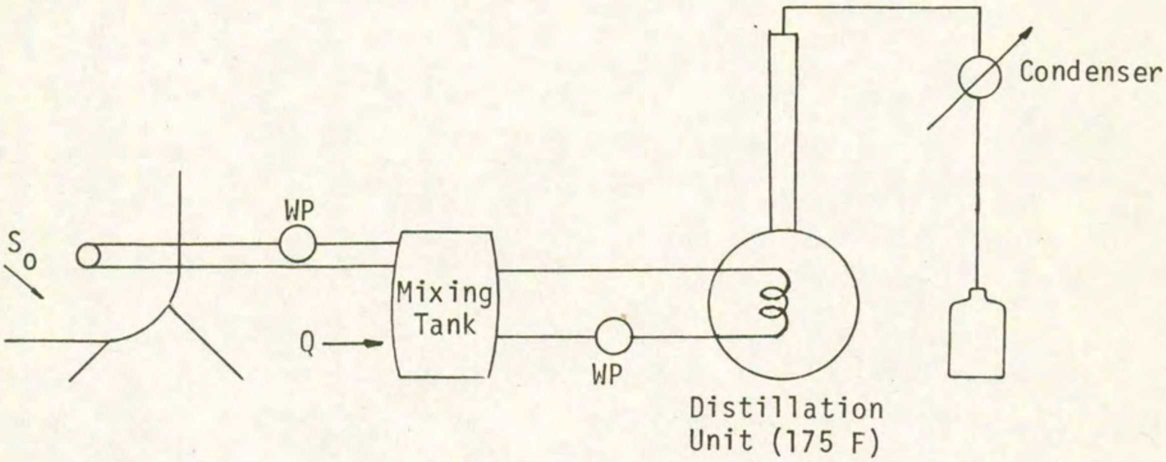
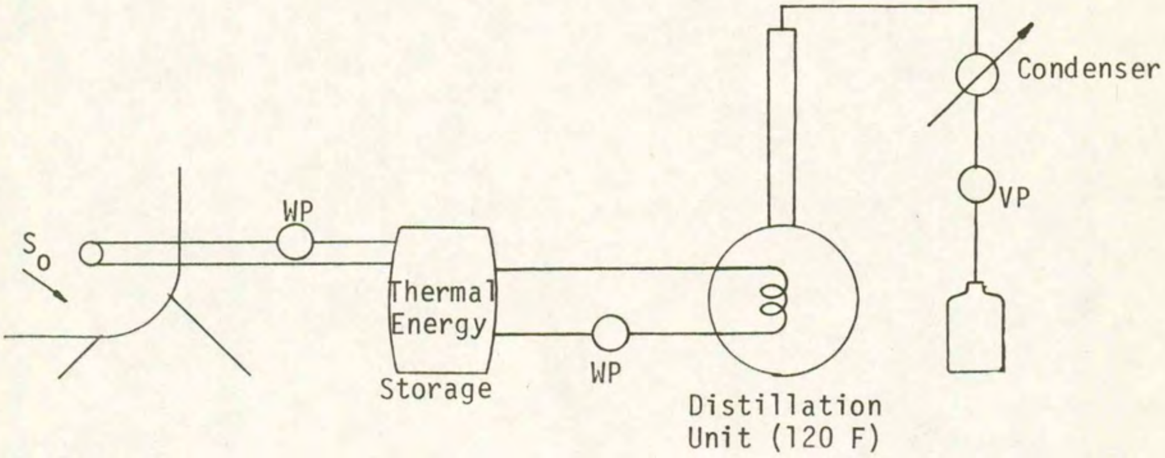


Figure 8.5 Conceptual Designs (cont'd)

Design 5

Tracking Concentrating Collector or CPC, Continuous Operation, Combustion Back Up Energy Source





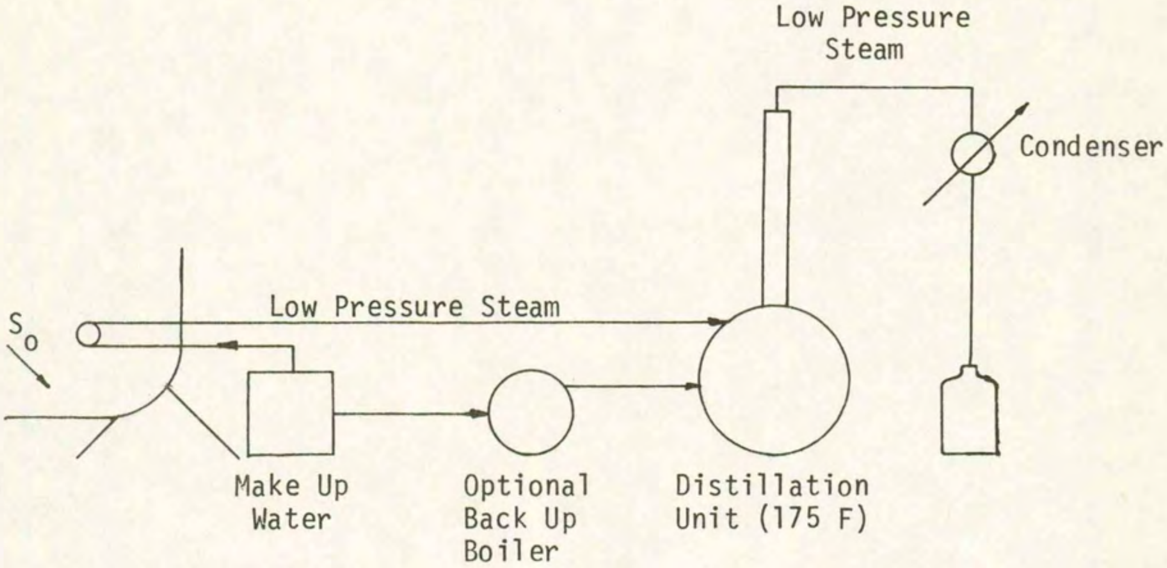
Design 6

Tracking Concentrating Collector or CPC, Vacuum Distillation, Continuous Operation, Thermal Energy Storage Back Up

Figure 8.5 Conceptual Designs (cont'd)

Design 7

Tracking Concentrating Collector or CPC, Low Pressure Steam Generation, Possible Back Up Energy System



Design 8

Flat Plate Collector, Heat Pump Temperature Augmentation, No Back Up Energy Source

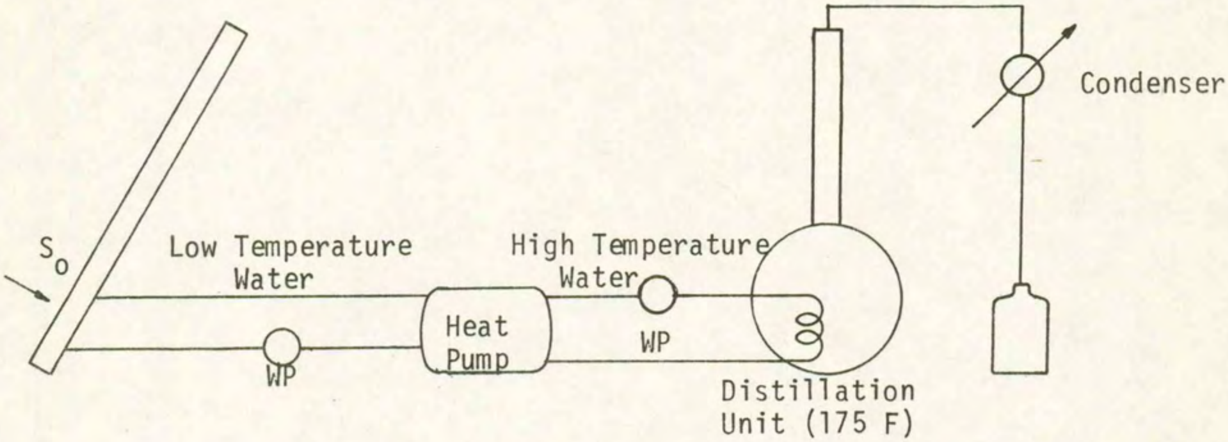
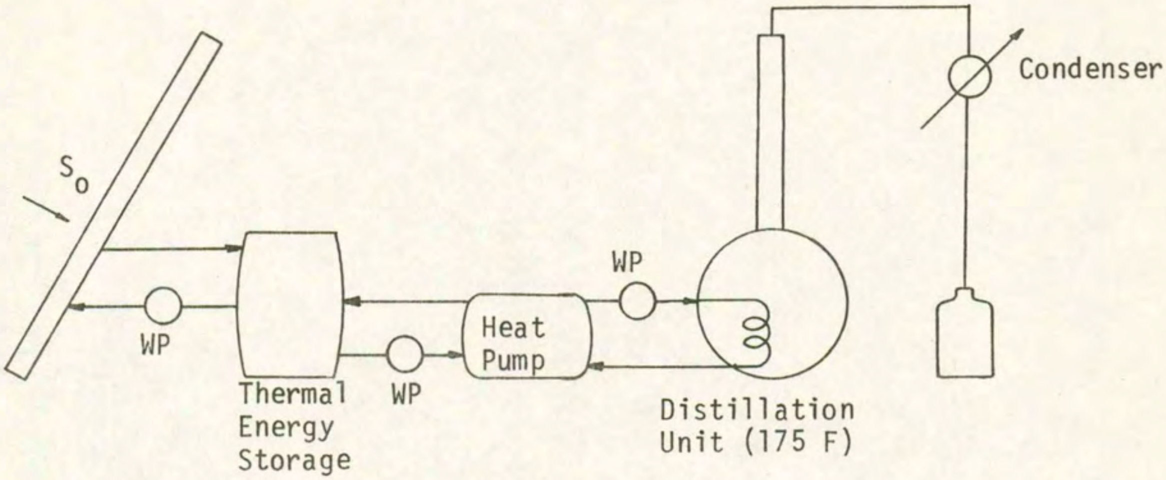
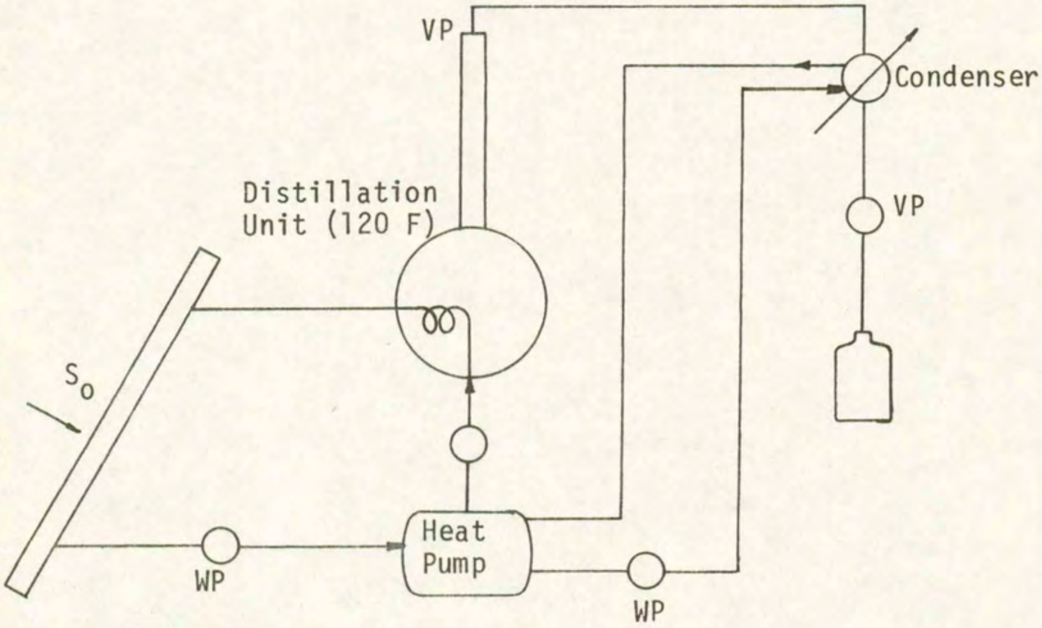


Figure 8.5 Conceptual Designs (cont'd)

Design 9

Flat Plate Collector, Heat Pump Temperature Augmentation, Thermal Energy Storage, Continuous Operation

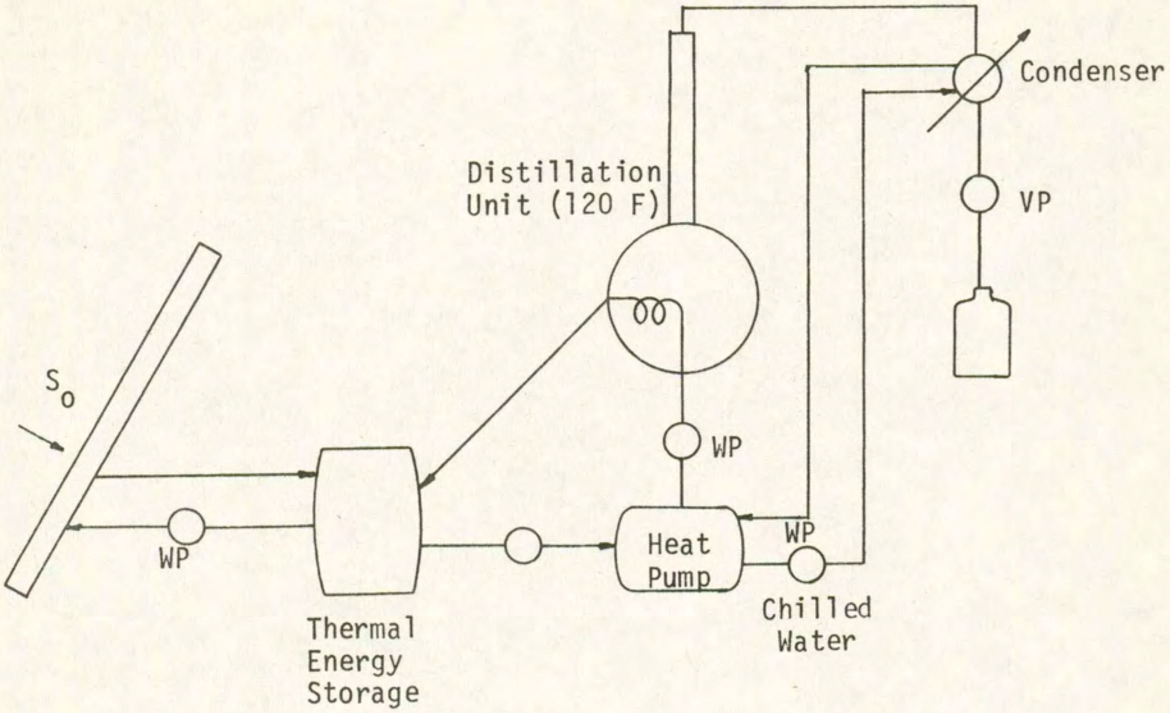




Design 10

Flat Plate Collector, Vacuum Distillation, Heat Pump Temperature Augmentation, Continuous Operation, Thermal Energy Storage

Figure 8.5 Conceptual Designs (cont'd)



Design 11

Flat Plate Collector, Vacuum Distillation, Heat Pump Temperature Augmentation, Continuous Operation, Thermal Energy Storage

Figure 8.5 Conceptual Designs (cont'd)

Table 8.4

Computer Simulation of 10,000 gal/yr
Continuous Production Over 3 Months.

	January			June			October		
Reboiler Temp.	Collector Area	Collector Efficiency	Storage Mass	Collector Area	Collector Efficiency	Storage Mass	Collector Area	Collector Efficiency	Storage Mass
10,000 gal/yr, Continuous Production Over 3 Months, 2 Covers, Water Storage									
110°F	3630 ft^2	31.3	25,400 lb	1310 ft^2	48.0	17,000 lb	1840 ft^2	48.1	23,900 lb
115	↓	31.6	30,000	↓	48.0	20,000	↓	48.1	28,300
120	↓	31.8	36,700	↓	47.9	24,500	↓	47.9	34,500
125	↓	32.0	47,200	↓	47.5	31,500	↓	47.6	44,500
130	↓	32.2	66,100	↓	47.1	44,200	↓	47.2	62,300
10,000 gal/yr, Continuous Production Over 3 Months, 2 Covers, Phase Change Storage at 136°F									
110°F	3140 ft^2	37.5	16,500 lb	1150 ft^2	54.5	10,100 lb	1730 ft^2	51.1	14,600 lb
115	↓	↓	↓	↓	↓	↓	↓	↓	↓
120	↓	↓	↓	↓	↓	↓	↓	↓	↓
125	↓	↓	↓	↓	↓	↓	↓	↓	↓
130	↓	↓	↓	↓	↓	↓	↓	↓	↓
10,000 gal/yr, Daytime Operation on Solar, Back Up Energy Otherwise, Water Storage									
110°F	630 ft^2	45.0	14,000 lb	410 ft^2	58.0	8,600 lb	450 ft^2	56.0	12,300 lb
115	635	44.0	15,800	415	57.0	9,300	455	55.0	13,300
120	700	43.0	17,600	460	56.0	10,800	500	54.0	15,500
125	735	41.0	19,300	470	55.0	11,900	515	53.0	17,000
130	780	40.0	22,000	500	54.0	13,500	545	52.0	19,500

Table 8.5

Computer Simulation of

10,000 gal/yr Continuous Production Over 3 Months,

Phase Change Storage, Reboiler Temperature of 120 F

Month	Cover 1		Cover 2		Cover 3	
	Collector* Efficiency	Collector Area	Collector Efficiency	Collector Area	Collector Efficiency	Collector Area
Jan	7.9	14,500 ft^2	37.5	3,100 ft^2	50.2	2,300 ft^2
June	36.8	1,700 ft^2	54.5	1,100 ft^2	61.8	1,000 ft^2
Oct	29.9	2,900 ft^2	51.1	1.700 ft^2	59.4	1,500 ft^2

*Expressed as a percentage.

efficiency are shown in Table 8.5. Table 8.6 shows the effect of selective absorber coating on collector performance. Nonselective absorber paint has a solar absorptance of 0.95 and an infrared emittance of 0.95. Selective absorber paint exhibits an absorptance of 0.95 and a typical emittance of 0.1, which reduces reradiated energy. The reduction in reradiated energy has the most effect during winter operation when there is a large temperature difference between the absorber and ambient air.

Conceptual designs 4-7 utilize either a non tracking CPC or a tracking concentrating collector. These designs are for illustrative purposes. Considerable engineering must be performed to establish both the technical feasibility and the system parameters necessary for an economic analysis. The design variations based upon the concept of utilizing a CPC or tracking parabolic collector are enumerated in Fig. 8.5. Low pressure steam is generated in design 7, and this steam is injected directly into the distillation unit.

Conceptual designs 8-11 utilize a heat pump to boost the working fluid temperature. The advantage of the heat pump is that 1) the collector can operate at a lower temperature for a higher thermal efficiency, 2) low cost thermal energy storage (grubbers salt or water) can be utilized, 3) chilled water is produced in the heat pump cycle and this water can be used in the condenser unit making possible high vacuum operation, which requires chilled water condensing, and 4) overall collector area is reduced for the same output since the collector is operating more efficiently with the heat pump providing part of the process heat. The heat pump does consume electrical energy and the trade off of electrical energy consumption versus

Table 8.6

Computer Simulation

10,000 gal/yr, Continuous Production Over 3 Months, Phase Change Thermal

Energy Storage, 2 Covers, Reboiler Temperature of 120 F

	January		June		October	
Abosrber	Efficiency (%)	Collector Area (ft^2)	Efficiency (%)	Collector Area (ft^2)	Efficiency (%)	Collector Area (ft^2)
Regular						
ϵ = 0.95	37.5	3140	54.5	1148	51.1	1732
α = 0.95						
Selective						
ϵ = 0.95	52.1	2235	63.8	963	61.4	1448
α = 0.10						

the above four advantages must be evaluated. Use of a heat pump is intriguing but requires careful engineering to match distillation unit, solar collector, and heat pump characteristics. Also heat pumps are very expensive, even more so for the custom models likely required for this application. The high capital investment ($25,000+ for small scale) and electric utility charges, probably make the heat pump design feasible only for the commercial producer who desires anhydrous alcohol via high vacuum distillation.

8.4.5 Conclusions

Solar energy utilization can play a significant role in fuel alcohol production. Distillation preheating or nearly total distillation energy requirements can be met with the outlined conceptual designs. Solar assisted distillation requires a greater initial investment in equipment and controls, but decreases purchased energy over the plant life time. This economic trade-off determines the viability of solar assisted distillation. These economics associated with solar assisted fuel alcohol production are addressed in Chapter 9.

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9. ECONOMICS

9.1 Introduction

The purpose of this study is to compare the cost of energy for a fuel alcohol plant utilizing either a solar collector or a fossil fuel boiler or some combination thereof. The cost of these forms of energy differs in that solar energy represents an initial investment whereas a boiler incures fuel costs over the entire plant lifetime. There are two costs to be considered in the analysis. First, the initial investment cost of the energy delivery system consisting of either a solar collector or boiler must be determined. The boiler does realize economics of scale in that increasing boiler capacity decreases the boiler cost per unit of supplied energy. Solar collectors have a linear output and costs as size increases, except for possible discounts on large arrays. The second cost is fuel. For solar collectors, fuel is free with the exception of that required to run the pumps and controls. For boilers, fuel is a linear cost per Btu and this cost becomes more important as the size of the unit increases. Some reduction in fuel cost may be realized for the large consumer, although the future of such pricing structures is unknown.

To yield a representative comparison, the energy delivery systems were compared on an equivalent annual cost (EAC) basis [1,2]. EAC basis sums capital and energy costs over the plant lifetime and brings the worth of those dollars back to the present and averages this sum over the plant lifetime.

Factors for fossil fuel cost escalation and the opportunity cost of alternative investments (for example, bank deposits) are accounted for.

Opportunity costs of 10 and 15 percent were used in the analysis, which are typical of the current interest rates. Estimation of fuel price increases over time is a difficult task. Due to future fuel price uncertainty, several different scenarios were modeled. Based upon a report by the Colorado Energy Research Institute [3] and conversations with local fuel dealers, the estimated fuel cost escalation figures above the inflation rate are 2-10 percent over the next four years and 2-3 percent thereafter. For this study the extreme case of no fuel price increase and the more probable case of 10 percent price increase per year above the inflation rate for the first 4 years and 2 percent increase thereafter were studied. Plant lifetime is estimated at 20 years.

The methodology of determining EAC is standard in economical analyses. Figure 9.1 illustrates the basis of the method. The cost of fuel is shown on a yearly basis with the cost increasing over time. EAC is calculated using the relationships and definitions cited in Table 9.1 and Fig. 9.2, and yields a continuously compounded opportunity (interest) rate [2].

This analysis gives a gross economic picture since numerous site specific variables such as taxes, salvage value, major equipment overhauls, and insurance are not included. However, the analysis is a first step in determining production feasibility. A person interested in a specific application can follow the calculations using their own figures. If favorable economics are found at this stage then further refinement of cost can define the true economics of the plant. Finally, the costs developed from this analysis illustrate (1) the overall viability of solar assisted ethanol production, (2) where major costs are incurred, and (3) areas where further research might bring down fuel production costs.

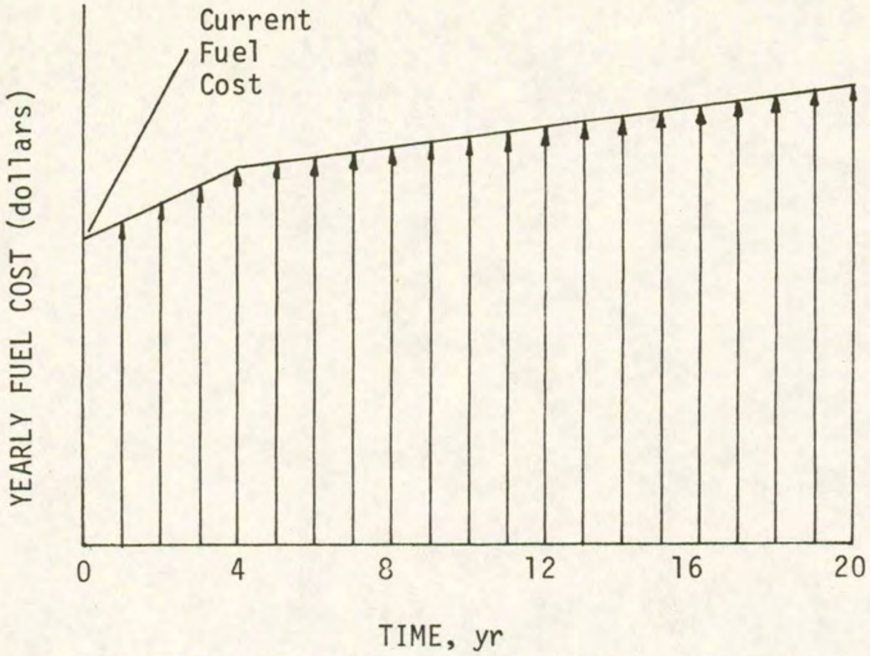

Figure 9.1 Fuel Costs Over Time

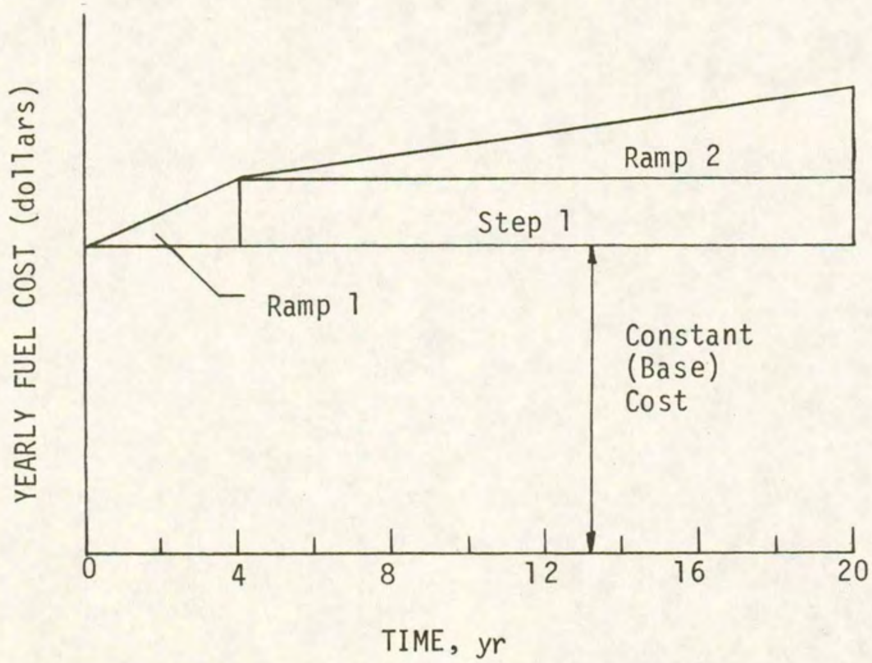

Figure 9.2 Equivalent Annual Cost Functions

Table 9.1

Computation of Equivalent Annual Cost

EAC = (Present Worth of Step 1 + Ramp 1 + Ramp 2 + Initial Investments)

$$\times \left(\frac{j}{1 - e^{-jN}}\right) + C$$

where:

$j = \ln (1 + i)$; i = current interest rate

N = plant lifetime = 20 years

C = current fuel cost/yr

Present Worth Step 1

$$= \frac{(G_1 t_1)(1 - e^{-jt_2})}{j}$$

Present Worth Ramp 1

$$= \frac{G_1}{j^2} (1 - e^{-jt_1}) - \frac{t_1 G_1 e^{-jt_1}}{j}$$

Present Worth Ramp 2

$$= \frac{G_2}{j^2} (1 - e^{-jt_2}) - \frac{t_2 G_2}{j} e^{-jt_2}$$

where:

G_1 = Slope of Ramp 1 in dollars/yr

G_2 = Slope of Ramp 2 in dollars/yr

t_1 = length of first time interval

t_2 = length of second time interval

$N = t_1 + t_2$

9.2 Preheating Economics

This section addresses small and large scale fuel alcohol plants which would utilize solar energy to preheat the make-up water for fermentation. The fermentation tank would be filled with make-up water which would by cycled through the solar collector until a temperature of 130 F is obtained. The initial temperature of the make-up water is 50 F, which represents the lowest probable temperature. Based upon these parameters and known solar collector performance [4,5], the collector array size could be established. Throughout the economic analysis, a boiler size of 20 HP with a cost of $7,800 was imposed as a minimum. Boiler costs were determined by conversations with several national distributors and all boilers operate at a pressure of 14 psia, thus circumventing the need for a certified boiler operator.

The EAC method of comparing costs was performed for several scenarios, and results are presented in Table 9.2 for small and large scale plants. Small scale is designed to produce 10,000 gal/yr over a 100 day period and this represents the on farm producer, who, because of other responsibilities, is unable to operate the plant continuously. Larger scale plants produce 3,000,000 gal/yr and operate continuously. Small scale scenarios for natural gas and propane used either as the sole energy source or as back up source were examined along with cases of no fuel price escalators and price escalators as previously discussed. Opportunity costs of 10 and 15 percent were examined for the above cases. Propane represents a likely fuel candidate for the rural producer who has no access to a natural gas pipeline. Propane was assumed to have twice the cost of natural gas on

Table 9.2

Preheating Equivalent Annual Costs

	No Solar Assistance				Solar Assisted				
	Natural Gas		Propane		Gas Back Up		Propane Back Up		Total
Case	No Price Increase	Price** Increase	No Price Increase	Price** Increase	No Price Increase	Price** Increase	No Price Increase	Price** Increase	Solar
Small Scale									
10% O.C.*	$ 1,165	$ 1,310	$ 1,455	$ 1,750	$ 1,770	$ 1,800	$ 1,830	$ 1,890	$ 1,120
15% O.C.	1,450	1,600	1,740	2,045	2,335	2,365	2,395	2,455	1,490
Large Scale									
10% O.C.	86,800	130,800	--	--	120,200	129,000	--	--	123,600
15% O.C.	87,200	131,800	--	--	154,200	163,100	--	--	164,400

*O.C. = Opportunity Cost

**Price increases above inflation at 10% first 4 years, 2% thereafter a Btu basis and the same price escalators as natural gas. The above scenarios were also performed for a large scale producer except that natural gas was the only fossil fuel considered. Since the large scale plant has some freedom in its location, it was assumed that a site near a natural gas pipeline would be selected. Finally, the case where a 20 percent larger collector array and water thermal storage of one day supply of make up water is examined as a total solar powered system. For this system, excess collected energy is stored for usage on cloudy days.

Results presented in Table 9.2 illustrate the economic viability of this application of solar energy. For 15 percent opportunity costs, the case of no natural gas price increase represents the least expensive energy source at an EAC of $1,450 for the small scale producer. However, there is only a minor difference in EAC between this case and a total solar energy system with an EAC of $1,490. Propane fueled systems, even with no price increase, are more expensive than the total solar energy system with an EAC of $1,740 at 15 percent opportunity cost. Large scale results are less favorable for solar energy. This finding is likely due to a smaller ratio of invested capital in the boiler per Btu output. Consequently, as larger energy sources are needed proportionately less initial capital is needed for the boiler, and less opportunity costs are foregone with available capital. However, for the collector, the cost for additional energy (hence a larger collector) is nearly a linear function, and with larger units more capital is required up front and more opportunity costs are foregone. The large scale EAC for solar systems of $123,600 is 30 percent higher than the natural gas EAC of $86,800 for a 10 percent opportunity cost and no fuel price increase.

With fuel price increase, solar EAC is 10 percent less than fossil fuel systems at 10 percent opportunity costs. The case of solar collectors supplemented with a boiler and fuel price increases represents a slightly lower EAC than a total solar powered system for the large scale producer at a 15 percent opportunity cost. This result is due to a 10 percent higher initial investment in the latter case. The opportunity costs foregone with large initial solar collector investment, as illustrated with the last result, are a significant factor throughout the analysis.

9.3 Distillers Grain Drying

This section reviews the assumptions and results of the economics of drying distillers grain. Distillers grain drying energy values were obtained on a per gallon of ethanol product basis from Chapters 4 and 8. Based upon small and large scale daily fuel alcohol production of 100 and 8160 gal, respectively, and the above mentioned energy values, boiler and water collector array sizes were established. The capacity to dry the daily distillers grain production over a 6 hour period was imposed upon the system, and the solar back up energy source was assumed to operate 20 percent of the year with a 50 percent capacity of full load.

As shown in Table 9.3, the EAC for solar energy applied to this process was significantly higher across the spectrum of fossil fuels, opportunity costs, and system sizes. Total solar system costs are not attractive and, therefore, have not been itemized. At 10% opportunity cost on the small scale, solar collectors with natural gas back up have an EAC of $2,990, three times higher than the EAC for a natural gas system with price increases. The costs for large scale production show

Table 9.3

Distillers Grain Drying Equivalent Annual Costs

	No Solar Assistance				Solar Assisted			
	Natural Gas		Propane		Gas Back Up		Propane Back Up	
Case	No Price Increase	Price** Increase	No Price Increase	Price** Increase	No Price Increase	Price** Increase	No Price Increase	Price** Increase
Small Scale								
10% O.C.*	$ 955	$ 1,000	$ 1,040	$ 1,125	$ 2,955	$ 2,990	$ 3,020	$ 3,090
15% O.C.	1,245	1,295	1,330	1,440	3,910	3,940	3,975	4,045
Large Scale								
10% O.C.	26,400	39,000	--	--	167,800	169,100	--	--
15% O.C.	26,900	39,800	--	--	222,300	223,600	--	--

*O.C. = Opportunity Cost

**Price increase above inflation at 10% first 4 years, 2% thereafter an even greater difference. These results are attributed to 1) higher operating temperatures which yielded lower collector performance, 2) larger initial investment in solar collectors per Btu of useful energy, and 3) some economics of scale with the larger boiler operation.

9.4 Solar Assisted Distillation

The economic results presented in this section are perhaps the most interesting of the economic analyses. The assumptions and constraints for results of solar assisted distillation are discussed along with the associated EAC values.

A distillation energy requirement of 21,000 Btu/gal and a reboiler temperature of 120 F were used throughout the analysis. Based upon these values, boiler and collector array sizes were established. Results of EAC calculations are presented in Table 9.4. In the small scale analysis the option of producing the daily quota of fuel during the day with solar energy was examined and proved more economically attractive than the systems which produce one-third of the daily quota with solar energy and the remainder with fossil fuels. Small scale EAC values at 10 percent opportunity cost were $3,600 for total solar and $4,500 for solar with natural gas back-up that increases in price. However, without year round utilization, collectors erected for small scale application have difficulty in proving economic justification compared to a natural gas system. The EAC of propane with price increases is $3,640 which is comparable to the total solar option. With year around use on large scale production, the solar option with natural gas back up is viable with a 10 percent opportunity cost and fossil fuel price escalation with an EAC value of

Table 9.4

Distillation Equivalent Annual Costs

	No Solar Assistance				Solar Assisted				
	Natural Gas		Propane		Gas Back Up		Propane Back Up		Total
Case	No Price Increase	Price** Increase	No Price Increase	Price** Increase	No Price Increase	Price** Increase	No Price Increase	Price** Increase	Solar
Small Scale									
10% O.C.*	$ 1,800	$ 2,265	$ 2,710	$ 3,640	$ 4,100	$ 4,500	$ 4,865	$ 5,660	$ 3,600
15% O.C.	2,100	2,610	3,005	4,020	5,300	5,700	5,990	6,805	4,800
Large Scale									
10% O.C.	281,900	426,100	--	--	300,100	415,600	--	--	--
15% O.C.	282,300	428,400	--	--	329,500	446,500	--	--	--

*O.C. = Opportunity Cost

**Price increases above inflation at 10% first 4 years, 2% thereafter

$415,600 as compared to $426,100 for natural gas. A 15 percent opportunity cost causes the large initial investment of the solar assisted system to be uneconomical by about $18,000 per year. With large scale product it is informative to note the substantial rise in EAC from no fossil fuel price increase to a price increase.

9.5 Conclusions

The results of the economic analysis demonstrate an economically favorable application of solar energy in preheating and distillation processes. Distillers grain drying was decidedly unfavorable, but refinement in the engineering assumptions may prove the process to be economically attractive. The major factors influencing economic viability are the opportunity costs of invested capital and the operating fuel employed. Estimations of values to be assigned to these factors are somewhat objective and must be reviewed as deregulation of conventional fuels occurs.

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10. CONCLUSIONS AND RECOMMENDATIONS

The investigation of solar assisted fuel alcohol production in the State of Iowa examined concerns related to 1) literature review, 2) solar energy availability and corn production, 3) fermentation of fuel alcohol, 4) distillation of fuel alcohol, 5) simulation of solar energy applications in fermentation and distillation, 6) fuel alcohol energy balance, 7) conceptual designs of solar assisted fuel alcohol production, and 8) economics of solar assisted fuel alcohol production. Conclusions drawn for this study are outlined below.

There is a lack of accurate information about the technical and economical aspects of solar distillation in particular, and fuel alcohol production in general. Iowa does have a nearly constant supply of solar energy and sizeable corn crop which solar energy can assist in the transformation to fuel alcohol. Fermentation proved to be a more difficult task to accomplish than had been originally expected, and solar energy can and should make an energy contribution to this process. Solar preheating of fermentation make up water has a sound economic backing. Distillation experimentation and modeling proved this area is worthy of further research for results show both the technical and economical promise of integrating solar energy and distillation. The energy balance of fuel alcohol production is positive without solar assistance, and solar assistance can make significant contributions to the energy balance. These facts should be made known to interested parties. The developed conceptual designs of solar energy utilization in fuel alcohol production form a reserve from which a design may be chosen, studied, engineered, and possibly built. Economics have shown the viability of solar assisted fuel alcohol production in certain applications. Refinement of the economic assumptions, especially fuel prices, is recommended.

Based upon the above conclusions combined with personal observations, it is recommended that a yearly seminar be held for fuel alcohol producers and those contemplating production in Iowa. The fuel alcohol wheel is being invented many times over in Iowa. These meetings would provide a forum for technology transfer. It is recommended that a board of directors be established to organize these meetings. The board should have members from the state government, state Universities, Vocational-Technical Schools, Corn Promotion Board, Development Commission, Energy Policy Council, and most importantly small and large scale producers.