Chapter 8

FERMENTATION

Chapter 8.– FERMENTATION

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Chapter 8
FERMENTATION

Introduction

Ethanol, or "grain alcohol," is a versatile and commercially important liquid which has been used for a variety of purposes for centuries. Ethanol is the intoxicant in alcoholic beverages and, prior to the industrial age, society's most common contact with ethanol was as an ingredient of beer, **wine, or liquor.**

Beverage alcohol is a major item of commerce and a source of substantial tax revenues. In addition, ethanol is also a key industrial chemical and is used as a solvent or reactant in the manufacture of organic chemicals, plastics, and fibers. Ethanol has a long history as a combustible fuel for transportation vehicles and space heating. Except under unusual circumstances (e. g., wartime Europe), ethanol has been little used for these purposes in the 20th century, having been largely displaced by petroleum-based motor and boiler fuels.

Beverage alcohol is usually produced by fermentation processes, but the processes are designed to achieve various qualities of taste and aroma which are irrelevant to fuel alcohol production. Most industrial ethanol is produced from ethylene, a gas derived from petroleum or natural gas liquids. Rising oil prices have made biomass-derived ethanol competitive with ethanol derived from petroleum but it is unclear whether the chemical industry will turn to biomass or coal for its supply of ethanol.

All processes for the production of ethanol through fermentation consist of four basic steps: 1) first the feedstock is treated to produce a sugar solution; 2) the sugar is then converted to ethanol and carbon dioxide (CO_2) by yeast or bacteria in a process called fermentation; 3) the ethanol is removed from the fermented solution by a distillation* process which yields a solution of ethanol and water that cannot exceed 95.6 percent ethanol (at normal pressures) due to the physical properties of the ethanol-water mixture; and 4) in the final step, the water is removed to produce dry ethanol. This is accomplished by distilling once again in the presence of another chemical.

The main distinctions among the processes using different feedstocks are the differences in the pretreatment steps. Sugar crops such as sugarcane, sweet sorghum, and sugar beets yield sugar directly, but the sugar often must be concentrated to a syrup or otherwise treated for storage or the sugar will be destroyed "by bacteria. Starch feedstocks such as corn and other grains require a rather mild treatment with enzymes (biological catalysts) or acid to reduce the starch to sugar. And. cellulosic (cellulose containing) feedstocks such as crop residues, grasses, wood, and municipal wastepaper require more extensive treatment to reduce the more inert cellulose to sugar.

Processes utilizing each of the ethanol feedstock types are considered below. I n addition, the environmental effects of ethanol distilleries are discussed as are various process changes that could lower costs. Although ethanol is emphasized in this chapter, it should be remembered that other alcohols (e. g., butanol) and chemicals could be produced from the sugar solutions, but technical and economic uncertainties are too great to include a detailed consideration of these alternatives at present.

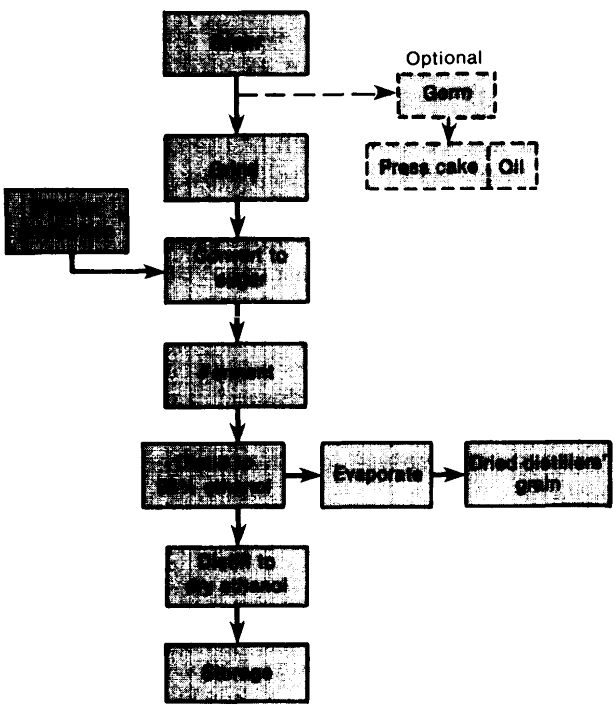
***Distillation consists of heating the ethanol-water solution and passing the vapor through a column in which the vapor condensed and revaporized numerous times, a process that successively concentrates the ethanol and removes the water**

Ethanol From Starch and Sugar Feedstocks

Ethanol can be produced from starch and sugar feedstocks with commercially available technology. Starch feedstocks are primarily grain crops such as corn, wheat, grain sorghum, oats, etc., but also include various root plants such as potatoes. The sugar feedstocks are plants such as sugarcane, sweet sorghum, sugar beets, and Jerusalem artichokes. Since these feedstocks are all crops grown on agricultural lands under intensive cultivation and can be converted with commercial technology, they are considered together.

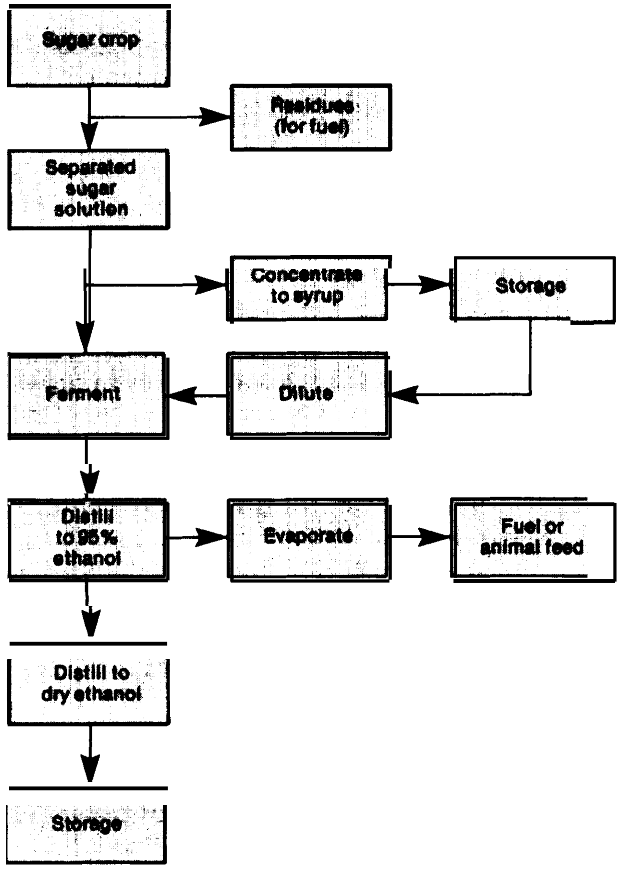
The processes for producing ethanol from starch and sugar feedstocks are shown schematically in figures 26 and 27. The energy consumption of these processes is discussed next, followed by a description of process byproducts, cost calculations, and onfarm processes.

Figure 26.—Process Diagram for the Production of Fuel Ethanol From Grain



SOURCE Office of Technology Assessment

Figure 27.—Process Diagram for the Production of Fuel Ethanol From Sugarcane or Sweet Sorghum



SOURCE: Office of Technology Assessment

Energy Consumption

Most ethanol distilleries in the United States today were designed for beverage alcohol production, with little emphasis on energy usage. A fuel ethanol distillery can take advantage of newer technology and the low purity requirements of fuel ethanol to reduce its energy consumption. Nevertheless, both the type of fuel used and the amount of energy consumed at the distillery will continue to be important determinants of the efficacy of fuel ethanol production in displacing imported fuels.

In the plant currently producing most of the fuel ethanol today, the germ (protein) in the corn feedstock is removed in a separate feed processing plant. Consequently, the distillery receives a more or less pure starch from the grain processing plant and the waste still age (material left in the fermentation broth after the ethanol has been removed) is fed into a municipal sewage system, so that the energy needed to pretreat the corn and to process the waste stream is not included in the distillery energy usage. Nevertheless, the distillery consumes **30,000** Btu/gal of ethanol and 96.5 percent of this is in the form of natural gas.[1] If all processing energy inputs are included, fuel consumption is about 65,000 to 75,000 Btu/gal of ethanol (exclusive of the energy needed for waste stream treatment).[2] Furthermore, the economics of this process are predicated on income from process byproducts, such as corn oil, for which the markets are uncertain if large volumes are produced.

OTA's analysis indicates that the fuel used at the distillery cannot soon be reduced to an insignificant fraction of the energy contained in the ethanol. Thus, if the displacement of imported fuels (oil and natural gas) is to be maximized, fuel ethanol distilleries should be required to use abundant or renewable domestic fuels such as coal or solar energy (including biomass).

A distillery that might be more common in a large-scale ethanol program has been designed by Raphael Katzen Associates. ' This distillery would produce a dry animal feed byproduct, known as distillers' grain (DC) (see next section on byproducts). Although the distillery uses some equipment to dry the DC which is not in common use in ethanol distilleries, all of the equipment is commercially available. The design reduces the number of distillation columns to the minimum using conventional technology (two columns: one to produce **95** percent ethanol and one to produce dry ethanol) and uses "vapor recompression" evaporation for drying the DG. The distillery is coal-fired and consumes 42,000 Btu of coal and 13,000 Btu of purchased electricity* to produce 1 gal of ethanol which has a lower heating value of 76,000 Btu. ** The energy breakdown for the Katzen design is shown in table 52.

Table 52.–Energy Consumption in a Distillery Producing Fuel Ethanol From Corn

Process step	Thousand Btu of coal/gal of ethanol[a]
Receiving, storage, and milling, ...	0.8
Conversion to sugar (including enzyme production).	16.0
Fermentation	0.6
Distillation . . . . . . , ...	24.8
Distillers' grain recovery	6.2
Miscellaneous	6.6
Total	55.0

[a] Assumes 10,000 Btu of coal per kilowatthour of electricity

SOURCE Raphael Katzen Associates, *Grain Motor Fuel Alcohol, Technical and Economic Assessment Study* (Washington, D C Assistant Secretary for Policy Evaluation, Department of Energy, June 1979), GPO stock No 061-000 .00308-8

At first thought, one might expect the energy demand of a distillery using sugar plant feedstocks to be less than that for starch feedstocks, since the energy needed to reduce the starch to sugar is no longer required. The situation is, in fact, quite the opposite. The processes for extracting the sugar from the feedstock and concentrating it to a syrup (highly concentrated sugar solution) are quite energy intensive. The average energy usage for a sugar feedstock (based on sugarcane) would be about 85,000 Btu of coal per gal lon of ethanol produced on the average, ' or slightly more than the energy content in the ethanol. If the bagasse, i.e., plant matter left over after the sugar is extracted, is used to fuel the boiler, then 110,000 Btu of bagasse would be needed to produce 1 gal of ethanol. (This assumes a 70-percent boiler efficiency for bagasse, as opposed to 90 percent for coal.)

For both the grain and sugar feedstocks, crop residues could be used to fuel the distilleries. In both cases there is sufficient resi-

'R Strasma, "Domestic Crude Oil Entitlements, Application for Petroleum Substitutes, E RA-03° submitted to the Department of Energy by Archer Daniels Midland, Co , Decatur, Ill , May 17, 1979 update

[2] Ibid

'Raphael Katzen Associates, *Grain Motor Fuel Alcohol, Technical and Economic Assessment Study* (Washington, D C Assistant Secretary for Policy Evaluation, Department of Energy, June 1979), CPO stock No 061-000-00308-9

*1O,OOO Btu/kilowatthour

* *Lower heating value is measured when water vapor is the product of combustion The higher heat value, when liquid water is the product, is 84,000 Btu/gal

'Ibid

due produced together with the starch or sugar to fuel an energy-efficient distillery, although the quantity may be only marginally adequate for sugar feedstocks.[5] If one requires that sufficient residues be left on the land to provide adequate soil erosion protection, then the available residues are not adequate in most cases. [6]* Crop residues gathered from adjacent croplands where the crops are not used for ethanol production could easily supplement the shortfall, however.

Since the sugar feedstocks are generally delivered to the distillery with much of the residue, which subsequently arises as a waste byproduct of the sugar extraction step, it is more likely that residues will be used to fuel these distilleries, although it is technically feasible in both cases.

If crop residues are used to fuel distilleries, then the fossil fuel usage at the distillery will be negligible. The fossil energy used to collect and transport residues and replace their nutrient value to the soil would have to be included. OTA estimates this energy to be about 10,000 Btu/gal of ethanol for grain feedstocks and about 3,000 Btu/gal for sugar feedstocks. (These estimates assume that no grain residues are normally harvested with the grain and that the entire sugar plant is harvested and transported to the distillery. Therefore, the grain-fed distillery needs 10.3 lb of residue per gallon of ethanol and the sugar-fed distillery needs a supplement of 3 lb of residue per gallon of ethanol.)

‘R A Nathan, “Fuels From Sugar Crops, ” published by Technical Information Center, Department of Energy, TID-22781, July 1978.

‘Ibid

● As an example, the national average available crop residues for corn are about 7,3 lb/gal of ethanol (see ch 3) With a 70-percent boiler efficiency, this would provide 70 percent of the energy needed at the distillery (assuming 6,500 Btu/lb)

For sugarcane and sweet sorghum (syrup variety), the total crop residues are about 11 lb of combustible matter per gallon of ethanol The residues required to protect against soil erosion vary greatly If all of the residue is used, one gets about 80 to 85 percent of the distillery energy requirement (assuming 30-percent leaves with 6,500 Btu/lb and 70-percent cane with 9,000 Btu/lb and 70-percent boiler efficiency) And in areas where residues are needed to protect the soil from erosion, the available residues might be only the cane, which would be about 60 percent of the distillery energy requirement

Process Byproducts

All of the material in the feedstock, except for the sugar or starch (most of which is converted to alcohol), become byproducts of distillation. in addition, the excess yeast or bacteria grown in the fermentation step can also serve as a byproduct. The grain feedstocks are high in protein and, consequently, the byproduct credits will be larger than with sugar feedstocks.

The grain protein can be removed as “gluten” before distillation and oil, such as corn oil, can be extracted. As mentioned above, however, the oil market is uncertain and the required selling price for such oil is too high for it to be considered as a fuel.

The grain processes considered most likely for large-scale fuel ethanol production would ferment a mash (crushed, cooked, and treated grain plus water) that still contains all the non-starch components of the grain. The material left after the ethanol has been removed, called “still age,” has in it protein, dead yeast, and bacteria as well as various other materials contained in the grain. This stillage can be fed to animals directly or can be dried (to produce DG) for transport and, again, used as an animal feed. The wet stillage, however, spoils in 1 to 2 days, so care must be exercised when feeding the still age wet. [7]

The high protein content makes DG a suitable protein supplement to animal feed, although its high fiber content limits the quantity that can be fed and the types of animals that can consume it. Although DG contains about half the protein per pound of material as does soybean meal, a common protein supplement, the types of protein in DG are such that the cattle use it more effectively and experiments indicate that 1.5 lb of DG can substitute for 1

‘E W Kienholz, et al , "Grain Alcohol Fermentation Byproducts for Feeding in Colorado, " Department of Animal Sciences, Colorado State University, Fort Collins, Colo , 1979 lb of soybean meal. * [8]9 Consequently, the byproduct of distilling 1 bu of corn can displace the meal from about **0.25** bu of soybeans.**

Other experiments have indicated that DC causes the cattle to digest more of the starch in their feed than would be digested without DG[10] thereby giving DC an enhanced feed value, since less total corn could be fed to animals if part of the corn were converted to ethanol and the resulting DC fed in place of the corn. These results, however, occur only when the animal is fed a starch-rich and protein-poor diet. Feed rations commonly used today have a more nearly optimum protein-starch balance, so this effect would not occur, and the feed value of DC is only as a replacement for other protein concentrates used in animal rations.

The quantity of DC that can be fed to cattle has been estimated to correspond to an ethanol production level of 2 billion to 3 billion gal/yr.[12] As mentioned above, the protein in the grains could be removed before fermentation, and this protein feed ("gluten") would be suitable for a larger variety of animals. Theoretically, if the byproduct replaces all domestic consumption of crushed soybeans used for animal feed,[13] a production level of 7 billion gal/yr could be achieved before all crushed soybeans had been replaced with distillery byproduct (assuming the byproduct of fermenting 1 bu of corn displaces the soybean meal from 0.25 bu of soybeans). The byproduct, however, is not a perfect substitute for soybean meal and the actual level at which the animal feed market becomes saturated is probably considerably lower than this.

Other uses for DC are possible. Brewers' yeast is used as a B vitamin source by some people and the protein could possibly be used as a human protein source. It is not clear, however, whether this source of protein will gain consumer acceptance. The distiller byproduct could also be exported as an animal feed supplement, but if it competes with indigenous soybean meal producers (such as in Europe), import tariffs or quotas may be imposed.

While there are numerous possibilities, most proposals are vague and involve some obvious problems. Consequently, byproduct credits could drop or disappear in a large-scale ethanol program based largely on grain feedstocks.

If the protein in grains is removed in the pretreatment or sugar feedstocks are used, the still age consists primarily of yeast or bacteria, and has smaller feed value than DC. (The distillery producing most of the fuel ethanol used today removes the protein in the pretreatment and returns the still age to sewage treatment.) Although there is a limited market for this stillage, it is likely that it will either be dried and used as a fuel or subjected to anaerobic digestion with the resulting biogas used as a fuel. Drying and burning the byproduct result in slightly more energy— an estimated 8,000 Btu/gal of ethanol. *

Other possible byproducts of fermentation include oils, vitamins, other alcohols, various organic acids (e. g., vinegar), fusel oil (a mixture of alcohols), and other chemicals. The processes, however, are generally controlled so that the major chemical byproduct is fusel oil. This would probably be combined with the

'Cattle break down some proteins in the rumen and later use the resultant ammonia in the Intestines to synthesize new proteins Other proteins pass through the rumen and are absorbed directly in the intestine Depending on the relative proportions of the two classes of proteins, the effective quantity of usable protein will vary

'T K lopfenstein, Department of Animal Sciences, University of Nebraska, Lincoln, Nebr , private communication, 1979

'M 1 Poos and T Klopfenstein, "Nutritional Value of Byproducts of Alcohol Production for Livestock Feeds," Cooperative Extension Service, University of Nebraska, Lincoln, Nebr , Animal Science Publication No 79-4, 1979

' 'One bushel of distilled corn yields about 18 lb of DG One bushel of soybeans produces about 48 lb of soybean meal

[10]W P Garrigus, University of Kentucky, *Proceedings of 10th Distillers' Feed Conference*, Cincinatti, Ohio, Mar 3, 1955

"Klopfen$tein, op cit

[12]R L Meekhof, W E Tyner, and F D Holland, "Agricultural Policy and Gasohol," Purdue University, West Lafayette, Ind , May 1979, contractor report to OTA These authors assume a 21 substitution of DG for soybean meal and 3 billion gal of ethanol per year as the saturation point Using 1 51 as the ratio, however, reduces this to 225 billion gal/yr

[13]*Agricultural Statistics, 1979* (Washington, D C U S Department of Agriculture, 1979), GPO stock No 001- 000-04069-1

'If the material is dried, 11,000 Btu (2 lb) of material result per gallon of ethanol The drying however, requires an estimated 3,000 Btu additional input energy Anaerobic digestion would produce about 5,000 Btu of biogas (assuming 4 ft[3] biogas/lb solids) with the process requ iring about 1,000 Btu fuel alcohol, resulting in a 0.7-percent increase in the quantity of fuel produced.

CO_2 is also a byproduct of fermentation which is used in carbonated beverages, dry ice, and, to a small extent, in chemical processes. Moreover, CO_2 has many interesting properties that are currently being researched and recovery may eventually become more widespread and profitable.

Ethanol Production Costs

Raphael Katzen Associates has performed a detailed cost calculation on a 50-million-gal/yr coal-fired distillery that purchases its electricity from an electric utility. 14 Including coal-handling and pollution control equipment and allowing the production of dried DC, the total distillery would cost an estimated $53 million.

Inflating this to early 1980 dollars (20 percent) results in a distillery investment of $64 million. (These figures do not include engineering fees which could be small if a large number of distilleries are built, but which are estimated at $6 million, in 1978 for a single distillery.)

A distillery designed solely for sugar crop feedstocks would cost considerably more. As mentioned above, the sugar has to be concentrated to a syrup for storage, since the feedstock is available for only part of the year, during and somewhat after the harvesting season. Hence, the pretreatment equipment has to be able to handle a larger capacity than the distillery for part of the year, while standing idle for part of the year. In addition storage tanks are needed for the syrup. if the bagasse and crop residues are used as fuel, however, then some of the pollution control equipment needed to remove sulfur emissions can be eliminated, due to the very low sulfur content of the biomass. In all, a 50-million-gal/yr distillery for sugarcane or sweet sorgham would cost an estimated $100 mill ion in 1978[15 16] or $120 million in 1980, assuming the feedstock is available for half of the year and half year's syrup storage is required. These assumptions about the length of time that the feedstock will be available may be somewhat optimistic for Midwestern grown sweet sorghum, however, and the cost could be higher. If the raw feedstock is available for only 3 months per year, OTA estimates the distillery would cost about $140 million in 1978 dollars.

Although it might be possible to avoid concentrating the extracted sugar solution to a syrup by using antibiotics or various chemicals, a major cost of the pretreatment is the equipment needed to remove the sugar solution from the raw plant material. Furthermore, storage of large quantities of dilute sugar solution would be expensive. Consequently, improvements in the economics of using sugar feedstock will require methods for storing the raw sugar feedstocks inexpensively and in a way that the sugar need not be removed and concentrated. Possibilities include pretreatment with chlorine gas, ammonia, or sulfur dioxide (to change the acidity and provide a toxic environment for bacteria). OTA is unaware, however, of any work in this area that would serve as a basis for cost calculation.

An alternate approach is to build a distillery capable of handling either starch or sugar feedstocks. Katzen has calculated that this 50-million-gal/yr distillery would cost $93 million in 1978 dollars.[17]

The ethanol costs are influenced by the capital investment in and financing of the distillery, the distillery operating costs, and the byproduct credits. For a coal-fired 50-mill ion-gal/yr distillery using starch feedstock, the capital charges are about $0.21 to $0.42/gal of ethanol, depending on the financing arrangements. These charges, however, can vary significantly with interest rates, depreciation allowances, tax credits, and other economic incentives.

The major operating expense is the feedstock cost less the byproduct credit. For corn at $2.50/bu, the feedstock costs $0.96/gal of

[14] Raphael Katzen Associates, op cit
[15] Ibid
[16] F C Schaffer, Inc , in E S Lipinsky, et al , *Sugar Crops as a Source of Fuels; Vol II* Processing and Conversion Research, final report to Department of Energy, Aug 31, 1978

[17] Raphael Katzen Associates, op cit

ethanol and the byproduct credit is about $0.38/gal ($110/ton of DG), resulting in a net feedstock cost of $0.58/gal. Because farm commodity prices are extremely volatile, the net feedstock and resultant ethanol cost could be quite variable. A $0.50/bu increase in corn grain prices (and a proportionate increase in the byproduct credit), for example, would raise the ethanol cost by $0.1 2/gal.

Tables 53 and 54 show the cost of ethanol produced from various feedstocks. Although the costs will vary depending on the size of the distillery, ethanol can be produced from corn ($2.50/bu) in a coal-fired **50-million-gal/yr distillery for $0.95 to $1 .20/gal. About $0.10 to $0.30/gal should be added to these costs for deliveries of up to 1,000 miles** from the distillery. (Most ethanol is currently delivered in

Table 53.–Early 1980 Production Costs for Ethanol From Grain and Sugar Crops (in a 50-million-gal/yr distillery)

	Graln[a]	Sugar[b]
Fixed capital	$64 million	$120 million
Working capital (10% of fixed capital)	6.4 million	12 million
Total Investment	$70.4 million	$132 million
	$ per gallon of 99.6% ethanol	
Operating costs		
Labor	$0.08	$0.09
Chemicals	0.01	0.01
Water	0.01	0.01
Fuel (coal at $30/ton for grain feedstock and crop residues at $30/ton for sugar feedstock)	0.08	**0.04**[c]
Subtotal	$0.18	$0.15
Capital charges		
15 to 30% of total investment per year[d]	0.21-0.42	0.40-0.79
Total	$0.37-$0.60	$0.55-$0.94

[a]Includes drying Of distillers grain
[b]Includes equipment for extracting the sugar from the feedstock concentrating it to a syrup fo'storage
[c]Bagasse-fueled distillery appropriate for sweet sorghum and sugarcane supplemental fuel requirement is 3 lb of residue Per gallon of ethanol
[d]There are Many often complex formulae to compute actual capital costs Economic factors considered mcludedebl/equity ratio depreciation schedule, income lax credit rate of inflation terms of debt repay ment. Operating capital requirements and Investment lifetime However, a realistic range of possibilities for annual capital costs would lie between 15 and 30% of total capital investment
The upper extreme of 30% may be obtained assuming 100% equity finance and a 13% aftertax rale of return on Investment The lower extreme of 15% may be obtained assuming 100% debt financing at a 9% rate of Interest Both calculations assume constant dollars, a 20-year project lifetime, and include a charge for local taxes and Insurance equal to 3% of fixed capital costs For a more detailed treatment of capital costs see OTA, *Application 01 Solar Technology to Today's Energy Needs* VOI II ch 1

SOURCE Off Ice of Technology Assessment and Raphael Katzen Associates *Grain Motor Fuel Alcohol, Technical and Economic Assessment Study* (Washington D C Assistant Secretary for Policy Evaluation Department of Energy, June 1979), GPO stock No 061.000 -00308-9

Table 54,–Cost of Ethanol From Various Sources

Feedstock	Price[a]	Net feedstock cost[b] ($/gal ethanol)	Ethanol cost ($/gal)	Yields[c] (gallons of ethanol per acre)
Corn	$2.44/bu	$0.57	$0.94-$1.17	220
Wheat	3.07-4.04/bud	0.73-1.08[d]	1,10-1.68	86
Grain sorghum	2.23/bu	0.49	0.86-1.09	130
Oats	1.42/bu	0.59	0,96-1.19	75
Sweet sorghum	15.00/tone	0.79	1.34-1.73	380[e]
Sugarcane	17.03/tonf	1.26	1.81-2.20[f]	520

[a]Average of 1974-77 seasonal average prices
[b]The feedstock cost less the byproduct credit The difference in feedstock costs might not hold over the longer term due to equilibration of prices through large-scale ethanol production
[c]Average of 1974.77 national average yields
[d]Range due to d! fferent prices for different types of wheat
[e]Assuming 20 fresh weight tons/acre yield $300/acre production costs
[f]Excludes 1974 data due 10 the anomalously high sugar Prices that Year

SOURCE *Agricultural Statistics 1978* (Washington O C U S Department of Agriculture), and Office of Technology Assessment tank trucks, but as production volume grows other forms of transportation, such as barge shipments, rail tank cars, and petroleum product pipelines, * could decrease the transportation cost to as low as $0.03 to $0.05/gal under favorable circumstances.)

As shown in tables 53 and 54 the major tradeoff between starch and sugar feedstocks is that the starch-fed distilleries require considerably less investment than the sugar-fed ones, but the ethanol yield per acre cultivated may be larger with the sugar feedstocks. As noted in chapter 3, however, these yield figures are highly unreliable for sweet sorghum, and sugarcane cannot be grown on most cropland potentially available for energy crop production. If comparative studies of potential ethanol feedstocks grown under comparable conditions show that certain sugar crops produce more ethanol per acre than the starch crops, then there may be a tendency to turn to sugar feedstocks as farmland prices rise. Moreover, if the grain byproducts are difficult to sell, then economics could favor sugar crop feedstocks. For now, however, the lower capital investment required for grain-fed distilleries gives them an advantge over sugar-fed distilleries.

Onfarm Distillation

Apart from commercial distilleries, considerable interest has been expressed in individual farmers or farm coops producing ethanol. A number of factors, however, could limit the prospects of such production.

Technology for producing 90 to 95 percent ethanol (5 to 10 percent water) is relatively simple. Several farmers are or have constructed their own distilleries for this purpose. In addition prefabricated distilleries for producing 90 to 95 percent ethanol are available both at the farm size (15,000 gal/yr)[19] and coop size (several hundred thousand gallons per year)[20] for a cost of about $1 for each gallon per year of capacity, but there is insufficient onfarm operating experience to establish the reliability or expected operating life of these distilleries. OTA is not aware of smaller distilleries, but there is no fundamental reason why they cannot be built. There will, however, be a tradeoff between the cost of small distilleries and the amount of labor required to operate them.

A farmer must consider a number of site-specific factors before deciding to invest in an onfarm skill. Some of the more important of these are:

- **Investment. –** How much does the still and related equipment cost?
- **Use of the ethanol. –** Will the ethanol be used onfarm or sold? What equipment modifications are necessary? Will the farmer be dependent on a single buyer, such as a large distillery that will upgrade 95 percent ethanol to dry ethanol?
- **Labor. –** Does the farmer have access to cheap, qualified labor, or is it better to make a larger investment for an automatic distillery?
- **Skill.–** Although ethanol can be produced easily, the process yield—and thus the cost — as well as the safety of the operation can depend critically on the skill of the operator.
- **Equipment lifetime.–** Less expensive distilleries may be constructed of materials that are destroyed by rust after a few years' operation.
- **Fuel.–** Does the farmer have access to wood, grass, or crop residues and combustion equipment that can use these fuels? Can reliable, inexpensive solar stills be constructed for the distillation step?

  If oil or natural gas is used in the distillery, would it be less expensive to use this

*Various strategies can be used to eliminate potential problems with the water sometimes found in petroleum pipelines. If ethanol is being transported, the total volume of ethanol in the batch can be kept large enough so that the percentage of water in the delivered ethanol is within tolerable limits If gasohol is transported, it can be preceded by a few hundred barrels of ethanol which will absorb any water found in the pipeline, thereby keeping the gasohol dry. Other strategies also exist or can be developed[18]

[18]L J Barbe, Jr , Manager of Oil Movements, EXXON Pipeline Co , Houston, Tex , private communication, August 1979

[19]Paul Harback, United International, Buena Vista, Ga , private communication, October 1979

[20]Robert Chambers, president, ACR Process Corp , Urbana, Ill , private communication, September 1979

fuel directly as a diesel fuel supplement in a retrofitted diesel engine?

- **Byproduct. –** Can the farmer use the wet byproduct on his/her farm? Will this unduly complicate the feeding operations or make the animal operation dependent on an unreliable still? What will drying equipment cost and how much energy will it consume?
- **Water. –** Does the farmer have access to sufficient water for the distillery?

Under favorable circumstances, it might be possible to produce 95 percent ethanol for as little as $1/gal* plus labor with a labor-intensive distillery. If the ethanol is used in a diesel tractor, the ethanol would be equivalent to diesel fuel costing $1.70/gal, or about twice the current diesel fuel prices, Under unfavorable circumstances, the cost could be several times as great. Due to a lack of experience with onfarm distilleries, however, these cost estimates may be low.

Onfarm or coop production of dry ethanol could become competitive with commercially distilled ethanol, however, if relatively automatic, mass-produced distilleries capable of using fuels found onfarm and producing dry ethanol and dry DC could be sold for about $1 for each gallon per year of capacity and if farmers charge little for their labor. OTA is not aware of any package distilleries for producing dry ethanol that are available at this price.

*Assuming equipment costs of $1 for each gallon per year of capacity, the costs per gallon of ethanol are: $0.58 for net feedstock cost, $0.20 for equipment costs (operated at 75 percent of capacity), $020 for fuel (assuming $3/m million Btu and 67,000 Btu/gallon), and $0.05 for enzymes and chemicals, resulting in $1 03/gal of ethanol or $0.98/gal of 95 percent ethanol

Meeting this price goal for automatic, onfarm, dry ethanol production facilities will probably require process innovations, particularly in the ethanol-drying step, and could well involve the use of small, inexpensive computers (microprocessors) for monitoring the process. A major constraint, however, could be the cost of sensors, automatic valves, etc. that would be required.

For some farmers, however, the cost or labor required to produce ethanol may be of secondary importance. The value of some degree of liquid fuel self-sufficiency and the ability to divert limited amounts of corn and other grains when the market price is low may outweigh the inconvenience and/or costs. 1 n other words, farmers may consider the technology to be an insurance against diesel shortages and hope that it will raise grain prices. **Although insurance against diesel shortages certainly can be achieved by purchasing large diesel storage tanks at a cost below an ethanol distillation and storage system, increased grain prices for the entire crop would make the economics considerably more favorable to farmers but would be a very expensive way for the nonfarm sector to provide fuel to farmers. As** evidence of the interest, the Bureau of Alcohol, Tobacco, and Firearms had received over 2,800 applications for onfarm distillation permits by mid-1979 and they expected 5,000 by the end of the year. 2. **As** a profitable venture in the absence of large subsidies or grain price increases, however, onfarm production of ethanol is, at best, marginal with current technology.

[2]William Davis, Bureau of Alcohol, Tobacco, and Firearms, U S Treasury, Washington, D C , private communication, July 1979

Cellulosic Feedstocks

The feedstocks with the largest potential for ethanol production–both in terms of the absolute quantity of ethanol and in terms of the quantity of ethanol per acre of cultivated land– are the cellulosic, or cellulose containing, feedstocks. These include wood, crop residues, and grasses, as well as the paper fraction of municipal solid waste.

Wood, grasses, and crop residues contain cellulose, hemicellulose, and lignin. The cellulose can be reduced, or hydrolyzed, to sugars that can be fermented to alcohol. The hemicel**lulose** can also be reduced to sugars capable of being converted to ethanol with other types of bacteria. The lignin, however, does not convert to alcohol and can be used as a source of chemicals or dried and used as a fuel. Generally, paper is primarily cellulose with varying amounts of partially broken lignin.

The removal of hemicellulose from wood, grass, or crop residues and its reduction to sugar are relatively straightforward. In fact, hemicellulose from biomass is the prinicpal source of the chemical feedstock furfural. Although hemicellu lose is not now used as a source of ethanol, the fermentation step can probably be developed without excessive difficulty.

The cellulose, on the other hand, is embedded with lignin, which protects it from biological, but to a much lesser extent chemical, attack. Thus, the reduction of cellulose involves treating the lignocellulose material with acid or pretreating the material either chemically or mechanically to make it susceptible to biological reduction with enzymes.

What was apparently the first acid hydrolysis of wood was described in a German patent issued in 1880.22 Modifications of this process were used to produce animal fodder in several countries (mostly for the sugar) during World War 1. At the end of the war, the economic basis became obsolete. Between World Wars 1 and 11, however, other acid hydrolysis processes were used mostly in Germany to produce sugar and alcohol, partly because of materials shortages but partly in an attempt at self-sufficiency.[23] Other plants were also built in Switzerland and Korea.

During World War 1, pilot plants were built in the United States for producing ethanol from wood wastes. Acid hydrolysis processes underwent a series of modifications during World War II. Following World War II, however, virtually all of the wood-ethanol plants were closed for economic reasons. * Today commercial wood sugar plants are in operation only in the U.S.S.R. and in Japan but several other countries have expressed interest in developing the technology, and one plant in Switzerland is again being used for pilot studies. 24

Clearly it is technically possible to produce ethanol from lignocellulosic feedstocks today. The failure of these processes to remain economically viable except under special circumstances has been due, in large part, to the relatively low costs of petrochemicals and ethylene-derived ethanol. With oil prices rising, the primary competitor is likely to be grain- and sugar-derived ethanol. There are, however, improvements and developments in the lignocellulose processes which can make them competitive with the current costs of ethanol from these other feedstocks. Alternatively, large rises in farm commodity prices could make the cellulosic processes competitive without technical developments.

While there are processes whose economics rely on large byproduct credits or special financing that could be in commercial operation before 1985, the key to achieving economic competitiveness without these conditions is to develop processes which:

- produce high yields of ethanol per ton of biomass,
- do not require expensive equipment,
- allow nearly complete recovery of any expensive process chemicals, and
- do not produce toxic wastes.

No processes currently in existence fully satisfy all of these criteria, although there are processes that satisfy two and sometimes three of the criteria. Nevertheless, R&D currently underway could yield significant results in 3 to 5 years. With a normal scaleup of 5 years, one or more processes satisfying these criteria could become commercial by the late 1980's.

The generic aspects and historical problems with producing sugars from lignocellulosic feedstocks are now discussed, followed by a Slightly more detailed description of various processes currently under investigation. Final-

[22] H F J Wenzl, *The Chemical Technology of Wood*, translated by F E Brauns (New York: Academic Press, 1970).

[23] Ibid

*One ethanol plant that uses the sugar-containing waste stream of a sulfite paper-pulping plant is still in operation. It is, however, primarily a waste treatment plant and less than 10 percent of the paper-pulping processes used in the United States produce a suitable waste stream

[24] J L Zerbe, Program Manager, Forest Service Energy Research, U S Department of Agriculture, Forest Products Laboratory, Madison, Wis , private communication, 1980

ly, a generic economic analysis is presented for a hypothetical advanced distillery for producing ethanol from lignocellulosic feedstocks.

Generic Aspects and Historical Problems With Pretreatment

As mentioned above, lignocellulosic materials consist of cellulose, hemicellulose, and lignin. Typically, such material would first be treated with dilute acid to remove the hemicellulose, which then would be fermented in a separate step to ethanol. The remaining lignin-cellulose combination would be treated with concentrated acid at low temperatures (perhaps 100° to 110° F) or dilute acid at high temperatures (300 °to 4000 F) to either dissolve the cellulose from the lignin or to cause the material to swell, thereby exposing the cellulose for hydrolysis. Alternatively, the material can be exposed to a number of different chemical or mechanical pretreatments which render the cellulose susceptible to hydrolysis. The hydrolysis is then accomplished by further exposure to acid or by the action of enzymes (biological catalysts).

The relative amounts of cellulose, hemicellulose, and lignin can vary considerably among the various lignocellulosic materials. If pure cellulose is converted completely to ethanol, however, the theoretical maximum yield is 170 gal of ethanol per ton of cellulose. The yields per ton of hemicellulose are similar. Consequently for a lignocellulosic material that is so percent cellulose, 20 percent hemicellulose, and 25 percent lignin, the theoretical yield is about 120 gal/dry ton of biomass fermented. A yield of 85 to 90 percent of this is a reasonable practical goal, which would result in yields of 100 to 110 gal of ethanol per ton of biomass fermented. The expected yield, however, will vary with the exact composition of the feedstock. For municipal solid waste (29 percent paper and 21 percent yard wastes and wood packaging[25]), the average yield could be about 60 gal of ethanol per ton assuming a 90-percent overall conversion efficiency.

The historical processes have generally used acid hydrolysis. The dilute acid methods (Modified Rheinau, Scholler-Tornesch, Madison, Tennessee Valley Authority, and Russian Modification of Percolation processes) all suffer from a similar ailment,[26] The high temperatures and acidic conditions needed in the processes cause the resultant sugars to decompose, thereby lowering the overall ethanol yield. The concentrated acid processes (Rheinau-Bergius and Hokkaido), on the other hand, have resulted in good product yields. The economics, however, have historically suffered due to the loss of large quantities of acid in the processes, Nevertheless, one of the oldest concentrated acid processes (Rheinau-Bergius) is currently being reexamined to see if this economic conclusion necessarily pertains today (see below).

Publications over the past 20 years in the Soviet Union have reported good experimental results with impregnating wood with acid followed by mechanical grinding. The details for an assessment of the commercial viability of this process, however, are not available. On the other hand, a mechanical pretreatment is also involved in the Emert (formerly Gulf Oil Chemicals) process discussed below. Historically, the mechanical pretreatments needed have been quite expensive, but the researchers indicate that this is not a problem with the Emert process.[27] Finally, a variety of other processes or combinations of processes aimed at exposing the cellulose to hydrolysis are currently being researched. The most important of these are considered below.

Processes Currently Under Development

Emert Process

The development of this process started in 1971 under Gulf Oil Chemicals Corp., but was transferred to the University of Arkansas Foun-

[25] Materia l and Energy From Municipal Waste (vol 1, Washington, D C Office of Technology Assessment, 1979), GPO stock No 052-001-00692-8

[26] I Goldstein Department of Wood and Paper Science, North Carolina State University, Raleigh, N C , private communication, 1979

[27] G H Emert and R Katzen, "Chemicals From Biomass by Improved Enzyme Technology, " presented in the symposium *Biomass as a Non-Fuel Source*, sponsored by the AC S/CSJ Joint Chemical Congress, Honolulu, Hawaii, Apr 1-6, 1979

dation for scaleup (the transfer reportedly occurred because Gulf had made a management decision to concentrate its efforts on fossil fuels). This process is the most advanced of the enzymatic hydrolysis methods and, with proper financing, can probably be brought to commercial-scale operation by 1983-85.

The method consists of a pretreatment developed for this process which involves grinding and heating the feedstock followed by hydrolysis with a mutant bacterium also developed for this purpose. A unique feature is that the hydrolysis and fermentation are performed simultaneously in the same vessel, thereby reducing the time requirements for a separate hydrolysis step, reducing the costs and increasing the yield (since a sugar buildup during hydrolysis could slow the hydrolysis and decrease the overall yield). Also the process does not use acids, which would increase equipment costs. The sugar yields from the cellulose are about 80 percent of what is theoretically achievable,[28] but the small amount of hemicellulose in the sawdust is not being converted.

The process has been brought to the pilot plant stage and funds are currently being sought for a demonstration (1 million gal/yr) facility as part of the scaleup process. Based on the pilot plant experience, Emert estimates the selling price for the ethanol to be $1 .49/gal (1983 dollars, 100-percent private equity financing, and 10-year amortization).[29] With 80-percent municipal bond financing, he estimates the selling price to be $1.01/gal (1983 dollars, 20-year amortization).

These cost estimates are based on a feedstock of So-percent "air classified" municipal solid waste (i. e., the paper and plastic fraction) at $14/ton, 25-percent saw mill waste at $21/ton, and 25-percent pulp mill waste at $14/ton. These costs are all on the low end of estimates for 1978-79 prices and consequently represent optimistic estimates. Furthermore, by 1983, inflation would increase these costs. More realistic 1983 feedstock costs (50 to 100 percent higher than those cited) would raise the ethanol cost by about $0.10 to $0.20/gal.

[28] Ibid
[29] Ibid

The cost estimates also assume a large byproduct credit for dried fermentation yeast and hydrolysis bacteria ($0.40/gal ethanol). Most of this comes from the hydrolysis bacteria and an animal feed value for this material has not been established. In addition, large-scale production could lead to a saturated animal feed market similar to that with grain distillation and subsequent loss of the byproduct credit.

Furthermore, problems encountered with scaling up a process virtually always lead to cost increases above those estimated. Consequently, these cost estimates could be too low by $0.20 to $0.70 or more per gallon of ethanol. Nevertheless, with municipal bond financing, this process could well be competitive with ethanol produced from corn in a privately financed distillery by 1983. (Assuming 7-percent annual inflation as apparently was done in Emert's calculations, $1 .10/gal ethanol in 1979 would sell for about $1 .45/gal in 1983).

While no cost estimates are available for this process using woodchips, grasses, or crop residues as feedstocks, Emert reports that experiments have shown that modifications in the thermal-mechanical pretreatment enables ethanol yields of 70 to 75 gal/ton of feedstock.[30] The increased costs for these feedstocks ($40 to $50/ton in 1983 up from $30 to $40/ton in 1979) would add $0.30 to $().45/gal to the ethanol price. Consequently, it is less likely that this process using these feedstocks would be competitive with corn-derived ethanol, unless corn and other grain prices rise more rapidly than general inflation.

In sum, it appears that this process could be competitive with grain-derived ethanol if municipal wastepaper is used as a feedstock and the distillery receives special financing. A reliable determination of the competitive position of other feedstocks and financing arrangements are less certain and probably cannot be determined until a full-scale plant has been built.

[30] G H Emert, private communication, October 1979

Reexamination of Rheinau-Bergius Process

Much of the detailed information on the Rheinau-Bergius process has been lost. Since the acid hydrolysis of wood involves subtle chemical processes which can change dramatically with small changes in the process conditions, the detailed process chemistry of hydrolysis with concentrated hydrochloric acid is being reexamined at North Carolina State University. The research should provide a basis for reevaluating the process as **a source of ethanol and chemicals and determining whether sufficient quantities of the acid can be recovered to make the process economic at today's prices.**

Tsao Process

This process is being developed at Purdue University with the major emphasis on crop residues as a feedstock and is currently progressing to the pilot plant stage. Although there have been numerous changes in the process as the research has proceeded, in the currently preferred process hemicellulose is removed first with dilute acid and then, the cellulose and lignin are dissolved in concentrated (70 percent) sulfuric acid. The acid is recovered by precipitating the cellulose-lignin from the acid through the addition of methanol, then the methanol is removed from the acid by distillation. Following this pretreatment, enzymes hydrolyze the cellulose.

The use of methanol to aid in recovering the acid is a novel aspect of this process. As the recovery has been proposed, however, the methanol is likely to react to form toxic byproducts such as dimethyl sulfate, dimethyl ether, dimethyl sulfoxide, and other compounds. The loss of process methanol as well as the disposal of these toxic wastes would increase the costs. In addition, there are several places in the process where more expensive equipment will be needed than has been included in most cost calculations due primarily to the corrosive effects of the acid.[31 32] Although novel acid recovery processes of this type should be thoroughly investigated, it has not yet been satisfactorily demonstrated that the process proposed would be economically competitive as a source of fuel ethanol.

University of Pennsylvania—General Electric Process

In this process, woodchips are heated in an alkaline solution containing water, sodium carbonate, and butanol (a higher alcohol). Since butanol is only partly soluble in water, the solution consists of two phases (similar to oil floating on water). The hemicellulose goes to the water phase, the lignin dissolves in the butanol, and the cellulose remains undissolved. Following removal of the cellulose, and cleaning to remove traces of butanol, it can be hydrolyzed either with acid or enzymes and the hemicellulose can be converted to ethanol without removing it from solution. The butanol is then cooled, which causes the lignin to precipitate from solution, the solution is filtered, and the butanol recycled to the process.

Clearly the process economics will depend heavily on the cost of producing the process butanol and the quantity of butanol lost to the waste stream. On the other hand, the butanol-water sodium carbonate solution is considerably less corrosive than other chemicals used to remove lignin and therefore could result in lower equipment costs. At this stage, however, the processes are not well enough defined to provide a meaningful cost calculation.

U.S. Army —Natick Laboratories

Work done at this laboratory has contributed substantially to the basic knowledge about the enzyme system that converts cellulose to sugar. '3 These researchers first identified the three-enzyme system involved in the hydrolysis and have developed fungus mutants with improved enzyme productivities. **Not** only is this research applicable to ethanol production, but it also provides information for those interested in retarding cellulose degradation such as that which occurs with jungle rot.

"I?aphael Katzen Associates, op cit

¹²I Goldstein, op cit

"E T Reese, "History of the Cellulose Program at the U S Army Natick Development Center, " Biotechnology *and Bioenergy Symposium,* No 6, p 9, 1976

The system developed at Natick, however, requires relatively pure cellulose (such as in paper); it has not been effective on lignin-containing materials such as grasses, crop residues, and wood. Recently, attention has been directed at a mechanical process (ball milling) for reducing raw materials to extremely fine particles in order to use the Natick fungus, but this pretreatment is expensive and would probably make the process uneconomic, although detailed economic analyses are not available from the current pilot plant operation.

University of California at Berkeley (Wilke)

Wilke has concentrated on changing the pretreatment step of the Natick process by using acid and hammer milling of the wastepaper and field residues feedstocks. Nevertheless, a critical step involving the recycling of enzymes has not yet been demonstrated.

Iotech Process

This process is proprietary and the subject of patent applications in the name of the Canadian Research and Development Corp. Apparently, the novel aspect of the process is the pretreatment of the material before hydrolysis. In this process woodchips are exposed to high--pressure steam for several seconds, followed by explosive decompression. The product is said to be highly susceptible to hydrolysis.

Generic Economics of Lignocellulosic Materials to Ethanol

The processes described above represent a sampling of the possible approaches to ethanol production from lignocellulosic materials. The descriptions were necessarily brief and could not include all of the ramifications or aspects of the various research groups' efforts.

The chemistry and physics of lignocellulosic materials are complex, and there are few predictive theories that enable one to evaluate unambiguously the various approaches. Furthermore, the competition between research groups is enormous and details are often proprietary.

Nevertheless, the process at the most advanced stage of development (of those being developed) appears to be the Emert process. But as this process now stands and with a successful scaleup, the ethanol could sell for $0.30 to $0.60/gal more than corn-derived ethanol and the price difference could be greater if woodchips rather than sawdust are used as a feedstock. As mentioned above, however, special financing of the distillery (and an inexpensive feedstock source) could lower the selling price to a level competitive with the corn-derived ethanol from distilleries not specially financed. (Because of the larger investment, special financing lowers the price more than it would for corn distilleries.)

Alternatively, distilleries based on the older acid hydrolysis methods can be built to produce ethanol and chemical feedstocks. Katzen Associates, for example, has reevaluated the Madison process* on this basis and found that the ethanol could be sold at about $1 .50/gal without byproduct credits (1978 dollars) .34 The economics, however, depend on the byproduct credits for the chemical feedstocks, but the chemical industry is unlikely to make the commitment necessary to support a large fuel ethanol industry until more information is available on the relative merits of biomass- and coal-derived chemical feedstocks.

As suggested earlier, the key to producing ethanol from lignocellulosic materials at a price competitive with corn-derived ethanol without relying on special financing or large byproduct credits is the R&D currently aimed at reducing equipment costs, increasing overall yields, and ensuring a good recovery of process chemicals without the production of toxic wastes.

*Dilute acid hydrolysis process Products are ethanol, furfural, and phenol

"Raphael Katzen Associates in *The Feasibility of Utilizing Forest Residues for Energy and Chemicals* (Madison, Wis Forest Products Laboratories, March 1976), report No PB-258-630

R&D **currently underway could fulfill these criteria. If so, the production costs might look something like** those in table 55. These costs represent plausible cost goals for the production of ethanol from lignocellulosic materials.

Distilleries can and may be built before these criteria are fulfilled, but the economics will depend on favorable financing and atypically low feedstock costs or in securing a market for chemical byproducts. Some distilleries based on these circumstances are likely to be built before the late 1980's. **It is** unlikely, however, that such circumstances will sustain a large fuel ethanol industry.

Table 55.-Plausible Cost Calculation for Future Production of Ethanol From Wood, Grasses, or Crop Residues (in a 50-million-gal/yr distillery, early 1980 dollars)

	Dollars
Fixed investment ... , ..., ., ..., ...	$120 million
Working capital ... . . ., ., . . ., . . .,	12 million
Total investment ... . . ., ., ...	$132 million
	$/gallon
Labor, chemicals, fuel ., ., ., ..., . .	$0.30
Feedstock ($30/ton, 110 gal/ton) ., ., ., . . .	0.27
Capital charges (15 to 30% of total investment)	0.36-0.72
Total . . .., ., ..., ., ...	$0.93-$1.29

SOURCE : Office of Technology Assessment

Environmental Impact of Ethanol Production

The major potential causes of environmental impacts from ethanol production are the emissions associated with its substantial energy requirements, wastes from the distillation process, and hazards associated with the use of toxic chemicals (especially in small plants). A variety of controls and design alternatives are available to reduce or eliminate adverse effects, however, so actual impacts will depend more on design and operation of the plants than on any inevitable problems with the production process.

New **large energy-efficient ethanol plants probably will require at least 50,000 Btu/gal of ethanol produced to power corn milling,** distilling, still age drying, and other operations (see "Energy Consumption" discussion). Small plants will be less efficient. Individual distilleries of 50-million-gal/yr capacity will use slightly more fuel than a 30-MW powerplant; * a 10-billion-gal/yr ethanol industry (the approximate requirement for **a 10 percent alcohol blend** in all autos) will use about the same amount of fuel needed to supply 6,000 to 7,000 MW of electric power capacity.

New source performance standards have not been formulated for industrial combustion facilities, and the degree of control and subsequent emissions are not predictable. The most likely fuels for these plants will be coal or biomass (crop residues and wood), however, and thus the most likely source of problems will be their particulate emissions. Coal and biomass combustion sources of the size required for distilleries—especially distilleries designed to serve small local markets–must be carefully designed and operated to avoid high emission levels of unburned particulate hydrocarbons (including polycyclic organic matter). Fortunately, most distilleries will be located in rural areas; this will reduce total population exposure to any harmful pollutants. Particulate control equipment with efficiencies of 99 percent and greater are available, especially for the larger plants. If all energy requirements are provided by a single boiler, high efficiency control would be easier to provide. This is also true for any sulfur oxide (SO_x) controls (scrubbers) that may be required if the facility is fueled with high-sulfur coal.

Other air emissions associated with ethanol production include fugitive dust from raw material and product handling; emissions of organic vapors from the distillation process (as much as 1 percent of the ethanol, as well as other volatile organics, may be lost in the process); and odors from the fermentation tanks. These emissions may be tightly controlled by water scrubbing (for odors and organics) and cyclones (for dust).

* Assuming 1 0,000 Btukilowatthour

The "still age" — the waste product from the first still (or "beer still'')–will be extremely high in organic material with high biological and chemical oxygen demand, and will also contain inorganic salts, and possibly heavy metals and other pollutants. When corn is the biomass feedstock, the stillage is the source of dried DC, which is a valuable cattle feed whose byproduct value is essential to the economics of the process. Thus, it will be recovered as an integral part of the plant operation and does not represent an environmental hazard. On the other hand, sugarcane stillage has far lower economic potential as a byproduct; its recovery is unlikely except as a response to regulation.

The stillage and other wastes from all ethanol plants have severe potential for damaging aquatic ecosystems if they are mishandled. The high biological and chemical oxygen demand levels in the stillage, which would result in oxygen depletion in any receiving waters, will be the major problem. 35 Control techniques are available for reducing impacts from these wastes. Biological treatment methods (activated sludge, biological filters, anaerobic digestion, etc.] and land disposal techniques used in the brewing industry are suitable for ethanol production, but controls for stillages from some crop materials will require further development and demonstration.

Because fermentation and distillation technologies are available in a wide range of sizes, small-scale onfarm alcohol production may play a role in a national gasohol program. The scale of such operations may simplify water effluent control by allowing land disposal of wastes. On the other hand, environmental control may in some cases be more expensive because of the loss of scale advantages. Current experience with combustion sources indicates that high emissions of unburned particulate hydrocarbons, including polycyclic organic matter, are a more common problem with smaller units. Because smaller units are unlikely to have highly efficient particulate controls, this problem will be aggravated. Also, SO_x scrubbers are impractical for small boilers, and effective SO_x control may be achieved only with clean fuels or else forgone. Because local coals in the Midwest tend to have high sulfur contents (5 percent sulfur content is not unusual), small distilleries in this region may have objectionably high SO_x emission rates. Finally, small plants will be less efficient than large plants and will use more fuel to produce each gallon of alcohol.

The decentralization of energy processing and conversion facilities as a rule has been viewed favorably by consumer and environmental interests. Unfortunately, a proliferation of many small ethanol plants may not provide a favorable setting for careful monitoring of environmental conditions and enforcement of environmental protection requirements. Regulatory authorities may expect to have problems with these facilities similar to those they run into with other small pollution sources. For example, the attempts of the owners of late-model automobiles to circumvent pollution control systems conceivably may provide an analog to the kinds of problems that might be expected from small distilleries if their controls prove expensive and/or inconvenient to operate.

The same may be true for considerations of occupational safety. The current technology for the final distillation step, to produce anhydrous (water-free) alcohol, uses reagents such as cyclohexane and/or ether that could pose severe occupational danger (these chemicals are toxic and highly flammable) at inadequately operated or maintained distilleries. Similar problems may exist because of the use of pressurized steam in the distillation process. Although alternative (and safer) dehydrating technologies may be developed and automatic pressure/leak controls may eventually be made available (at an attractive cost) for small plants, in the meantime special care will have to be taken to ensure proper design, operation, and maintenance of these smaller plants.

[35] *Caribbean Rum Study,. Effects of Distillery* Wastes *on the Marine Environment* (Washington, D C Off Ice of Research and Development, Environmental Protect Ion Agency, April 1979)

Process Innovations

The processes for producing ethanol from sugar and grains are well established, but the traditional concern of the industries who operate them has been the flavor (or, in some cases, chemical purity) of the product. With the production of fuel ethanol, on the other hand, the principal concerns are cost and energy efficiency. There are several possible process improvements — at various stages of development — which can result in modest reductions in the processing cost and energy usage. Except for improvements in grain and sugar processing, the R&D could also be applicable to the production of ethanol from cellulosic materials. Some possible improvements in grain processing, fermentation, and alcohol recovery are mentioned below.

Grain and Sugar Processing

Developments in the last 20 years have led to more or less continuous grain preprocessing techniques which have lowered the costs over the traditional batch processes. Novel methods have been proposed, however, such as heating the mash with electrical current rather than process steam. This allows production of a more concentrated sugar solution, thereby reducing the load on evaporators at later stages in the operation. While this is a more energy-intensive pretreatment, it could lower the overall processing energy. [36]

The principal problem with sugar feedstocks, as noted, is the necessity of processing large quantities of feedstock to a syrup for storage. At least one research group is studying ways to store the sugar crops without reduction to syrup,[37] but the details are proprietary.

Fermentation

The key to cost reductions in fermentation is the use of methods for maintaining a high yeast or bacteria concentration in the mash, so that the fermentation proceeds rapidly—thereby reducing the size and number of fermentation vessels required. The two ways of doing this are through ***continuous fermentation*** or through recycling of the yeast.

Continuous fermentation processes have been tested in full-scale operation. Due to the possibility of infection of the mash (resulting in the production of products other than ethanol), the processes have two complete fermentation systems to allow periodic switchover and sterilization. The added cost for this equipment effectively nullifies the cost advantage of continuous fermentation. 38 Improved handling techniques, which can assure sterile operation, may obviate the necessity for this redundancy in equipment.

One type of continuous fermentation that is under R&D uses a vacuum over the fermentation mash. The ethanol is drawn off by the vacuum as it is produced, with the necessary heat for the evaporation of the alcohol being supplied by the fermentation process itself. This would reduce the need for cooling water as well as accelerate the fermentation (which is slowed by high ethanol concentrations). While added equipment costs might reduce or nullify the potential savings, the question of whether this will be the case has not been resolved.

Another way of maintaining a high yeast concentration is by recycling the yeast (after it is separated from any grain solids that are to be sold as a byproduct). A hybrid of yeast recycling and continuous fermentation involves a device called a countercurrent flow fermentation tower,[39] in which the yeast flows one way (counter to the current) while the sugars to be fermented flow in the opposite direction. The high yeast concentrations require additional cooling of the mash, which increases the cooling equipment costs somewhat, but research in this area can probably result in some overall cost savings.

“Raphael Katzen Associates, *Grain Motor Fuel Alcohol, Technical and Economic Assessment Study,* **op** cit

“E Lipinsky, Battelle Columbus Laboratories, Columbus, Ohio, private communication, 1979

“Raphael Katzen **Associates,** *Grain Motor Fuel Alcohol, Technical and Economic Assessment Study,* op. cit

[39]Ibid

Distillation

The distillation **process** in the corn-to-fuel-ethanol distillery considered above consumes nearly half of the energy used at the distillery. Lowering the energy requirements for separating the ethanol from the mash is desirable for a fuel ethanol facility in any case, but the increased equipment costs for advanced ethanol separation techniques could counter part or all of the potential cost savings from lower fuel use and smaller boiler and fuel-handling requirements. Consequently, R&D into this area must address both the energy use and the equipment cost.

One way to lower the energy requirements of distillation is to produce a mash with an ethanol concentration higher than the usual 10 **percent. This would require development of yeast or bacteria that are tolerant of the high alcohol concentrations. Since it would be expected that any yeast or bacteria producing ethanol would produce it more slowly at the higher ethanol concentrations, this might require longer fermentation times with a consequent increase** in the cost of fermentation equipment. It may be possible, however, to combine this with advanced fermentation methods to provide an overall savings.

Several methods have been suggested for removing the ethanol from the water. These include:

- membranes using reverse osmosis (something like a super filter that allows the water or ethanol to pass through the membrane while preventing the other component from doing so);
- absorption agents (solids which selectively absorb the ethanol are then separated from the solution, with the ethanol finally being removed from the solid); and
- liquid-liquid extraction (extracting the ethanol into a liquid that is not soluble in water, physically separating the liquids, and removing the ethanol from the other liquid).

All of these processes, however, are likely to require that the yeast and grain sol ids be removed from the mash first, so that they do not interfere with the ethanol concentration step (e.g., by clogging the membrane). Little research has been done in producing a clarified solution from the mash, hence, the costs for these methods are highly uncertain.

Numerous other suggestions exist, and research in these areas may eventually produce usable results. One example is the use of supercritical CO_2. When gases are subject to high pressures at suitable temperatures, they form a fluid which is neither gas nor liquid, but is called a supercritical fluid. The properties of supercritical fluids are largely unresearched, but there are proprietary claims that supercritical CO_2 could be suitable for extracting ethanol from the mash. The pressure would then be lowered, the CO_2 would become a gas, and the ethanol would liquefy.

Another possibility is the use of phase separating salts. Salts, when dissolved in a liquid change the liquid's structure and properties. It has been suggested that there may be salts which would attract the water (or ethanol) so vigorously and selectively that the ethanol-water mixture would separate into two phases, with one being predominantly water and the other predominantly ethanol.

These novel approaches should be investigated, but it is not possible to predict when or if results applicable to commercial fuel ethanol production will emerge.

Producing Dry Ethanol

In a large, commercial distillery, the production of dry ethanol only costs $0.01 to $0.03/gal (of ethanol) more than the production of 95 percent ethanol .40 (The difference in the selling price per gallon of 99.5 percent ethanol and 95 percent ethanol is due primarily to the fact that the latter contains 4.5 percent less ethanol per gallon of product.) Furthermore, with modern heat recovery systems, the production of dry ethanol requires very little additional energy. Consequently, little economic or energy savings are available here.

"I bid

On the other hand, the additional cost of equipment for producing dry ethanol automatically onfarm with conventional technology may be prohibitive. If the distillery is of the labor-intensive type, however, the additional equipment cost would be small since the same still could be used to produce 95 percent ethanol and then later used to distill to dry ethanol.

Drying agents or desiccants, however, may be a suitable substitute for the conventional process. These materials would selectively remove the water from 95 percent ethanol. various chemicals are known to do this and recent research indicates that corn stover or corn grain may even be suitable.[41] It is not known, however, how much ethanol would be lost in the process or, if grain is used, whether the absorbed ethanol would inhibit the production of sugar from the starch. While the processes are undoubtedly technically possible, the economics are still highly uncertain.

[41] M. R Ladisch and K Dyck, *Science,* vol 205, p 898, 1979