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ETHANOL FROM SUGAR CROPS:

A CRITICAL REVIEW

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EXECUTIVE SUMMARY

The burdens imposed by rising petroleum prices and periodic production shortfalls create especially great hardships for less developed countries. Interest in ethanol from sugar crops as a means of alleviating this situation is especially high in LDC's that have warm humid climates and relatively large rural populations. This critical review is presented to development planners who are interested in this energy option.

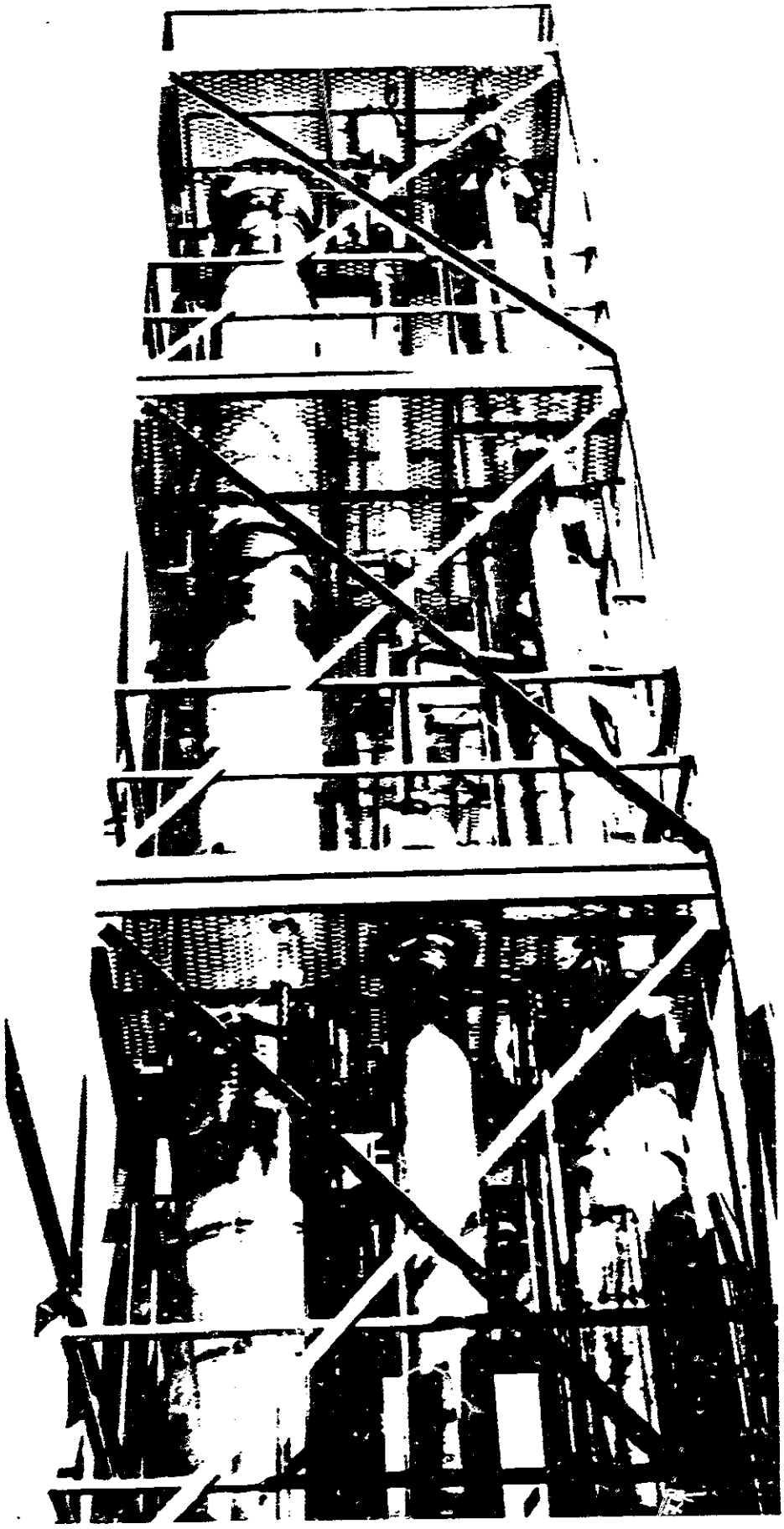
Ethanol from sugar crops is not a panacea that will free LDC's from imports of petroleum products. However, many tropical and subtropical LDC's are likely to find it attractive to expand sugar crop production to obtain foreign exchange to pay for imports of petroleum products and/or produce domestic ethanol to substitute for a portion of petroleum imports. Each country needs to conduct site-specific investigations to determine which option or blends of options should be undertaken.

For most LDC's, sugarcane appears to be the most attractive sugar crop. However, sweet sorghum has a role to play, especially on more marginal and drier land. Sugar beets may become attractive in the future because of their storage characteristics and some advances in processing and conversion.

The state of sugar crop processing and conversion to ethanol is healthy in that Brazil has shown that a large number of ethanol facilities can be built within a relatively short time and started up satisfactorily. There are innumerable process improvements under investigation at many research and development centers. There are so many improvements that appear desirable that those initiating an ethanol industry in a LDC may choose unwisely. A firm distinction must be made between technology development and construction of commercial facilities based on proven technology.

The three major problems that are encountered in production of ethanol from sugar crops are the adverse environmental effects that accompanied the stillage (still bottoms) that are produced to an extent of 10 gallons of waste per gallon of ethanol, the high cost of conventional milling equipment, and the loss of potential revenues from raw sugar sales when sugar crop juice is committed to ethanol when the world price

of sugar is relatively high. An option of considerable importance is the development of energy uses for the fibrous residues (bagasse). Cooking fuel or electricity are immediate uses. By the year 2000, technology may be developed to produce ethanol from bagasse instead of (or in addition to) the simple sugars.



Stills and scaffolding, beer still and rectifier

Source: Gasohol U.S.A.

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INTRODUCTION

Economic development is closely linked to the availability of fuels that can be obtained at reasonable prices without undue adverse effects on foreign trade balances. The lesser developed countries (LDC) now face a more critical task in planning their development because of the rapid escalation in the price of petroleum. Even if political instability does not cut off oil with catastrophic results, continued escalation of petroleum prices at 3 percent over the inflation rate will hamper greatly the progress of LDC's in the next few decades.

Viewed in this context, the development of domestic fuel sources that do not involve loss of foreign exchange properly is viewed as a high priority item. Many LDC's have climates, labor forces, and land area for the production of fuels from biomass. Among the most attractive fuels is ethanol and among the most attractive types of biomass for ethanol production are the sugar crops (sugarcane, sugar beets, sweet sorghum, and their close relatives). The pioneering efforts of Brazil in ethanol from sugar crops through its Proalcool program shows that substantial quantities of gasoline replacements can be manufactured and that agricultural employment, development of entrepreneurial skills, and other benefits can be obtained. Brazil has encountered and continues to encounter numerous economic, environmental, and technical problems in the implementation of Proalcool, but this experience in itself is useful for the other LDC's that wish to emulate the successes of Brazil's program and to avoid pitfalls.

This critical review of the concept of deriving ethanol from sugar crops has been undertaken at the request and sponsorship of the U.S. Forest Service under a contract with the U.S. Agency for International Development. The views are those of Battelle staff, not of the

other agencies. This document is designed to provide information and guidance for energy planners and engineers who propose preliminary design concepts in specific LDC's.

SUGAR CROP-BASED ETHANOL SYSTEMS

Sugar crops are important for LDC's. They are a source of foreign exchange for many LDC's. World sugar production and consumption are summarized in Tables 1 and 2. Price changes in recent years are shown in Figure 1. An overview of systems for the manufacture of ethanol from sugar crops is shown in Figure 2. Although sugar crops generally yield more ethanol per unit of land area than do grains, this energy crop would be an important user of prime agricultural land. All of the sugar crops are heavy consumers of potash fertilizer, which usually needs to be imported. Sugar crops do not require as much nitrogen fertilizer as do grains, but this may be another important input. Thus, the ethanol from sugar crop system begins with a commitment of significant resources and factors of production.

The harvested sugar crop is transported to central processing facilities for ethanol production. Infrastructure requirements at this stage include good roads and large, heavy duty trucks. At the processing facility, the juice is extracted by one of the several technologies to be discussed later in this report. The sugar crop juice then could be fermented and distilled to make ethanol or crystallized to make raw sugar. Which of these activities (or both) should be undertaken depends on the availability of fuels and sweeteners in the country, export prospects, and strategic considerations. One option used by the Brazilian sugar industry is to take a first crop of crystalline and raw sugar that is cheap to make and commands a good price and to ferment the remainder to ethanol. The percentage that is fermented versus the percentage that is crystallized depends on the prospects for profit in the two markets.

When the sugar juice is extracted from a sugar crop, a residue remains. For practical purposes, the residue from sugarcane and sweet sorghum are indistinguishable. They are known in the trade as "bagasse". Sugar beet pulp has a significantly different composition and will be discussed separately. One promising use for bagasse is the production of steam and electricity at the facility so that the production of ethanol

TABLE 1. WORLD SUGAR PRODUCTION AND CONSUMPTION

YEAR*	PRODUCTION	CONSUMPTION
	(In Thousands of Metric Tons)	
1980	88,000	--
1979†	91,570	89,963
1978	91,308	85,931
1977	86,869	81,788
1976	81,756	79,128
1975	78,450	76,390
1974	79,349	78,881
1973	76,788	77,263
1972	73,226	75,373
1971	72,205	73,882
1970	73,776	71,575
1969	67,258	67,542
1968	65,936	65,042
1967	65,165	64,882
1966	62,628	62,259
1965	66,329	58,741
1964	54,745	54,261
1963	51,172	54,479
1962	52,351	55,602
1961	56,073	52,734
1960	49,564	48,858
1959	51,034	47,561
1958	45,172	44,704
1957	42,339	42,228

Source: Sugar y Azucar Yearbook, 1980, and The Sugar Journal, February, 1980.

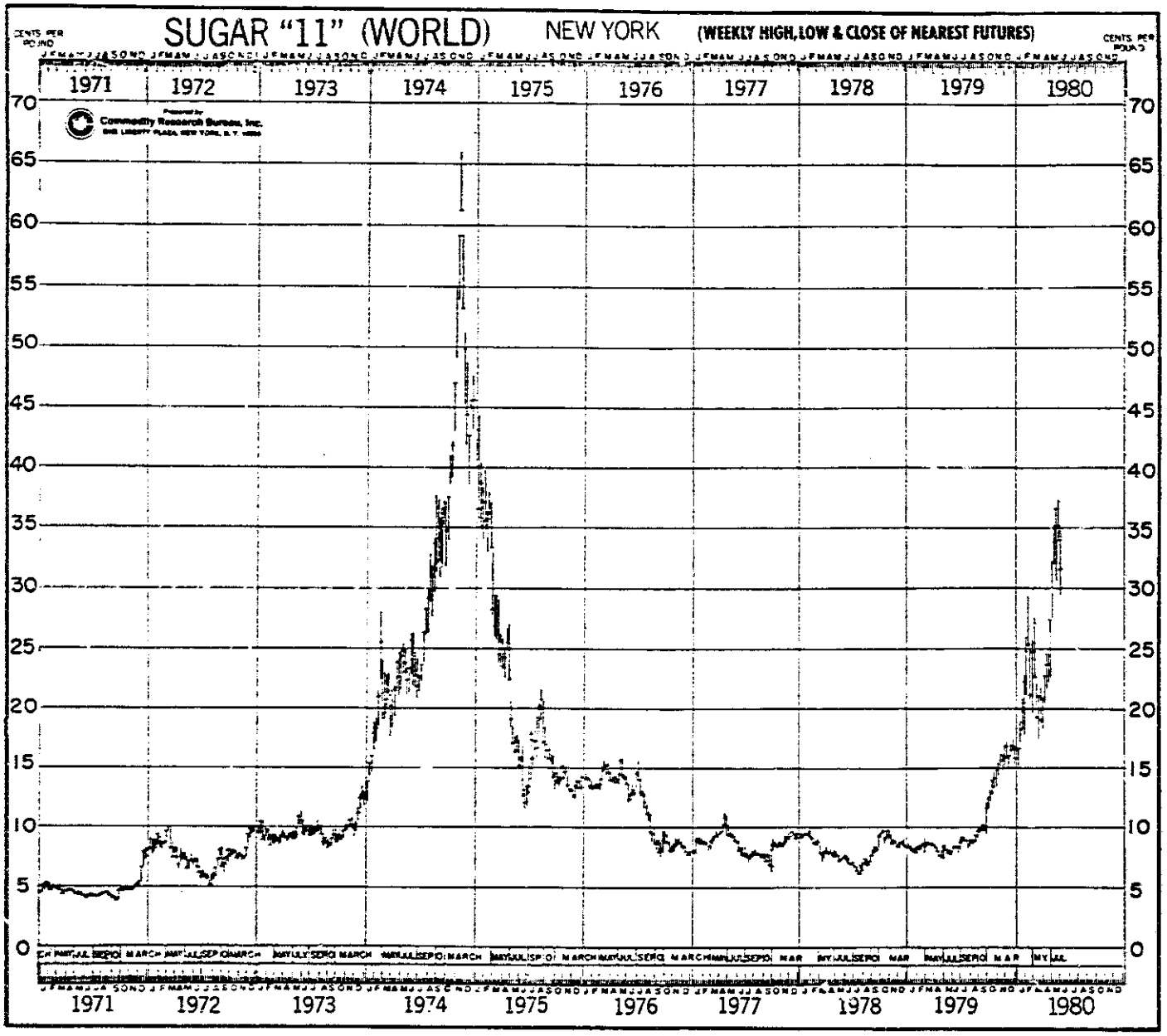
* Crop Year Ending August 31.
† As Estimated August 29, 1979.

TABLE 2. SUGARCANE PRODUCING AREAS, YIELDS, PRODUCTION, AND CONSUMPTION IN SELECTED COUNTRIES

	Area[a] 1000 hectare	Yield[a] m ton/ hectare	Production[b] Metric Tons	Consumption[c] Metric Tons
Africa				
Egypt	105	89	9,345	966,000
Kenya	50	68	3,400	279,000
Mauritius	81	84	6,804	38,700
South Africa	205	94	19,270	1,133,000
Swaziland	16	110	1,760	25,000
Asia				
Bangladesh	154	36	5,544	130,000
India	3220	56	180,320	6,100,000
Indonesia	175	80	14,000	1,557,000
Philippines	505	50	25,250	1,087,000
Thailand	394	43	16,942	607,000
Oceania				
Australia	290	81	23,490	786,000
North America				
Costa Rica	35	63	2,205	130,000
Cuba	1260	54	68,040	552,000
Dominican Republic	171	69	11,799	182,000
Guatemala	91	65	5,915	216,000
Mexico	438	72	31,536	2,934,000
Panama	43	60	2,580	63,000
United States				
Florida	121	74	8,954	-
Hawaii	90	112	10,080	-
Louisiana	122	54	6,588	-
South America				
Brazil	1518	56	85,008	5,289,000
Colombia	80	117	9,360	856,000
Ecuador	35	78	2,730	280,000
Guyana	56	76	4,256	36,000
Peru	58	107	6,206	546,000

Sources: Sugar y Azucar Yearbook, 1980; and James E. Irvine, Reference 4.

(a) Data presented by Irvine in Reference 4 for 1977-78 crop season.
(b) 1977-78 crop season, derived from Irvine, Reference 4.
(c) Mostly during calendar 1978. Otherwise, most recently available data.



Source: Commodity Research Bureau

FIGURE 1. RAW SUGAR PRICES

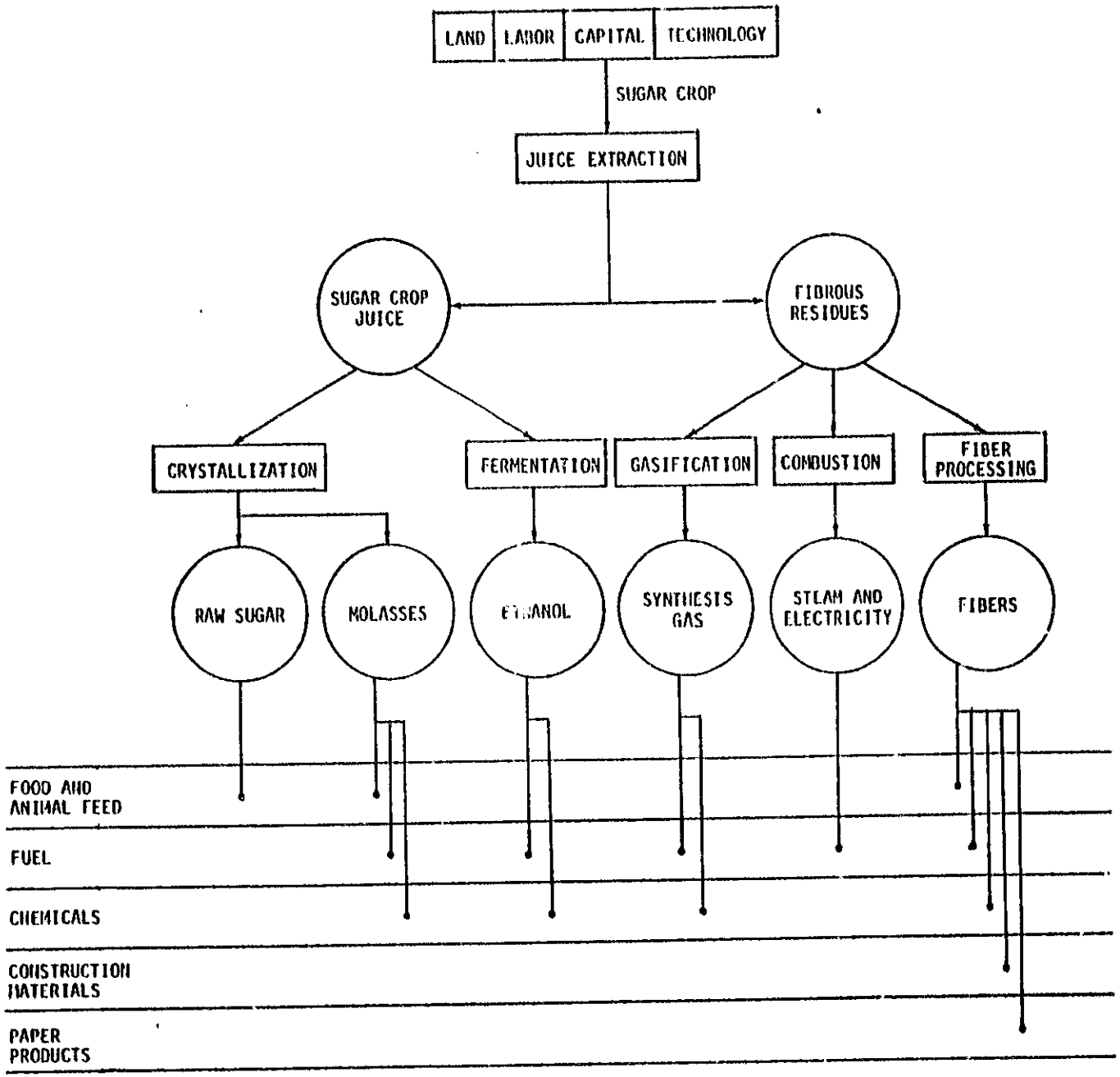


FIGURE 2. OVERVIEW OF SYSTEMS FOR MANUFACTURE OF ETHANOL FROM SUGAR CROPS

(and raw sugar, if desired) are somewhat insulated from world fuel price inflation. With efficient bagasse combustion systems, additional electricity can be manufactured or used locally. Alternatively, bagasse can be converted into paper, particle board, fuel pellets for consumer use, or plywood substitutes. The relative merits of using bagasse for energy versus wood substitutes depends on the status of the forest products industry in the LDC making the decision.

Sugar beet pulp is sufficiently digestible by cattle and other ruminant animals to make it too valuable to make steam and electricity from. Therefore, sugar beet and fodder beet-based ethanol systems would require other fuels. Recent development in bagasse upgrading indicates that this product also can be made into a synthetic hay that may have more value than electricity in certain site-specific situations.

Raw Sugar Facility Retrofit

The construction of an ethanol production facility at an existing raw sugar production facility is much lower in cost than would occur with a new "grass roots" facility. An ethanol add-on may cost only 25 percent as much as a grass roots facility. The presence of steam generation facilities, cane unloading and storage facilities, bagasse handling equipment, and many other items contribute to the relatively low cost and speed of implementation of a project to produce ethanol at existing raw sugar facility.

The primary disadvantages of the retrofit strategies are

(1) Small scale by fuel market standards

(2) Usually relatively ineffective boilers

(3) Raw sugar orientation by plant management

(4) Obsolescent technology.

Addition of an ethanol plant to a sugar mill to optimize the efficiency of raw sugar production would be helpful for the individual sugar factory but may not contribute enough ethanol to reduce petroleum imports perceptively. This comment applies to the smaller countries but not to Brazil or the Phillipines where there are a large number of sizeable sugar factories.

The goal of plant managers has been to "balance the factory" by making enough steam and electricity to satisfy all internal needs. However, only a relatively few sugar mills are set up for maximizing the electricity to be obtained from bagasse, partly because this involves operating boilers at much higher pressures than was considered desirable when the plant investments were made.

Conventional Juice Extraction Technology

The establishment of new grass roots sugar crop extraction facilities could be the basis for an ethanol industry that is of sufficient scale to satisfy fuel markets. The major differences with existing sugar factories would be in the following elements:

(1) Highly efficient bagasse combustion system to generate steam and electricity

(2) If raw sugar is to be produced as well as ethanol, no provisions would be made for repeated crystallization of the sugar contained solutions after the first crop of raw sugar crystals are obtained

(3) Relaxation of requirements on parts of the system used to keep the product free of dirt and color bodies and to keep the initial crystallization solution low in invert sugar

(4) Optimization of the number of milling trains so that small amounts of sugar may be loss but sizeable reduction in capital investment obtained.

(5) Optimization of steam use via integration of steam consumption in distillation, raw sugar crystallization, incoming juice pasturization, etc.

These new systems provide many opportunities for increased efficiency.

The production of raw sugar also leads to the production of molasses. This concentrated sugar solution also can be converted to ethanol. It is advantageous in some respects compared with cane juice and is disadvantageous in other respects. Among the advantages are: its low cost compared

with raw sugar and its high concentration of sugars that permits efficiencies in distillation. Its major disadvantages are its limited availability compared with the fuel needs of the LDC and its composition which includes some ingredients that slow down the fermentation process.

Molasses is used as an animal feed because it contains considerable calories and has nitrogen compounds that can be assimilated by cattle. It is especially popular in Europe in competition with corn and other expensive grains. It is also popular as a source of rum. Although molasses has an excellent price in European markets, many LDC's have their sugar operations located too inconveniently to make good use of this market. Examples include the Ivory Coast and the Sudan. Such countries could benefit greatly by installation of ethanol facilities to exploit the otherwise large wasted resource.

Energy planners in LDC's need to work closely with planners involved in the development of agriculture, import substitution, and other aspects of the development process. A typical scenario may be the construction of a new sugar mill during times of rising sugar prices. The engineering study for an add-on ethanol plant might be done at the same time. Then the ethanol facility could be constructed in less than a year as the price of sugar begins its downward movement. By adopting this strategy, cheap sugar crop juice would be available during the early stages of the life of the ethanol facility. Henceforth, the facility could adjust its product mix depending on market conditions and sugar crop yields.

AGRONOMY OF SUGAR CROPS

The agronomic practices employed for the production of sugar crops in various countries is a complex function of such factors as the specific sugar crop, climate, soil resources, water resources, labor and energy availability, etc. Two of the sugar crops, sugarcane (*Saccharum officinarum*) and sweet sorghum (*Sorghum bicolor*) are tropical plants by nature, whereas the sugar beet (*Beta vulgaris*) and its relatives are temperately adapted. However, the effective production ranges of these crops cover areas between approximately 40^{0} north and south latitudes.

Domestication and crop improvement of the sugar crops have led to the development of cultivars and agronomic practices which maximize the yield of crystalline sugar (sucrose) under a given set of conditions. For the past decade, in addition to crystalline sugar production, interest has centered on the production of ethanol from sugar crops. With this reorientation of production goals, it has become apparent that strategies currently utilized for crystalline sugar production are not necessarily congruent with those optimized for ethanol yield maximization. A closer look at the strategic differences between crystalline sugar and ethanol production systems will now be presented.

Crystalline Sugar Versus Ethanol Production

Table 3 highlights the strategic differences in goals between crystalline sugar and ethanol production systems. The primary differences are:

(1) the primary product—the crystalline sugar production system attempts to maximize sucrose yield whereas the ethanol production system attempts to maximize total fermentable sugars (sucrose, glucose, and fructose);

(2) the value of fiber—in crystalline sugar production systems the ideal raw material is millable stalk/root with a high percentage of sucrose. The lower the quantity of stalk/root to be processed to yield a given quantity of sucrose the better, from a processing perspective. In the ethanol production system, maximization of dry matter is desired. This additional dry

TABLE 3. STRATEGIC DIFFERENCES IN GOALS BETWEEN CRYSTALLINE SUGAR AND ETHANOL PRODUCTION SYSTEMS

Crystalline Sugar Production	Ethanol Production
• Desire high yield of sucrose	• Desire high yield of total fermentable sugars
• Desire high ratio of stalk/root to total biomass	• Ratio of stalk/root to total biomass is <u>not</u> important
• Desire low yield of dry biomass	• Desire high yield of total dry biomass
• Desire high percentage of sucrose per unit dry biomass	• High percentage of fermentable sugars per unit dry biomass is <u>not</u> the highest priority
• Desire high ratio of sucrose to total fermentable sugars	• Ratio of sucrose to total fermentable sugars is <u>not</u> important
• Starch in sugar solution causes problems with crystallization	• Starch in sugar solution does <u>not</u> create problems
• Sucrose inversion is a problem	• Sucrose inversion is <u>not</u> a problem

matter may be utilized for the production of steam and electricity at the processing/conversion facility.

To maximize both total fermentable sugar and fiber yields, certain agronomic practices must be modified. This modification will involve increasing the plant population by narrowing the row spacing and/or decreasing the interplant spacing within the row. While this modification may adversely affect mechanized operations, in LDC's where mechanization is the exception rather than the rule, this change may be amenable to the labor-intensive system. Prior to mechanization, sugarcane was routinely spaced more closely. Furthermore, an attempt to close the production loop by recycling stillage to the field following distillation activities may be a key to the economic and environmental viability of the system. Under the labor-intensive systems encountered in the LDC's changes in agronomic practices may occur; however, these are a function of increased manpower availability rather than a reorientation in production goals from crystalline sugar to ethanol.

Sugarcane (*Saccharum officianarum* L.)

Botanical Description and Composition*

The basic structure of the sugarcane is closely related to that of other members of the family Gramineae, of which it is a giant member[(1)**]. The major structure of this perennial grass is the culm, stem, or stalk (the principal organ of sucrose storage). The stem is solid, 2.5 - 6m in height, usually erect and unbranched except for tillers (secondary stems) at the base. The stem is composed of a series of joints, 5 - 25 cm long and 1.5 - 6 cm in diameter consisting of a node and internode. The length, diameter, shape, and color of the joints varies with the cultivar but can also be influenced by climatic and other factors, particularly light and nitrogen status[(2)].

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* This description is based on Reference 12.

** The List of References is located on page 94.

The leaves are two-ranked as in other grasses, alternating on opposite sides. The number of mature green leaves during the "grand growth" period is about 10. As new leaves emerge, the older lower leaves dry and die and may drop off or be retained[2].

The root system is fibrous and composed of two components. The sugarcane plant is generally propagated by cuttings, therefore the first component of the system is a group of thin, highly branched roots which develop from the cuttings. The secondary roots, which develop from the secondary shoots as the plant matures, are thicker than the primary roots and penetrate the soil to a depth of 2 m or more. However, the roots most active in uptake of water and nutrients function in the upper 50 cm of the soil.

The flower of the sugarcane plant is a loose terminal panicle 25 - 50 cm long and silky in appearance. The extent of flowering varies greatly with cultivars and climate (photoperiod). For example, most sugarcane produced in the world is harvested prior to flowering.

In the United States, the proportion of total millable stalk to the total wet biomass varies greatly, ranging from 50 percent in 12-month old Hawaiian sugarcane to approximately 70 percent in 9-month old Louisiana cane[3]. The composition of the millable stalk is given in Table 4. The amount of each of three components is primarily genetically determined; however, the environment and cultural practices can affect the percentages of the components to a slight degree. The constituents found in the extracted juice of the stalk (Table 4) are primarily three sugars, of which sucrose is by far the major component.

Production Requirements

Table 5 highlights the basic production requirements for sugarcane.

Current and Potential Biomass Yield

Sugarcane has long been recognized as the earth's most efficient bioconverter on a large scale. The efficiency of sugarcane is due to:

TABLE 4. COMPOSITION OF SUGARCANE AND JUICE SOLIDS

Millable Stalk	%
Water	73 - 76
Solids	24 - 27
Soluble Solids	10 - 16
Fiber (dry)	11 - 16

Juice Constituents	Soluble Solids (%)
Sugars	75 - 92
Sucrose	70 - 88
Glucose	2 - 4
Fructose	2 - 4
Salts	3.0 - 4.5
Inorganic acids	1.5 - 4.5
Organic acids	1.0 - 3.0
Organic Acids	1.5 - 5.5
Carboxylic acids	1.1 - 3.0
Amino acids	0.5 - 2.5
Other Organic Non-Sugars	
Protein	0.5 - 0.6
Starch	0.001 - 0.050
Gums	0.30 - 0.60
Waxes, fats, phosphatides	0.05 - 0.15
Other	3.0 - 5.0

Source: Reference 3.

TABLE 5. SUGARCANE PRODUCTION

Climatic Requirements	-	Tropically adapted; grows well at temperatures from 21-40°C. Non-irrigated production occurs in areas with more than 115 cm of rain per year. A general rule among growers is 3 cm of rain produce approximately 1 ton of millable stalks.
Soil Requirements	-	Grows well on alluvial soils. In general, sugarcane grows on a diverse number of soils ranging from sandy loams to heavy clays with a pH range of 4.5 - 8.0.
Length of Growing Season	-	Sugarcane is a perennial grass and in most areas and reaches maturity 8 months to 24 months.

(1) High rates of photosynthesis

(2) A large, effective leaf area

(3) A long growing season.

The world's average yield of sugarcane is 56.6 tons/ha/yr (1977-1978), and assuming an average 72.5 percent moisture content, the average yield of dry matter (half sugar, half fiber) is 15.5 tons/ha/yr[4]. A number of sugarcane regions (Malawi, Zimbawbe, Swaziland, Iran, Hawaii, Colombia, and Peru) obtain yields averaging 100 tons/ha/yr or more. However, these high yields are only 36 percent of the theoretical maximum yield of sugarcane[5]. Thus, there is considerable room for yield improvement.

In small plot tests, utilizing narrow row spacings of 0.5 and 0.6 m, respectively, yields of 190 and 160 tons/ha/yr were obtained in Australia and the United States. Increased yields can be realized in many areas by applying approved cropping practices. In addition, yields may be improved through plant breeding. The sucrose and fiber content of commercial sugarcane cultivars range from 10 to 16 percent. Since these cultivars were developed through selection for low fiber, a change in selection pressure for high fiber and high total sugars would likely result in genotypes with a higher energy content per ton and per unit area[6].

Sugarbeet (*Beta vulgaris* L.)

Botanical Description and Composition

The sugarbeet is a herbaceous dicotyledon, a member of the family Chenopodiaceae, characterized by small, greenish, bracteolate flowers[7]. The major structure of this biennial shrub is the fleshly root (the principal organ of sucrose storage). At maturity, the beet is composed of three major segments: the crown, the neck, and the root. The crown is composed of the leaves and the leaf bases. Located just below it is the neck, which is the broadest part of the beet[7]. The cone-shaped root is found below the neck region.

The leaves are simple with a large blade and petiole. Flowers of the sugarbeet are perfect and incomplete. The fruit is an aggregate that yields a seedball with two or more viable seeds[8]. Because the entire fruit is used in planting operations, efforts have been made to develop a monogerm seed. Both mechanically and through breeding, a monogerm seed is currently available which allows the planting of a more uniform stand.

The composition of the sugarbeet root is given in Table 6. While Table 6 shows the typical root fermentable sugar content at roughly 13 percent (16 percent soluble solids at 78 percent sugar) it has been well documented that the fermentable sugar content may range from approximately 10 to 22 percent.

Production Requirements

Table 7 highlights the basic production requirements for sugarbeet.

Current and Potential Biomass Yield

The sugarbeet, unlike the other sugar crops, has been selected for temperate environments and may show limited potential for production in many of the LDC's. Yields in the current sugarbeet-producing countries average 30 tons/ha/yr of millable root. The highest national yield is that of Austria at 63.2 tons/ha/yr (1977-1978).

A serious problem that arises when considering the sugarbeet as a feedstock for alcohol is its susceptibility to pests and diseases. Currently, more research is concerned with enhancing pest and disease resistance than improving yields. Crop rotation frequently is employed to reduce sugarbeet pest populations. This method decreases the quantity and reliability of feedstock supply for the ethanol facility.

TABLE 6. AVERAGE COMPOSITION OF SUGARBEET ROOT

Millable Root	%
Water	78
Solids	22
Soluble Solids	16
Fiber (dry)	6

Juice Constituents	Soluble Solids %
Sugar (sucrose, fructose, and glucose)	78
Salts	22

TABLE 7. SUGARBEET PRODUCTION

Climatic Requirements	-	Temperately adapted; grows well at temperatures from 16-28°C. Non-irrigated production occurs in areas with more than 50 cm of rain per year.
Soil Requirements	-	Grows well in loam to heavy soils. Sugarbeet is tolerant to alkaline and saline soils but grows poorly on acid soils; the ideal pH range is 6 - 7.5.
Length of Growing Season	-	Sugarbeet is a biennial and the range of the growing season is 180-300 days.

Sweet Sorghum and Sweet-Stemmed Grain Sorghum (*Sorghum bicolor* L. Moench)

Botanical Description and Composition*

Like sugarcane, the sorghums are members of the grass family and are often grown in cultivation as a single-stemmed type, but also show great variation in tillering capacity, as determined by both cultivar and plant population[9]. The stem of the plant varies in hgeight from 0.5 to 4 m and, like sugarcane, can asscumulate and store sugar. The stem diameter ranges from 0.5 to 3 cm, the general size tapering from the base to the seedhead.

The number of leaves varies from 10 to 30, according to the cultivar and appear to alternate in two ranks. Leaves of the sorghum plant have long blades ranging from 30 to 135 cm[10] with a width of 1.5 to 13 cm.

The roots of sorghum are divided into a temporary and a permanent system[11]. A single radicle is produced by the seedling, followed by adventitious fibrous roots from the lowest nodes of the stem. The entire system may penetrate to a depth of 1 m with a spread of 1.5 m, depending on soil conditions and cultural practices.

The sorghum inflorescence, or "head", is a somewhat compact or loose panicle. A well-developed panicle may contain as many as 1,000 - 2,000 seeds. As an indication of the variation in seed size, sorghum cultivars range from 44,000 to 60,000 seeds per kilogram[7].

The proportion of total wet stalk to total wet biomass is highly dependent on the type of sorghum (whether sweet or sweet-stemmed grain) and the cultural practices employed, particularly the plant population and the row spacing. A general range for this value is 60 - 80 percent, the sweet sorghums being at the higher end of the range and the sweet-stemmed grain sorghums at the lower. Grain yields will range from 500 kg ha^{-1} with

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* (This description is based on Reference 12.)

the sweet sorghum to approximately 6000 kg ha^{-1} with sweet-stemmed grain sorghum. Tables 8 and 9 highlight the composition of the stalk and grain. Like sugarcane, the component percentages are genetically determined; however, environment and cultural practices influence the composition more with sorghum than with sugarcane.

The sorghum plant, whether sweet or sweet-stemmed grain, has a number of distinctive physiological and agronomic characteristics which increase its potential as a viable multiuse crop over a wide geographic range[12]. Firstly, sorghum exhibits the C_4 (Hatch-Slack) photosynthetic pathway and is therefore quite efficient in assimilating carbon dioxide. Also, sorghum lacks the process of photorespiration and is highly productive, achieving maximum short-term crop growth rates of approximately 51 g m^{-2} ground day^{-1} [13].

Secondly, sorghum utilizes water efficiently. The root system is fibrous and extensive. Ponnaiya[14] domonstrated the existence of heavy silica deposits in the endodermis of the root, forming a complete silica cylinder in the mature roots. This mechanical strength is of great importance in preventing collapse of the system during drought stress. A waxy cuticle covers the above-ground structure to retard drying. Unlike corn, sorghum has the ability to remain dormant during a drought period and then to become active rapidly following moisture reintroduction. The water requirement to produce one kilogram of sorghum dry matter ranges from 250 - 350 kilograms, whereas the requirement for wheat and soybean is approximately 500 and 700, respectively.

Production Requirements

Table 10 highlights the basic production requirements for sweet sorghum.

TABLE 8. AVERAGE COMPOSITION OF SORGHUM GRAIN

Constituent	%
Starch	60.4 - 76.6
Pentosans	1.8 - 4.9
Sugar	0.5 - 2.5
Protein	8.7 - 16.8
Fats and Waxes	1.4 - 6.1
Fiber	0.4 - 13.4
Ash	1.2 - 7.1

Source: Reference 12.

TABLE 9. COMPOSITION OF THE SORGHUM STALK

Sweet	
Water	67 - 80
Solids	20 - 33
Soluble solids	6 - 18
Fiber (dry)	12 - 20
Sweet-Stemmed Grain	
Water	65 - 75
Solids	25 - 35
Soluble solids	4 - 8
Fiber (dry)	20 - 30
Juice Constituents	Soluble Solids (%)
Sweet	
Sugar (sucrose, fructose, and glucose)	67 - 82
Salts	18 - 33
Sweet-Stemmed Grain	
Sugar (sucrose, fructose, and glucose)	40 - 75
Salts	25 - 60

Source: Reference 12.

TABLE 10. SWEET SORGHUM PRODUCTION

Climatic Requirements	-	Tropically adapted; grows well at temperatures from 18-40°C. Non-irrigated production occurs in areas with more than 45 cm of rain per year. Sweet sorghum is highly water-use efficient.
Soil Requirements	-	Grows well on a variety of soils, but best growth is achieved on higher-textured soils, i.e., loams and sandy loams. Sweet sorghum will tolerate considerable soil salinity.
Length of Growing Season	-	The effective season length ranges from 100 - 180 days.

Current and Potential Biomass Yield

Current commercial yields of sweet sorghum range from 33 to 44 tons of millable stalks/ha/crop season[15]. These yields are achieved with the use of older, early maturing cultivars and row spacings of one meter. Also, no hybrids of sweet sorghum have been developed for commercial use; therefore, if an analogy can be drawn between sweet sorghum and corn improvement, sweet sorghum is at the same stage of development as corn was in the 1930's.

Experimental yields of sweet sorghum have reached 120 tons/ha for a 6-month crop in the Texas Rio Grande Valley. Development of sweet-stemmed grain sorghum has occurred within only the past few years but results have been very encouraging[16]. These sweet-stemmed grain sorghum yields have reached 40 to 60 tons of millable stalks/ha (equivalent to 0.8 to 1.2 tons of fermentable sugars) in addition to 2 to 6 tons of starch/ha. It is quite apparent that, if sweet sorghum and sweet-stemmed grain sorghum received the same amount of funding and research interest as corn, sugarcane, or sugarbeet, they could well become useful crops in the LDC's agricultural systems.

SUGAR CROP PROCESSING

Introduction

Six major processing steps are commonly used to produce ethanol from sugar crops, Table 11. In the first step, the sugar containing juice is extracted from the plant material either by mechanical crushing or by crushing/water extraction techniques. The juice is then clarified to remove extraneous plant substances which could foul heat transfer surfaces in the multi-effect evaporation used to concentrate the juice. The additional capital and energy costs associated with juice concentration are in some cases offset by cost savings (i.e., energy and capital) in the down-stream processing steps. Juice concentration and clarification are not universally employed in all processing plants.

The sugar-containing juice is most commonly fermented in batch fermenters using various strains of yeasts. Fermentation times vary from approximately 12 to 40 hours. The fermentation produces a dilute ethanol stream, typically 7-10 percent by volume, which is then distilled to recover the ethanol. In some fermentation processes, the yeast is recovered prior to distillation and recycled to the fermenter. Yeast recycle reduces the fermentation time and increases the productivity of the fermentation.

Distillation to produce anhydrous ethanol involves the use of a third component, such as benzene, which is added to break the ethanol/water azeotrope. Other techniques such as adsorption have been used on a limited scale to produce anhydrous ethanol.

The aqueous stream from the distillation system contains non-carbohydrate components such as soluble salts which were originally present in the sugar juice and the yeast, i.e., when yeast recycle is not employed. Various methods have been developed for disposal of the stillage such as: drying to recover the nutritive value of the yeast, anaerobic digestion to produce methane, and combustion to recover valuable salt components.

TABLE 11. CONVENTIONAL PROCESSING STEPS

- Juice Extraction
- Clarification
- Evaporation
- Fermentation
- Distillation
- Stillage Disposal

Extraction

The first step in the production of alcohol fuels from sugar crops is the extraction of the sugar juice from the stalks. Mechanical disintegration of the stalks is brought about by cutting with knives followed by shredding[17]. The bulk of the juice is expressed by passage through heavily grooved crusher rolls. Sprays of water or thin juice directed on the blanket of bagasse as it emerges from the crushing mill aid in the extraction of the juice. Alternately, a diffuser may be used to extract the sugar from the shredded stalk[18]. Such a diffusion system may be operated in either one of two modes - diffusion of cane and diffusion of bagasse. In the first, the prepared whole cane passes through the diffusion unit. In the second, the stalks pass through one or two sets of mills where 65 percent of the juice is extracted, leaving about 35 percent of residual juice in bagasses to be recovered in the diffuser. Overall, about 97 percent of the sugar content of the crops is recovered. The mat of fiber inside a diffuser acts like a strainer or coarse filter; thus, the diffuser also acts as a clarifier. The juice obtained from the diffuser contains less turbidity and color than the clarified juice obtained by conventional milling.

The mechanical unit operations necessary for juice extraction are very energy intensive. Any process that lowers the energy consumption is likely to substantially reduce the cost of fermentable sugars. A process that has a great potential for attaining this objective is the Tilby Cane Separator Process[19,20]. The sugarcane or sweet sorghum stalk is separated into its individual components prior to obtaining the sugar. A schematic of this fractionation process is shown in Figure 3. Eight to twelve-inch segments of cane are fed end-first and at high speed to the inlet rolls of the machine. These segments are driven by the rolls against a splitting knife to produce two approximately equal cane halves. Each of the two halves then goes through four sets of rolls in series to accomplish

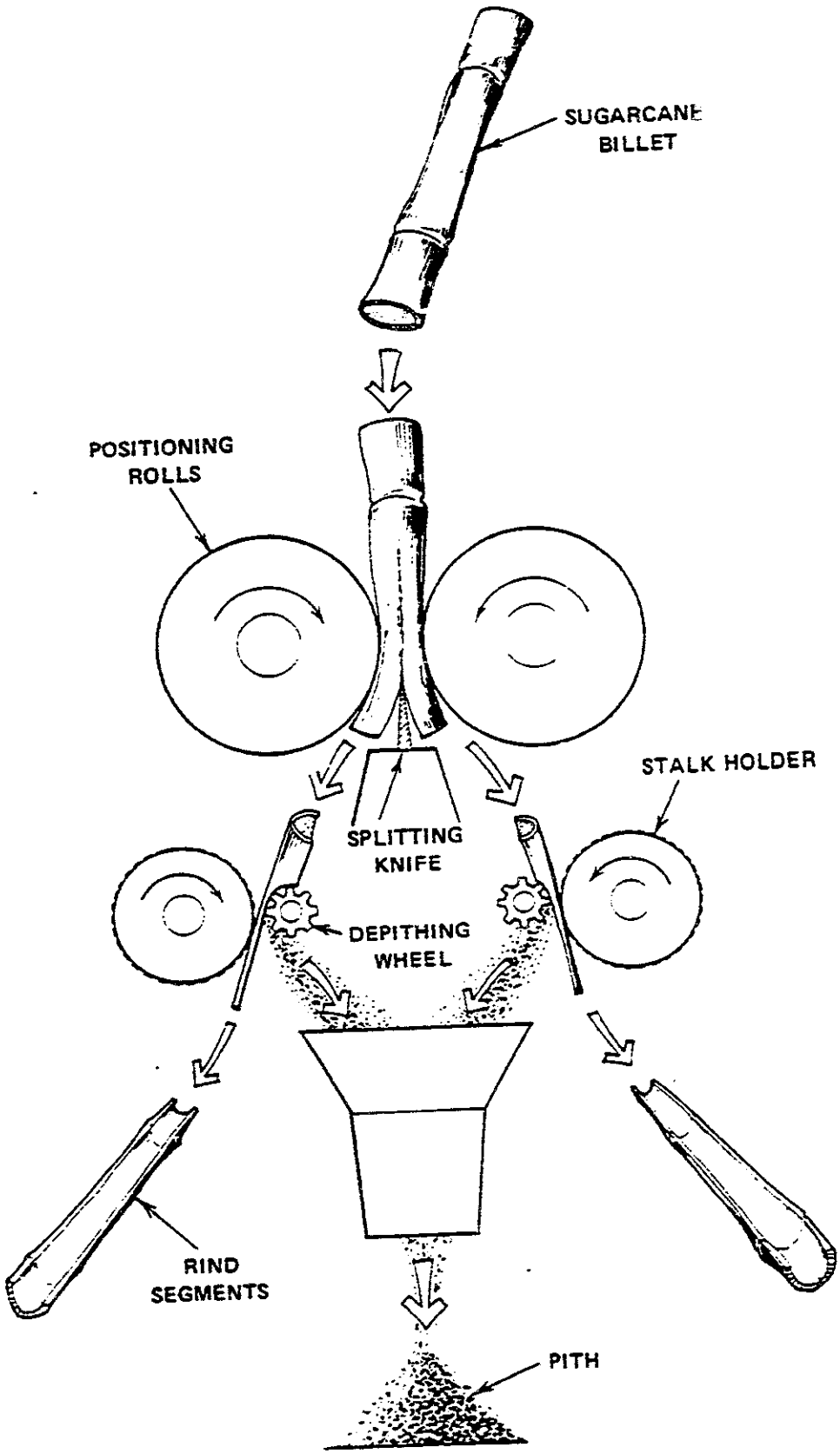

FIGURE 3. TILBY SEPARATOR PROCESS

SOURCE: ANDER-CANE, INC.

the following:

- The first set of rolls press the half cane stalk almost flat.
- The second set of rolls includes a cutting roll which acts to scrape off the interior or core which contains most of the pith. This pith falls onto a belt conveyor which carries it to the sugar extraction process.
- The third set of rolls includes a cutting roll which scrapes off the epidermis cells. The fraction removed here includes wax, coloring matter, and any dirt attached to the outside of the stalk. The epidermis then drops to a conveyor from which it is carried to further processing. The remaining clean rind fiber halves then go to the fourth set of rolls.
- The fourth set of rolls, which are optional, slits the rind material into narrow sticks approximately 1/4 inch by 8 to 12 inches. These sticks then drop to a conveyor by which they are carried to a diffuser for removal of a major portion of the residual sugar.

A preliminary material balance is shown in Figure 4. Sugars may be subsequently extracted from the pith fraction by gentle crushing or in a diffuser. The juice thus obtained is screened and may be sent directly to fermentation. However, in most cases the juice is first clarified by adding lime and heating to precipitate soluble impurities which are settled, together with insoluble solids in a gravity clarifier. The clear juice may then be fermented. If the distillery operation is to be conducted for the whole year, rather than just for the period of the cane harvesting season of five to six months, some or all of the juice may be concentrated by evaporation to a syrup of about 70 percent solids content, which will store economically, without signification deterioration.

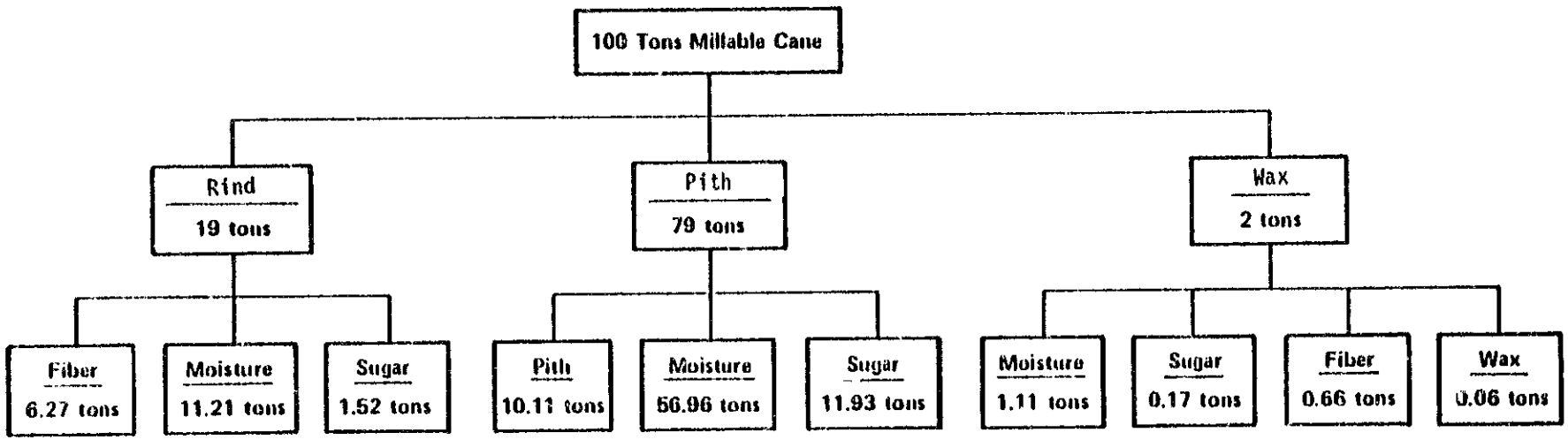

FIGURE 4. MATERIAL BALANCE FOR THE TILBY PROCESS

Studies conducted by SRI International[21] indicate that it may be possible to process enough cane in a 165-day season to permit operation of a facility to make ethanol for 330 days per year. This is accomplished by evaporating half of the juice to a microbiologically staple solution with steam in multieffective evaporators. The other half of the juice is fermented during the grinding season. During the off season, the high test molasses is converted to ethanol, using stored bagasse or purchased fuel. The multiple effect evaporators used for making the syrup could be the same ones employed in making raw sugar when the price of raw sugar is favorable.

An alternative to mechanical processing of stalks for sugar recovery has been proposed by a group of German researchers[22]. The sugar bearing stalks are coarsely chopped for better handling and fed into a reaction vessel, where they are treated by direct injection of low pressure steam. The combined influences of elevated temperature and pressure rapidly disintegrate the sugar containing cells, thus allowing to collect and separate the sugar containing solution from insoluble residues by a simple washing step. Both the heat treatment and washing are done continuously. The solution thus produced can be fermented directly after cooling without any further treatment or purification.

The EX-FERM process under development in Guatemala may eliminate the extraction of sugar from stalks before fermentation[23]. These researchers were able to ferment sugar cane chips directly without any purification or juice extraction. The sugar was fermented in-situ in the stalks. The alcohol thus produced could be subsequently recovered by extraction with water. If the feasibility of such a process on a commercial scale can be demonstrated, it will bring about a significant reduction in the cost of producing alcohol from sugarcane or sweet sorghum.

Fermentation Processes

A summary of the various fermentation processes which have been applied to ethanol production from sugar crops is given in Table 12. Most of the existing plants use batch or semi-continuous fermentation processes on molasses or mixtures of molasses with sugar juices obtained by conventional milling processes. Both conventional and new technologies are discussed in this section of the report.

Conventional Technologies

The process which has been used to the greatest extent commercially is the classical Melle Boinot semi-continuous process which is currently used Brazil[24,25]. The most notable feature of the Melle process is the use of yeast recycle to reduce the fermentation time and increase the productivity of the fermentation. The yeast is separated from the fermented beer by centrifugation and then treated wit. sulfuric acid at pH 2.8. The purpose of the acid treatment is to reduce the potential for bacterial contamination. In Brazil, fermentation times of 12-16 hours have been achieved to produce a final ethanol concentration of approximately 8 percent by volume. The conversion efficiency is approximately 90 percent.

New Technologies

A fermentation process created for the brewing industry by the APV Co. features the use of a tower fermenter[26]. In a tower fermenter, the medium to be fermented is pumped in at the bottom of a vertical column and passes through a dense suspension of yeast cells to the top, which is of expanded diameter. Here, some form of gas separation device is incorporated which allows a volume free from turbulence so that the yeast will settle back into the main body of the tower. The morphological characteristics of the yeast, as well as its fermentation capabilities, are particularly important in this mode of fermentation.

TABLE 12. FERMENTATION SUMMARY

Institution or Process Name	Microorganism	Continuous or Batch	Cell Recycle	Fermentation Time	EtOH Concentration	Conversion Efficiency or Yield	Reference
Sao Paulo State Factories	S. cerevisiae	Classical Melle discontinuous	After treatment at pH 2.8	12-16 hours	7.8 G.L. Wine	90% Pasteur's yield	24,25
Ex-Ferm	S. cerevisiae (115 strains) S. ellipsoideus S. geisenheim 49 S. formosenis S. carlsbergensis	Batch	Yes	1st cycle - 40 hr 2nd cycle - 24 hr	2.0-3.9 gm/100 ml 3.0-5.3 gm/100 ml	24-100% of theoretical	23,27, 28
New Zealand Brewing Process		Continuous series of stirred tank fermenters	Limited use	Total 35 hr residence time	--	--	26,29
APV System		Continuous tower fermenter	No	Less than 4 hr	--	--	26
University of New South Wales	Zymomonas sp.	Continuous or batch	Yes	Specific rates 2-3 times faster than yeast; higher productivity than yeasts	10% v/v in continuous 15% v/v in batch	Higher than yeast	30,31
Oak Ridge National Laboratory	Ditto	Ditto					31
CSIRO Process	Yeast	Batch-substrate fermented as heap of moist solid particles impregnated with yeast	Yeast separated centrifugally for reuse in next batch	16 hr	9.5% (w/w)	92% of theoretical	32,33
University of Canterbury	Yeast	Continuous 3-stage	--	6 hr Total residence time	4-7% (weight)	--	34
Vacuferm	S. cerevisiae Var. euipsoideus; Strain 223	Batch or continuous	No	12-20 hrs	<6% (weight)		35,36, 37,38

A novel approach to the fermentation of sugarcane has been developed in Guatemala. In the EX-FERM process, sugar extraction and fermentation are accomplished in one step[23,27,28]. The cane stalks are first crushed or processed in a Tilby separator to remove the sugar-containing pith. The crushed stalks or pith are then fermented with a minimum amount of added water in a batch fermenter for 40 hours. After this period, the fermented beer is drained off and added to a second batch of fresh cane. After a second fermentation period of 24 hours, ethanol concentrations of 3.0 - 5.3 gm/100 ml were achieved. The process is still experimental and has only been demonstrated at the bench or small pilot plant scale.

Other experimental fermentation processes which are noted in Table 12 are the CSIRO process[32,33] and the Vacuferm process[35,38]. In the CSIRO process, washed sugar beets are first chopped or mechanically pulped into approximately 3-5 mm particles and charged to the fermenter. The pH of the pulp is adjusted with sulfuric acid and the pulp is then mixed with a 10 percent (D.W.) suspension of dried or compressed bakers' yeast. The solid pulp is allowed to ferment for approximately 16 hours without the addition of water. The procedure enables the production of high strength beer (e.g., 9.0 percent ethanol w/w) with considerable capital savings by the elimination of highly expensive diffusion equipment for sugar extraction. The process has to date only been applied at the bench scale with sugar beets. However, it may be possible to extend the concept of semi-solid (i.e., no water addition) fermentation to other sugar crops such as sweet sorghum or sugar cane. The sugar containing pith could be separated using a Tilby separator and fermented in a manner similar to that described above for sugar beets.

It is common in alcohol fermentations that both the growth of yeast and conversion rate of sugar are inhibited by the alcohol formed. In the vacuferm process, this inhibition is removed by conducting the fermentation under reduced pressure and distilling off the alcohol as it is formed. This requires a pressure of 32 mm (30°C) so as not to kill the yeast.

Another approach to achieving higher fermentation rates is the use of microorganisms other than yeast produce ethanol. Specific fermentation rates 2-3 times faster than those typically obtained with yeast have been obtained at the University of New South Wales using <u>Zymomonas</u>[30,31].

While there has been no attempt to describe fermentation technology for feedstocks other than sugar crops in this review, the integration of sugar crops with starch crops such as cassava or with lignocellulose-to-ethanol processes could be advantageous in some situations. For example, starch crops might be used to extend the fermentation season of sugar crops such as sugar cane and sweet sorghum. Fink, et al.,[39] have demonstrated that starch can be added directly to freshly extracted (i.e., not clarified or concentrated) sweet sorghum juice to increase the carbohydrate concentration of the juice and thus produce higher concentrations of ethanol without affecting the activity of amylase enzymes used to convert the starch to dextrose.

It may also be desirable to use the pith fibers or bagasse from sugarcane and sweet sorghum as a feedstock for lignocellulose-to-ethanol processes such as the MIT process[40,41]. In the MIT process, a mixed culture of thermophilic bacteria (Clostridium thermocellum and C. thermosaccharolyticum) is utilized for its ability to hydrolyze and convert both cellulose and hemicellulose to ethanol.

Factors Affecting Yield and Cost

The major factors which affect ethanol production by fermentation are given in Table 13. The most serious operating problem is the potential contamination of the fermentation by undesirable microorganisms which can drastically reduce the yield of ethanol.

TABLE 13. FACTORS AFFECTING ETHANOL PRODUCTION

Factor	Nature of Problem
1. Microorganism characteristic	The type of microorganism used (e.g., bacteria or yeast) and their respective alcohol yields, growth rates and alcohol telerance character determine the size and throughput of the fermenters.
2. Operating mode	The alcohol yield can be substantially increased by recycling the cells. Yield can decrease in tower fermenters due to washout of viable cells.
3. Contamination	In batch fermentations, damage due to contamination of the fermentation broth with undesirable microorganisms can be limited to the particular batch that is being processed. On the other hand, in continuous operation, the contamination can go undetected for a period of time. Problems due to spontaneous genetic transformation of the microorganism can also arise in continuous processes.
4. Diffusion limitation	The transport of the substrate to the immobilized microbial cells is slowed down due to diffusion limitations.
5. Evaporative loss	Loss of ethanol by evaporation when open fermenters are used.
6. Temperature	The rise in fermenter temperature, if the removal of the heat generated during sugar metabolism is not efficient, will reduce alcohol yield.
7. Toxic substances	The physical and chemical processes used to extract fermentable sugars from biomass may produce substances that are toxic to the microorganisms being used for the fermentation.
8. Foaming	Excessive foaming reduces fermenter throughput. The foaming agents may be derived either from the biomass or may be generated by the microorganism.
9. Alcohol recovery	In processes, such as the EX-FERM, all the alcohol that is produced in-situ in the biomass may not be easily recoverable.
10. Sugar concentration	The alcohol content of the product stream is a function of the sugar concentration in the feed to the fermenter. A hydrolysis or extraction process that leads to a low sugar concentration would subsequently provide a product with low alcohol content.

Distillation

The recovery of alcohol from the fermentation broth is the most energy intensive step in the production of alcohol fuels from biomass. The conventional technology[24] encompasses the use of distillation for concentrating the ethanol to hydrous motor fuel grade (96° G. L. ethanol). Two columns are connected in series for such a process. The first column in the series is called the beer still. The dilute alcohol solution from the fermenter is introduced at the top of the beer still. Stillage is withdrawn from the bottom of this still. The overhead is fed to the rectifying column from which 96° G. L. ethanol is obtained. If anhydrous motor fuel grade (99.5^{o} G. L.) ethanol is the desired end product, an additional azeotropic distillation step becomes necessary. Benzene, heptane or cyclohexane are the most common solvents that have been used to form a ternary azeotrope with ethanol and water. The energy requirement for the conventional distillation systems are in the range of 3.5 - 5.5 kg of steam per liter of ethanol produced. Relatively simple changes such as feed preheating, reboiler use, feed point optimization and reflux rate control may reduce the distillation energy requirements by about 30 percent or more. The various alcohol recovery schemes that have been suggested, their energy requirements and their state of development are summarized in Table 14.

The production of alcohol fuels from biomass has tended to show an unfavorable energy balance for most systems studied, partly because of the large energy expenditure necessary for concentration of alcohol. The availability of bagasse at sugarcane processing facilities provides a cheap fuel for ethanol concentration that does not escalate with fossil fuel prices. Sweet sorghum bagasse also provides internally generated fuel. Sugar beets do not have a by-product that corresponds to bagasse.

A scheme for reducing the energy requirements of alcohol distillation has been commercialized by Raphael Katzen Associates International[42]. In this process, the reduction in energy consumption is realized by energy re-use, pressure cascading and waste heat recovery. For motor fuel grade anhydrous ethanol, the steam consumption is 1.8 to 2.5 kg/liter of 99.5^{o} G. L. alcohol; and for hydrous motor fuel grade alcohol, the steam consumption is 1.2 to 1.4 kg/liter of 96° G. L. ethanol.

TABLE 14. SUMMARY OF ETHANOL RECOVERY SCHEMES

System	General Description	Energy Required	Technology Availability	Reference
Sao Paulo State Factories	Two columns in series to 96 G.L.; dehydration with either glycerine or by tri-azeotropic distillation with benzol	Steam at 0.6 to 1 kg/cm^2;	Commercial	24
Atkin's Power Alcohol Process -- ATPAL Process	Vacuum fermentation -- 35% w/w E+OH distillate under vacuum; conventional azeotropic distillation system		Lab stage	43
Katzen Low Energy Pressure Distillation	Three column, pressure cascaded for internal energy recovery (anhydrous); similar two-column system for hydrous E+OH	Anhydrous motor fuel (199 proof) -- 1.8 to 2.4; hydrous motor fuel -- 1.2 to 1.4	Commercial	42
Ladisch and Dick	Atmospheric distillation, cellulose dehydration		Lab stage	44
Ladisch and Dick	Atmospheric distillation, CaO dehydration		Lab stage	44
Maiorella, Wilke, et al	Differential pressure fermentation, vacuum distillation		Lab stage	45
Maiorella, Wilke, et al	Differential pressure fermentation, atmospheric distillation		Lab/pilot	45
Maiorella, Wilke, et al	Vacuum fermentation, atmospheric distillation		Lab/pilot	45
Promon Technology Center -- CTP	Reboiler, feed preheating and optimization		Commercial	45
Construtore de Destilarias DEDINI S.A. --	Live steam distillation		Commercial	45
Sugar Beet -- New Zealand	Double staged beer still			

New Technologies

In the Atkin's Power Alcohol (ATPAL) process, the fermentation is carried on under vacuum so that the alcohol produced is vaporized continuouly[43]. The vaporized alcohol (at approximately 35 percent w/w ethanol) is immediately distilled under vacuum which has the effect of moving the azeotrope from 95.6 percent to 100 percent alcohol at pressure less than approximately 90 mm of Hg (abs.). Processing configuration involving differential pressure fermentation, vacuum fermentation or vacuum distillation and their combinations have been investigated by Maiorelle and his colleagues. Such alternative alcohol recovery schemes do promise a substantial reduction in the energy required for attaining the desired alcohol concentration. However, such processes are still in the laboratory or pilot scale development and are not likely to be commercially available in the near future.

The use of solid dessicants for dehydration of ethanol is also being vigorously pursued. If traditional dehydrants such as calcium oxide are utilized for concentrating ethanol, the steam requirement may be reduced to 1.3 kg/liter of alcohol. New, more adsorptive dehydrants of cellulosic nature could further reduce the steam consumption. In the process being developed by Ladisch and his colleagues at Purdue University, the dilute alcohol solution is first concentrated to about 80° G. L. by conventional distillation at atmospheric pressure. The remainder of the water is subsequently removed by adsorption on to a solid dessicant such as calcium oxide or cellulosic residues. Very encouraging results have been obtained from laboratory experiments[44]. Scale-up studies for such an alcohol recovery system are presently in progress[45].

Energy Balance

One of the most controversial aspects of ethanol production is the question of the overall energy balance. Ethanol cannot be considered as a truly renewable fuel unless the energy contained in a unit of ethanol is equal to or greater than the energy required to produce that unit. However, an energy ratio (Energy Output/Energy Input) less than unity may be acceptable if a premium is placed on the production of liquid fuels, assuming the liquid fuel balance for ethanol production is positive.

Table 15 contains a summary of many of the energy-balance analyses for sugar crops that have been prepared to date. It is interesting to note the wide disparity in the energy estimates resulting from differences in the basic assumptions made in preparing the estimates. For example, some authors do not include certain energy inputs to agriculture such as the energy expended to produce agricultural equipment. Also, some authors do not include excess energy (i.e., above that needed for processing) that could be derived from agricultural residues such as sugarcane bagasse. In general, variations in the processing-energy input result from differences in estimates for certain energy intensive processing steps, particularly distillation. More recent energy-balance analyses tend to reflect improvements in distillation technology which significantly decrease energy requirements.

In general, sugar crops which produce burnable residues as an integral part of the sugar extraction process, such as sugar cane and sweet sorghum, have a more favorable energy balance than other sugar crops or starch crops. All the crops given in Table 15 exhibit a positive liquid-fuels balance if solid fossil fuels such as coal or other biomass resources (e.g., wood) are readily available for supplying the processing-energy input.

TABLE 15. SUMMARY OF ENERGY-BALANCE ANALYSES*

Raw Material	Agriculture			Processing	Total Energy		Overall Energy Ratio	Reference
	Energy Input	Energy Output	Energy Ratio	Energy Input	Input	Output		
Sugar cane	2.14	18.00	8.5	--	--	--	--	46
	--	--	--	--	23.63	26.58	1.13	46
	2.14			0.07	2.21	6.09	2.75	46
	1.90			5.40	7.30	13.30	1.82	46
	40 GJ/ha	116 GJ/ha	2.90	--	--	--	--	46
	80 GJ/ha	416 GJ/ha	5.20	--	--	--	--	46
	--	--	6.05	--	--	--	1.78	46
	2.1	--	--	9.3	11.4	14.0	1.32	47
	23.1 GJ/ha	--	--	--	--	--	2.43	48, 49
	45 GJ/ha	--	8.40	--	--	--	--	50
Sweet sorghum	16.8 GJ/ha	--	--	--	--	--	1.89	48, 49
Sugar beets	--	--	4.1	--	--	--	--	46
	--	--	6.0	--	--	--	--	46
	--	--	1.22	--	--	--	0.56	46
	29 GJ/ha	116 GJ/ha	4.0	--	--	--	--	46
	--	--	1.22	--	--	--	--	46
	0.8	--	--	3.1	--	--	--	50
	38 GJ/ha	--	3.8	--	--	--	--	19
Cassava	--	--	--	--	60.05	26.58	0.44	46
	1.54	27.39	17.73	3.18	4.72	16.78	3.56	46
	21.5 GJ/ha	--	--	--	--	--	1.16	48, 49
Molasses	--	--	--	400-630 Kcal/ℓE+OH	--	--	--	24
	--	--	--	--	--	--	0.97	46

* Energy estimates in GJ/metric ton, dry weight.

Stillage

The untreated effluent from the initial distillation step in ethanol production - called "stillage" - is very high in biological and chemical oxygen demand. Hence it poses a serious pollution threat,if it is discharged into bodies of surface water. The typical composition of stillage from molasses, cane juice and manioc is tabulated in Table 16. This waste stream is produced at the rate of approximately 10-13 liters for each liter of alcohol. The stillage from corn and other grains is a valuable feed by-product because of its protein content. However, the stillage from some other ethanol crops is less valuable and may have to be strictly regulated to avoid damage to aquatic ecosystems.

Various methods for stillage treatment and disposal have been reviewed[50,51]. They fall into four major categories as shown in Table 17.

Where soils are known to be deficient in potassium, untreated stillage can be a valuable source of potash. Where the soil is low in humus matter, as it is in many areas of Brazil, the colloidal organic matter and organic acids in the effluent can increase the microflora of the soil. However, objections have been noted against land application of stillage because of odor, run-off and soil acidity problems. This has also become a concern in Brazil where stillage has been routinely applied to soil at a rate of 650-1000 m^3/Ha, depending upon soil pH. Problems also arise from uncontrolled excessive application rates. In one case, the spraying of stillage on the field gave rise to a proliferation of blood-sucking flies.

Alternately, the stillage may be concentrated by evaporation for any one of the following purposes: animal feedstuffs, direct use on land as a fertilizer and incineration to ash. Four or five effects are normally required for evaporation. A certain degree of evaporator design expertise is essential due to scale formation, mainly from the calcium salts, as the syrup will depend to a large extent on the efficiency of fermentation, the quantity and quality of organic non-fermentables in the substrate and

TABLE 16. COMPOSITION OF STILLAGE FROM VARIOUS SUBSTRATES

Substrate Type	Organic Matter %	CaO %	MgO %	K_2O %	N %	P_2O_5 %	SO_4 %
Molasses	6.34	0.36	0.10	0.78	0.12	0.02	0.64
Cane Juice	1.95	0.07	0.02	0.12	0.03	0.02	0.06
Manioc[a]	2.18	0.01	0.01	0.11	0.04	0.02	0.01

(a) Data from Instituto Nacional de Tecnologia - INT.

Source: Anon., (Instituto Nacional de Tecnologia - Int), Seminario Internacional Sobre Tratamento de Vinhoto (August 1976) Rio de Janeiro.

TABLE 17. STILLAGE TREATMENT METHODS

- Direct use as a fertilizer to the soil
- Evaporation to a syrup, with or without incineration
- Anaerobic digestion for methane generation
- Fungal biomass production

the ash content. An animal feed supplement, which is a fine, free-flowing powder produced by evaporation and drying of the residues from the alcohol fermentation of molasses, is commercially available in South Africa[53]. If the concentrated stillage is incinerated, the heat released from combustion can be used after recovery to provide all the steam for evaporation. Unfortunately, the potassium compounds in the stillage have a low ash fusion temperature, normally below 970°K. Fusion of the ash adversely affects the combustor maintenance and creates a practically insoluble solid with value as a fertilizer. Controlled combustion is therefore essential and investigations using a fluidized bed reactor have been performed[54]. A novel concept in fluidized bed combustion, the multisolid fluidized bed, under development at Battelle, may be suited for the disposal of stillage from sugar crops that also produce bagasse (Figure 5). The bagasse could be burned in the combustor while the thin stillage is fed to the external heat exchanger. Enough high pressure steam is produced by this process to meet all the steam requirements. The feasibility of such a system has already been demonstrated using municipal solid waste as the primary combustor fuel and domestic sewage sludge as the feed to the external direct contact heat exchanger[55].

The BOD of the stillage can be reduced to acceptable levels by anaerobic digestion[56]. By the use of several groups of anaerobic and facultative organisms at an optimum temperature of 32 C (mesophilic), the organic matter is assimilated and broken down, followed by the methanogenic organisms converting the products primarily to methane and carbon dioxide. The gas produced can vary between 580 and 720 liters per kg of BOD removal with a gas purity of 65 percent vol methan at a net calorific value of 6000 kcals/m^3.

A fourth alternative for stillage disposal would be to use it as a substrate for fungal biomass production. Torula yeasts have been grown on molasses stillage in Taiwan since 1973. This method of stillage processing is not very attractive because the resulting effluent still retains a high BOD, necessitating further processing. Moreover, the stillage supplies only the carbon and energy sources for protein growth. Nitrogen and phosphorus must still be obtained from extraneous sources.

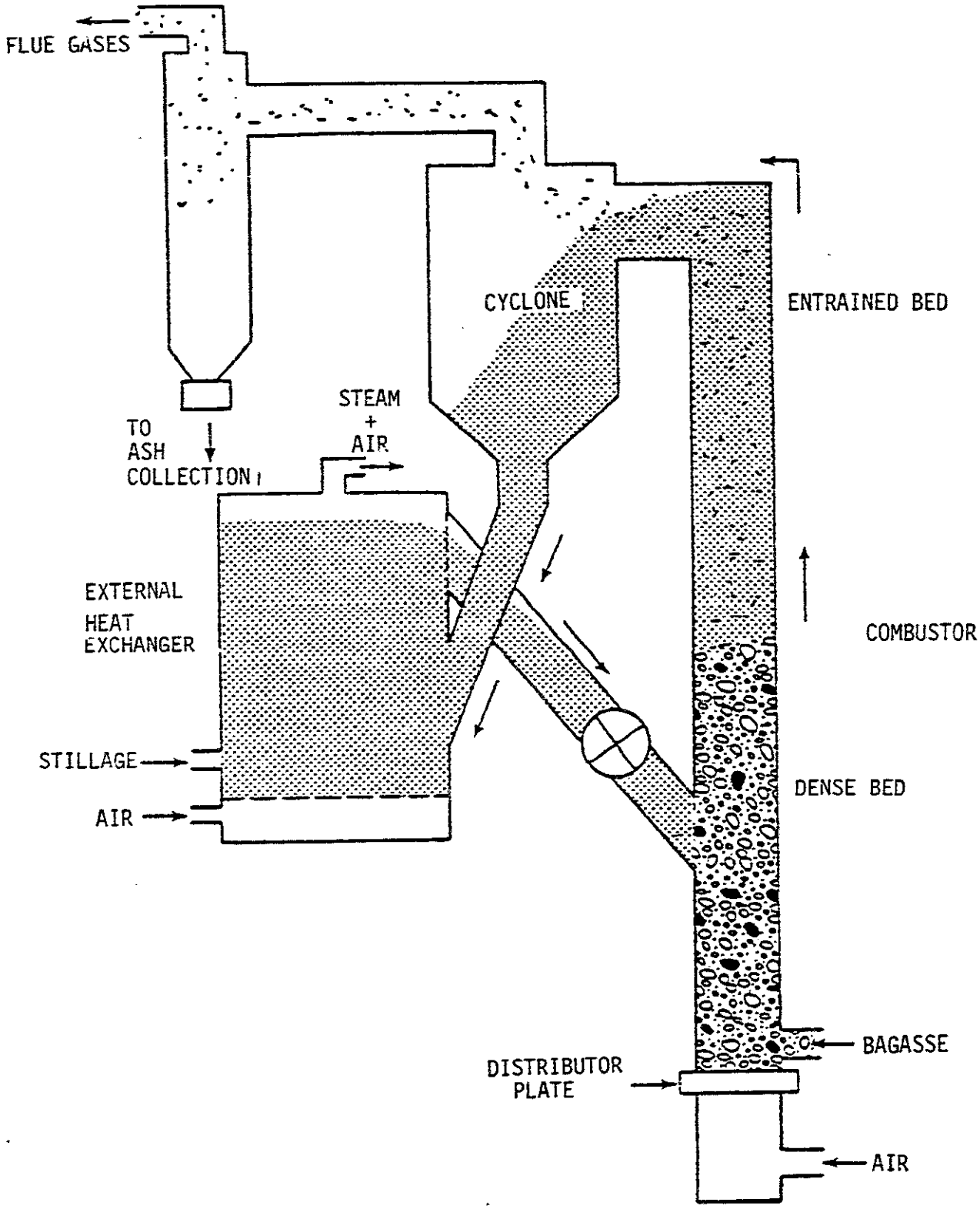

FIGURE 5. BATTELLE'S MS-FBC PROCESS WITH CONTACT EVAPORATION OF STILLAGE

SOURCE: Ballantyne, et al., in Jones, J. L., and Radding, S. B., Thermal Conversion of Solid Wastes and Biomass American Chemical Society, Washington, 1980, p. 111.

All the stillage disposal techniques described earlier are economically marginal at best. It is hoped that some of the emerging fluidized bed combustion technology as well as refined waste disposal methods will make stillage processing a more efficient and economically attractive undertaking.

SUGAR CROPS VERSUS OTHER CROPS AS ETHANOL SOURCES

Neither sugar crops nor starch crops are ideal as sources of ethanol because these carbohydrates are valuable for human food and/or animal feed. Carbohydrate crops grow on high quality land, compared with lignocellulosic crops and aquatic crops. The relative prices of carbohydrate crops and lignocellulosic crops (except for certain tree species that have added value as lumber or plywood sources) reflect this difference. Therefore, if everything else were equal, lignocellulosic crops would be preferred as sources for ethanol over carbohydrate crops.

The reason that fuel ethanol is made from carbohydrate crops and not from lignocellulosic crops is that the state of technology in obtaining ethanol from lignocellulose is not nearly as advanced as is the technology for carbohydrate crop conversion. Lignocellulose in trees and other terrestrial biomass is a complex material containing lignin which cannot be converted to ethanol by any reasonable process, hemicellulose which until recently has resisted conversion to ethanol in high yields, and cellulose which can be converted to ethanol but usually only in yields substantially lower than those obtained for sugar and starch. Recent advances in the conversion of lignocellulose to ethanol which are discussed briefly in the Fermentation section of this report increase greatly the likelihood that ethanol ultimately will be derived from lignocellulose. For example, the MIT process does convert both the cellulose and the hemicellulose in ethanol with little co-production of undesirable by-products. However, this process has only been carried out at the laboratory bench scale and many years will elapse before the process has been commercialized and refined to the point that it can be installed in forested areas of developing countries with assurance that the facilities will operate.

It appears unlikely that the new lignocellulose conversion technology will render obsolete well conceived facilities that use the sugar stalk crops (sugarcane and/or sweet sorghum). If the sugar crop facility is designed so that it can make both raw sugar and ethanol and burn bagasse as its fuel source, then these facilities can be reorganized to exploit the emerging lignocellulose technology. Bagasse is lignocellulose and could be converted to ethanol when the technology for such conversions become available.

Then the facility's fermentation and distillation units could be used for the lignocellulose to ethanol process while the sugar juice is converted to raw sugar instead of being converted to ethanol. Furthermore, this bagasse lignocellulose is likely to be as inexpensive or less than forestry residues because transportation to the sugar mill is covered in the cost of raw sugar. However, it may be necessary to bring in additional sugar crop or forestry biomass to fuel the boilers when part of the lignocellulose is diverted to making ethanol.

Starch crops appear to be desirable transition sources of ethanol and do help the economics of ethanol production by their storage stability that stretches the ethanol production season in countries needing season extension. However, the value of starch materials in alternative uses and the lack of associated lignocellulose puts these crops at an disadvantage.

TYPICAL PLANTS

The following information is provided as a baseline for those initially contemplating entry into ethanol production in developing countries. In practice, most new ethanol plants in developing countries will be add-ons to existing raw sugar factories. The idiosyncrasies of the existing operation will greatly change the venture from typical to atypical.

The state-of-the-art facilities described here were conceived and estimated by F. C. Schaffer and Associates of Baton Rouge, Louisiana, under a subcontract from Battelle Columbus Laboratories in a program that it conducted for the U.S. Department of Energy[57]. The estimates are in 1978 dollars; however, the experience curve in building plants has partially counterbalanced the inflation in equipment costs.

Typical Ethanol-from-Sugarcane Facility

A summary block diagram outlining the steps required to convert sugarcane into anhydrous ethanol is shown in Figure 6. The facility is designed to process 9,000 short tons of sugarcane per day (the design is for 10,000 short tons of cane per day with lost time assumed to be 10 percent). The daily production of anhydrous ethanol is expected to be 140,000 gallons, at a yield of 15.6 gallons of ethanol per ton of sugarcane.

The juice extraction is performed by a conventional sugarcane milling tandum. The extracted juice is clarified using commercially available clarifiers and rotary vacuum filters. The clarified juice is concentrated to about 20 percent total sugars so that economies can be achieved in the distillation step by starting with a 10 percent ethanol concentration in the distillation feedstock.

By using a high yeast concentration, a fermentation time of 18 hours is assumed to be achievable. This fermentation time is definitely shorter than standard U.S. practice and somewhat long by Brazilian standards[24]. To achieve the 12- to 16-hour fermentation times that are obtained in Brazil, the ethanol concentration in the distillation feedstock is allowed to be distinctly under 10 percent. In any event, variations in the fermentation time were found to have only a small effect on the economics because fermentation capacity is one of the less expensive capital items.

Distillation to 95.5° G.L. is performed in a topping/rectifying distillation column. Absolute ethanol is produced by means of the benzene azeotrope method.

The stillage is concentrated to 60 percent brix in a triple-effect evaporator and dried in a rotary dryer. These dried distillers' solubles could be blended with the spent yeast that is recovered from the yeast recycle operation. Although this by-product could be sold, no appreciable credit is taken in the financial analysis, because the costs of marketing and upgrading for sale are likely to equal the sales value.

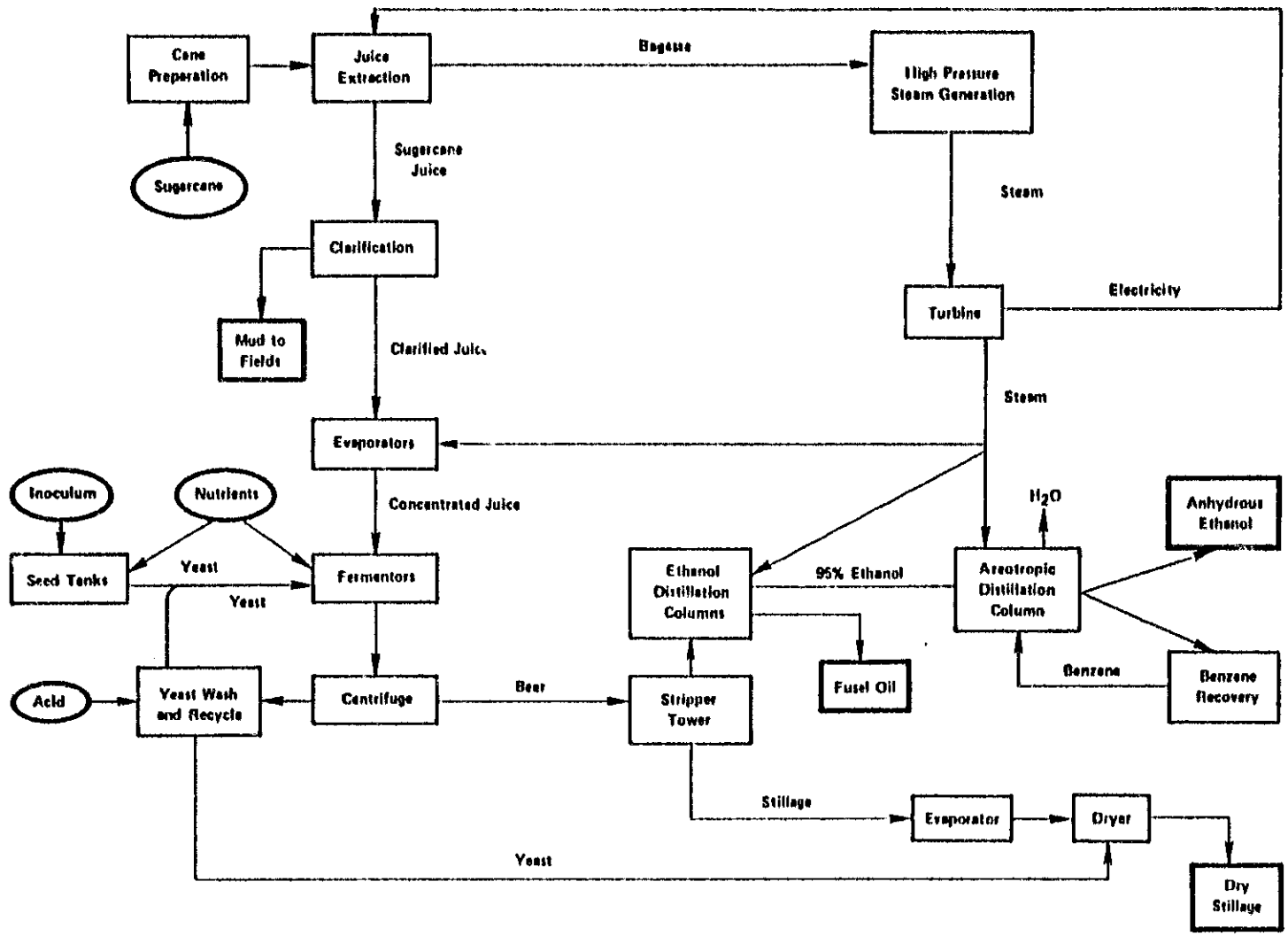

FIGURE 6. ETHANOL FROM SUGARCANE

The bagasse from the milling operations is burned in traveling grate furnaces to provide the total power requirements for the operation. The steam is sufficient for all distillation and evaporation operations. Thus, the facility is energy self-sufficient, even without bringing in trash from the field. At a milling rate of 9000 short tons per day, bringing whole cane instead of millable stalks to the mill could lead to the production of an additional 52,000 pounds per hour of steam for power generation. Using condensing turbo-generators, this additional steam could provide 3,500 kilowatts (kW). The total quantity of salable electricity under these conditions would be about 5,000 kW. With reasonable load factors and a 6-month operating season, the ethanol facility could produce its own electricity requirements and between 10 and 20 megawatts of power for the electric grid.

As shown in Table 18, the ethanol from sugarcane facility would have a capital cost of approximately $60 million.* The fermentation and distillation facilities constitute only about 25 percent of the total capital costs. The capital cost would be over $2 per annual gallon, assuming a 180-day season. The ready fermentability of a 20 percent solution of sugarcane juice accounts for the low capital requirements of the fermentation and distillation units. In contrast, molasses contains constituents that complicate the fermentation and distillation operations.

The facilities for bagasse handling and steam generation cost approximately as much as the facilities for fermentation and distillation. Even more expensive are the facilities for cane handling, milling, and juice processing. Within the fermentation and distillation facilities, the distillation unit is by far the most expensive single item, followed by the centrifuges. The fermentation tanks are among the cheapest pieces of equipment in the entire design.

Financial Analysis

This baseline financial analysis is not intended to substitute for a venture analysis for a company wishing to enter this field. It is

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* In 1978 dollars.

TABLE 18. COST ESTIMATE SUMMARY FOR FACILITY TO MANUFACTURE ANHYDROUS ETHANOL FROM SUGARCANE

Code No.	Description	Cost, $	
	I. Juice Processing and Steam Generation		
00-00-00	Site preparation	535,000	
01-00-00	Cane handling	2,754,000	
02-00-00	Milling	6,844,000	
03-00-00	Juice processing	4,366,000	
06-00-00	Bagasse handling and steam generation	11,084,000	
08-00-00	Electrical generation	2,268,000	
09-00-00	Water processing	628,000	
10-00-00	Chemical preparation	334,000	
11-00-00	Fuel handling	128,000	
12-00-00	Warehousing	223,000	
13-00-00	Plantwide piping	4,400,000	
14-00-00	Plantwide services	3,770,000	
15-00-00	Office and employee facilities	280,000	
		187,000	
16-00-00	Shops	187,000	
	Subtotal		37,801,000
	Indirect Costs		
	Spare parts	1,325,000	
	Field staff and expenses	570,000	
	Small tools and rentals	475,000	
	Temporary facilities	115,000	
	Builder's risk and insurance	795,000	
	Start-up services	475,000	
	Testing services	115,000	
	Contractor's fee	2,380,000	
	Contingency and miscellaneous	1,170,000	
	Subtotal		7,420,000
			45,221,000
	Engineer's cost and fee		3,165,000
	Engineer's travel and living		225,000
	Total juice processing and steam generation cost		48,611,000

TABLE 18 (Continued)

Code No.	Description	Cost in 1980 $	
	II. Fermentation and Distillation		
55-00-00	Mash preparation	310,000	
56-00-00	Fermentation	2,129,000	
57-00-00	Yeast separation and drying	592,000	
58-00-00	Distillation	3,960,000	
59-00-00	Alcohol storage	1,099,000	
60-00-00	Plantwide services	270,000	
	Subtotal		8,360,000
	Indirect Cost		
	Spare parts	295,000	
	Field staff and expenses	125,000	
	Small tools and rentals	105,000	
	Temporary facilities	25,000	
	Builder's risk and insurance	165,000	
	Start-up services	105,000	
	Testing services	25,000	
	Contractor's fee	525,000	
	Contingency and miscellaneous	260,000	
	Subtotal		1,630,000
			9,990,000
	Engineer's cost and fee		700,000
	Engineer's travel and living		50,000
	Total fermentation and distillation		$10,740,000
	III. TOTAL COMPLETE FACILITIES		$59,351,000
	Say		$59,500,000

Source: F. C. Schaffer & Associates, Inc.

designed to highlight the strong and weak points of manufacturing ethanol from sugarcane or sweet sorghum. For the purpose of discussion, it is assumed that a 40 percent equity investment is put up by a company in the private sector and that 60 percent of the capital is borrowed at 9 percent interest. Depreciation is taken at 18 years on the straightline basis. It is assumed that the company seeks a return on equity (not total investment) of 20 percent before taxes. This could represent a return of approximately 10 percent after taxes. Depending on the company and the nature of the government incentives, the estimates provided in this report could be replaced with other estimates.

The goal of the financial analysis presented in this section is estimation of a projected selling price for anhydrous ethanol. This projection is crucial in determining the size of government subsidies and in determining how competitive sugarcane-based ethanol will be with gasoline.

When the processing season is 6 months per year (Table 19) the projected selling price of the ethanol is about $1.50, if cane were $13.50. Recently, cane has sold for as much as $40 per ton in the United States. However, a developing country that cannot market all the sugarcane it produces due to quotas and international agreements has an arbitraty valuation for excess production. Furthermore, the price of raw sugar (and, therefore, sugarcane) fluctuates wildly. A longer processing season, such as could be obtained in many truly tropical countries has quite a favorable impact on ethanol costs (Table 20).

Ethanol from Molasses

Baseline design and economic studies for the conversion of molasses into ethanol also were performed by F. C. Schaffer and Associates in 1978. For illustrative purposes, the product to be sold is 95 percent ethanol, not anhydrous ethanol. An additional $0.03 to $0.05 cost would be incurred in making fuel ethanol. Molasses is a by-product of the manufacture of table sugar. The reader is cautioned against using these designs and calculations in the assessment of high test molasses or dextrose solutions of concentration comparable to that of molasses.

TABLE 19. PROJECTED SELLING PRICE OF ANHYDROUS ETHANOL, 180-DAY SEASON AND CANE AT $13.50/TON (1978 $)

Capital Cost	$59,500,000
Initial equity	23,800,000
Borrowed	35,700,000
Basis: 10 years annual average	
Short tons of cane ground per day	9,000
Gallons of 99.5° GL alcohol produced per day	140,400
Length of processing season, days	180
Gallons of 99.5° GL alcohol produced per year	25,272,000
Short tons of cane ground per year	1,620,000

	$/Gallon of 99.5° GL Alcohol	Annual Amount, $
Production Cost, Before Depreciation and Interest		
Cane cost @ $13.50/gross ton	0.87	21,870,000
Salaries, wages, payroll taxes, employee insurance & retirement	0.09	2,300,000
Chemicals	0.02	486,000
Repair parts	0.06	1,458,000
Insurance	0.02	400,000
Total production cost	1.06	26,514,000
Depreciation and Interest		
Depreciation (18 years straight line)	0.13	3,305,556
Average interest (9%)	0.08	1,992,777
Total depreciation and interest	0.21	5,298,333
Total Production Cost After Depreciation and Interest	1.27	31,812,333
Return on Initial Equity (20% before taxes)	0.19	4,760,000
Projected Selling Price	1.46	--

Source: F. C. Schaffer & Associates, Inc.

TABLE 20. PROJECTED SELLING PRICE OF ANHYDROUS ETHANOL, 330-SEASON AND CANE AT $13.50/TON (1978 $)

Capital Cost	$59,500,000
Initial equity	23,800,000
Borrowed	35,700,000
Basis: 10 years annual average	
Short tons of cane ground per day	9,000
Gallons of 99.5° GL alcohol produced per day	140,400
Length of processing season, days	330
Gallons of 99.5° GL alcohol produced per year	46,332,000
Short tons of cane ground per year	2,970,000

	$/Gallon of 99.5° GL Alcohol	Annual Amount, $
Production Cost, Before Depreciation and Interest		
Cane cost @ $13.50/gross ton	0.87	40,095,000
Salaries, wages, payroll taxes, employee insurance & retirement	0.05	2,500,000
Chemicals	0.02	891,000
Repair parts	0.04	1,782,000
Insurance	0.01	425,000
Total production cost	0.99	45,693,000
Depreciation and Interest		
Depreciation (18 years straight line)	0.07	3,305,555
Average interest (9%)	0.04	1,992,777
Total depreciation and interest	0.11	5,298,332
Total Production Cost After Depreciation and Interest	1.10	50,991,333
Return on Initial Equity (20% before taxes)	0.10	4,760,000
Projected Selling Price	1.20	--

Source: F. C. Schaffer & Associates, Inc.

Molasses is a complex material containing some nutrients needed by yeast and having some constituents that must be removed before yeast can effectively manufacture ethanol. Neither high test molasses nor dextrose solutions contain these other constituents. Therefore, the design equipment and the rate of fermentation differs considerably from that of molasses.

State-of-the-Art Facilities

Figure 7 is a diagram showing the steps in the conversion of molasses into ethanol by fermentation.

Capital cost estimates were conducted for two major cases:

(1) A small mill with a sugarcane processing capability of 3,000 tons per day which yields approximately 18,000 gallons of molasses per day

(2) A typical sub-tropical sugarcane milling operation with a capacity of 10,000 tons per day which would yield approximately 60,000 gallons per day.

These capital cost estimates are summarized in Tables 21 and 22, respectively. Molasses purification is a major cost element. Capital cost per seasonal gallon is much lower than with sugarcane.

Molasses fermentation differs from sugarcane juice fermentation primarily in the following respects:

(1) The molasses requires extensive purification with relatively concentrated sulfuric acid, creating sludge disposal problems

(2) The steam for the facility is provided by the exhaust from the table sugar processing facility that generates the molasses as a by-product. However, a separate package boiler that uses fuel oil also is needed.

(3) The process is much less energy intensive because molasses is a highly concentrated

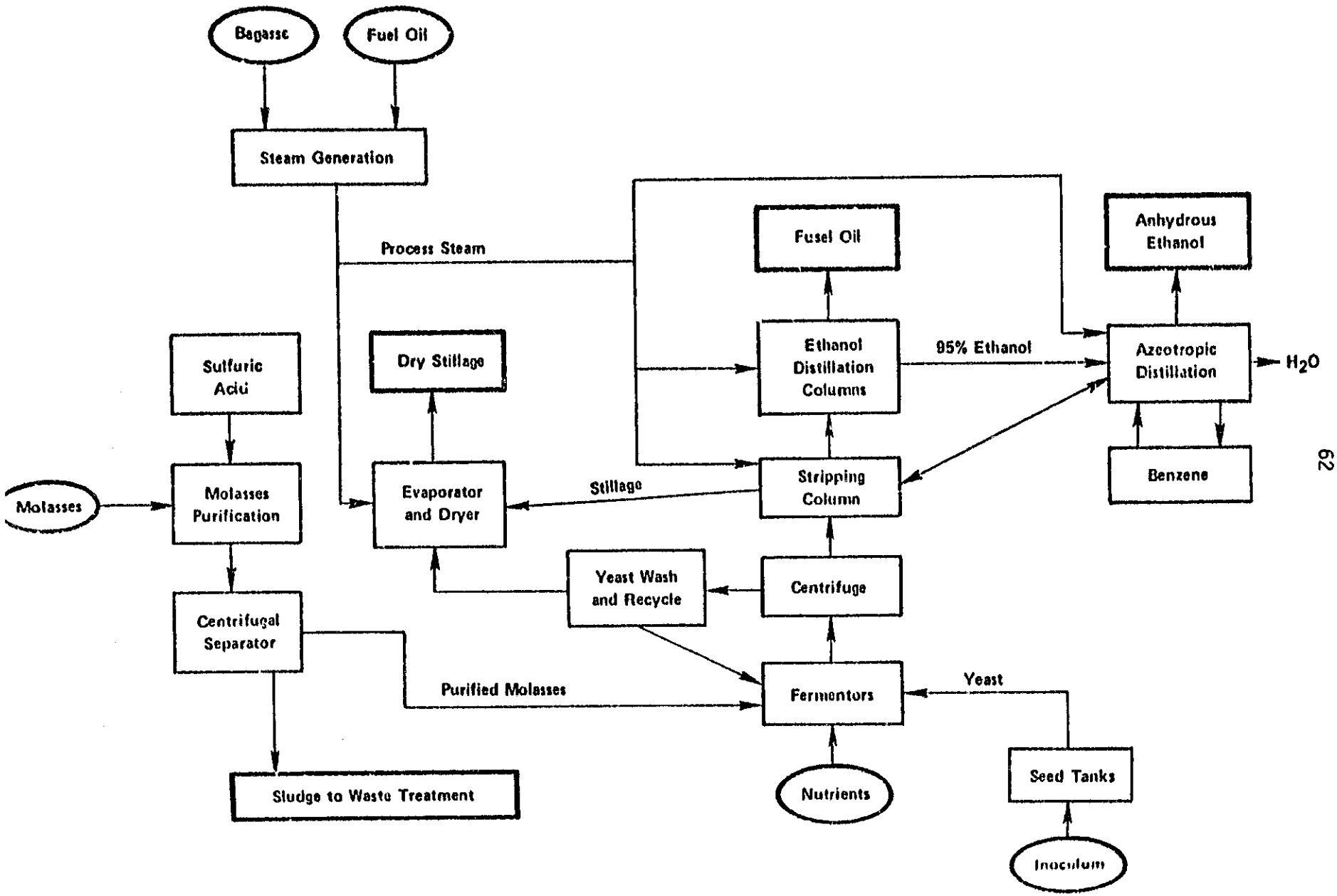

FIGURE 7. ETHANOL FROM MOLASSES

TABLE 21. COST ESTIMATE SUMMARY FOR FACILITY TO CONVERT 18,000 GALLONS OF MOLASSES PER DAY TO 95 PERCENT ETHANOL

Code No.	Description	Cost (1978 $)	
00-00-00	Site preparation	$ 50,000	
53-00-00	Molasses storage	7,000	
54-00-00	Molasses purification	451,000	
55-00-00	Mash preparation	61,000	
56-00-00	Fermentation	248,000	
58-00-00	Distillation	590,000	
59-00-00	Alcohol storage	510,000	
60-00-00	Plantwide services	411,000	
61-00-00	Distillery piping	435,000	
62-00-00	Distillery buildings	198,000	
	Subtotal		$2,961,000
	Indirect Costs		
	Spare parts	$ 100,000	
	Field staff and expenses	60,000	
	Small tools and rentals	50,000	
	Temporary facilities	12,000	
	Builder's risk and insurance	50,000	
	Start-up services	50,000	
	Testing services	15,000	
	Contractor's fee	200,000	
	Contingency and miscellaneous	150,000	
	Subtotal		687,000
			$3,648,000
	Engineers' cost and fee		255,000
	Engineers' travel and living		25,000
	TOTAL PLANT COST		$3,928,000
	Say		$3,950,000

TABLE 21 (Continued)

Code No.	Description	Cost	
To add steam generation and fuel handling			
06-00-00	Steam generation	$175,000	
11-00-000	Fuel handling	64,000	
	Subtotal		$ 239,000
	TOTAL PLANT COST		4,167,000
	Say		$4,200,000

Source: F. C. Schaffer and Associates.

TABLE 22. COST ESTIMATE SUMMARY FOR FACILITY TO CONVERT 60,000 GALLONS PER DAY OF MOLASSES TO 95 PERCENT ETHANOL

Code No. 22	Description	Cost	
00-00-00	Site preparation	$ 100,000	
53-00-00	Molasses storage	13,000	
54-00-00	Molasses purification	825,000	
55-00-00	Mash preparation	90,000	
56-00-00	Fermentation	687,000	
58-00-00	Distillation	1,042,000	
59-00-00	Alcohol storage	718,000	
60-00-00	Plantwide services	514,000	
61-00-00	Distillery piping	550,000	
62-00-00	Distillery buildings	251,000	
	Subtotal		$4,790,000
	Indirect Costs		
	Spare parts	$125,000	
	Field staff and expenses	70,000	
	Small tools and rentals	60,000	
	Temporary facilities	15,000	
	Builder's risk and insurance	100,000	
	Start-up services	60,000	
	Testing services	15,000	
	Contractor's fee	300,000	
	Contingency and miscellaneous	150,000	
	Subtotal		$ 895,000
			$5,685,000
	Engineers' cost and fee		400,000
	Engineers' travel and living		30,000
	TOTAL PLANT COST		$6,115,000
	Say		$6,125,000

TABLE 22 (Continued)

Code No. 22	Description	Cost	
To add steam generation and fuel handling			
06-00-00	Steam generation	$ 804,000	
11-00-00	Fuel handling	119,000	
	Subtotal		$ 923,000
	TOTAL PLANT COST		7,038,000
	Say		$7,050,000

Source: F. C. Schaffer and Associates.

raw material, whereas sugarcane juice needs to be evaporated to approximately 20 percent concentration

(4) Molasses is a storable material so that extended operations can be undertaken even in short season areas.

There are many differences between molasses and sugarcane juice, even though the chemical composition of the fermentable sugars is the same for both products.

Financial Analysis

The favorable effects of a long processing season that supplies energy self-sufficiency is shown in Table 23. With molasses available at the facility for $0.18 per gallon and with a 150-day per year processing season, the projected selling price of 95 percent ethanol would be approximately $0.90 per gallon. With molasses now selling for approximately $0.65 per gallon, the selling price of ethanol would have to be $2.17 per gallon to be equivalent to the 1978 case in attractiveness. However, many sugar factories in developing countries are not able to export to the West European animal feed markets that pay the attractive prices for molasses. Also, the price of molasses fluctuates. Therefore, it may still be good policy to make ethanol from molasses.

TABLE 23. PROJECTED SELLING PRICE OF 95 PERCENT ETHANOL, 150-DAY SEASON USING 60,000 GALLONS PER DAY OF MOLASSES (1978 $)

Capital Cost	$6,525,000
Initial equity	2,610,000
Borrowed	3,915,000
Basis: 10 years annual average	
Gallons of molasses used at 80° Brix per day	60,000
Gallons of 95° GL alcohol produced per day	22,223
Length of processing season, days	150
Gallons of 80° Brix molasses used per year	9,000,000
Gallons of 95° GL alcohol produced per year	3,333,450

	$/Gallon of 95° GL Alcohol	Annual Amount, $
Production Cost, Before Depreciation and Interest		
Molasses values @ 18¢/gallon	0.49	1,620,000
Operating labor cost (3 men/shift at $7/hr. + 20%)	0.03	90,720
Electrical power cost @ 1.2 KWH/gal. (1 KWH = $0.02)	0.02	80,003
Supplies, chemicals, etc. ($0.02/gal.)	0.02	66,669
Maintenance cost	0	12,000
Fuel cost (at 30¢/gal.) and 0.72 gals./gal. alcohol	0	0
Total production cost	0.56	1,869,392
Depreciation and Interest		
Depreciation (18 years straight line)	0.11	362,500
Average interest (9%)	0.07	218,536
Total depreciation and interest	0.18	581,036
Production Cost After Depreciation and Interest	0.74	2,450,428
Return on Initial Equity (20% before taxes)	0.16	522,000
Projected Selling Price	0.90	--

Anticipated Economics

Capital Costs

Estimates of the capital costs for plants to produce ethanol from sugar cane, molasses, and sugar beets are given in Table 24. On an annual basis (assuming 180 days/yr operation), the capital costs range from $0.28 to $0.90/liter/yr.* The cost of a sweet sorghum-to-ethanol plant would be similar to that for a sugar cane facility.

A number of factors affect the capital costs of ethanol plants:

- Type of Feedstock
- Plant Size
- Location

The effect of plant size is shown in Table 25 which contains estimates from a recent World Bank study[58]. The estimates show significant economies of scale over the annual (180 da/yr) capacity range of 3.5 million to 43 million liter per year.

The World Bank estimates given in Table 25 were based upon costs achieved in Brazil which were increased by 25 percent to reflect local conditions in developing countries. Factors such as the availability of local equipment and engineering services, local construction and implementation capabilities, etc., would have an appreciable effect on capital costs.

Production Costs

A summary of ethanol production cost estimates for several feedstocks are given in Table 26. In general, raw material costs constitute approximately two-thirds or more of the total production cost.

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* This is a measure of capital intensity. The facility would be amortized over a period of 10-20 years.

TABLE 24. CAPITAL COSTS

Feedstock	Capacity (liters/da)	Capital Cost (MM$)	Year of Cost Estimate	Reference
Sugar Cane	284,000	21	'77 dollars in 1985	59
Sugar Cane	525,000	60	'78	57
Sugar Cane	785,000	127	'76	28
Sugar Cane	120,000	7.6 - 14.3	'79	58
Molasses	120,000	6.1 - 11.4	'79	58
Sugar Beet	82,000	4.6	'80	34

TABLE 25. EFFECT OF PLANT SIZE ON CAPITAL COSTS

Annual[a] Capacity (million liters)	Capital Costs ($/liter/yr)
3.5	0.71
23	0.43
43	0.36

[a] 180 days/yr

TABLE 26. PRODUCTION COSTS

Raw Material	Raw Material Cost (¢/l)	Processing Cost (¢/l)	Total Cost (¢/l)	Year of Cost Estimate	Ref.
Sugar Cane	18.16	9.45	27.61	Nov., '77	61
Sugar Cane	22.41	7.74	30.15	Jun., '77	61
Sugar Cane	16.85	3.57	20.42	'75	61
Sugar Cane	18.35	12.15	30.50	Nov., '77	61
Molasses	11.48	3.22	14.70	Jan., '77	61
	-	-	18.76	March, '78	61
Sugar Beet	15.64	-	-	Jun., '77	61
	16.57	7.90	24.47	April, '78	61
	-	-	30 - 50	'80	34
Sweet Sorghum	22	11 - 24	33 - 46	Nov., '80	62
Cassava	10.08	6.89	16.97	'75	61
	-	-	42.00	'75	61

Processing costs are very sensitive to the length of the processing season as shown in Table 27. One method for extending the processing season is to process multiple sugar crops (e.g., sugar cane and sweet sorghum) at the same processing facility. Scantland, et al., have recently assessed the potential for using sweet sorghum to extend the processing seasons for sugar cane and sugar beets in the U.S.[63].

TABLE 27. PRODUCTION COST OF ETHANOL FROM SUGARCANE AS AFFECTED BY LENGTH OF PROCESSING SEASON ($/LITER)

	LENGTH OF SEASON, LITERS OF 99.5° ALCOHOL		
Item	90 Days, 45.3 MM Liters	180 Days, 95.5 MM Liters	330 Days, 174.8 MM Liters
Sugarcane	$0.40	$0.40	$0.40
Operating Cost	0.07	0.05	0.03
Depreciation and Interest	0.11	0.06	0.03
Total	$0.58	$0.51	$0.46

Source: See Reference 19.

PLANNING CONSIDERATIONS

The decision to enter into the production of ethanol requires a rather complex business analysis by LDC planners because opportunities for export sale of raw sugar and molasses are foregone in exchange for reduced dependence on imported oil.

The scenario that follows is fictional, but it illustrates the thought process that development planners in LDC's might use in considering ethanol from sugar crops as an alternative for obtaining a measure of energy independence. The information used in this initial evaluation generally is available in LDC's, although usually it must be sought from a number of separate government agencies.

First, the planners estimate the demand for gasoline in the future time period under consideration. In the fictitious LDC under consideration, there are approximately 0.5 million automobiles that obtain a fuel economy of 5 km per liter of gasoline. If the automobiles average 15,000 km per year, each automobile requires 3000 liters of fuel per year. The automobile fleet of 0.5 million vehicles requires approximately 1.5 billion liters of fuel per year. The planners expect a price of $0.50 per liter for imported gasoline, an annual cost of $750 million. Assume a goal of replacing 10 percent of gasoline imports with ethanol from sugarcane.

Ethanol Option

Ten percent replacement of 1.5 billion liters requires production of 150 million liters of ethanol. The planners next calculate the number of hectares of sugarcane land required to achieve an annual yield of 150 million liters of ethanol by the following procedure. One metric ton of fermentable sugars can generate about 620 liters of ethanol by fermentation. The planners discuss the composition of local sugarcane with the processing company, and they find that the sugar yield is approximately 6 tons per hectare. [This 6 tons is contained in a total yield of sugarcane on a net basis of 60 metric tons per hectare.]

Therefore, each hectare yields 3720 liters of ethanol. It follows that approximately 40,000 hectares could provide the 150 million liters of ethanol.

The planners find that the sugarcane processing season is 6 months per year, and the land devoted to sugarcane is concentrated in a few areas. Through discussions with engineering companies, the planners find that ethanol facilities are available in a wide range of sizes. They decide that ethanol could be produced by seven facilities, each of which would have a capacity of 120,000 liters per day. If the sugarcane lands were more dispersed geographically, it might be necessary to have more corresponding smaller ethanol facilities to satisfy the logistic constraints.

The cost of ethanol production is estimated as a function of sugarcane cost at the selected capacity of 120,000 liters per day over a 6-month processing season. For the purpose of discussion, the planners are assumed to have found that operating costs and capital recovery charges total $0.10 per liter for an add-on ethanol facility at an existing sugar mill and $0.20 per liter at a "grassroots plant" that requires construction of the milling and steam facilities, as well as the ethanol facilities. If sugarcane were free, these charges for capital and operations would require a revenue of $6 per ton of sugarcane to support the ethanol plant in the add-on case and $12 per ton of sugarcane in the grassroots case. However, sugarcane is not free, and Figure 8 shows how much the venture can afford to pay for sugarcane while still obtaining fuel for less than the $32 that imported gasoline would cost. This venture could afford to pay $26 per ton for sugarcane, if it is an add-on facility or $20 if it is grassroots. An increase in gasoline price due to shortages or cartel action significantly increases the affordable sugarcane cost from $26 per ton to about $35 per ton.

The planners find that the ethanol facilities could be purchased for approximately $40 million each. In the typical future years under consideration, gasoline is expected to be available for $0.50 per liter and the price would be subject to a high rate of inflation. Thus, the $40 million investment would save $75 million in foreign exchange every year, assuming that 150 million liters of gasoline did not need to be imported into the LDC.

The $40 million investment would apply only if facilities to process the sugarcane into sugarcane juice were already in place. If new processing facilities to mill the sugarcane and to convert it to ethanol were required, the investment might be on the order of $120 million. Furthermore, it may be necessary to clear, grade, and otherwise prepare the land for sugarcane production. Investments in harvesting and cane transport equipment may also be necessary. In that event, the investment in the agricultural part of the venture might equal or exceed the investment in the processing and conversion aspects.

Raw Sugar Option

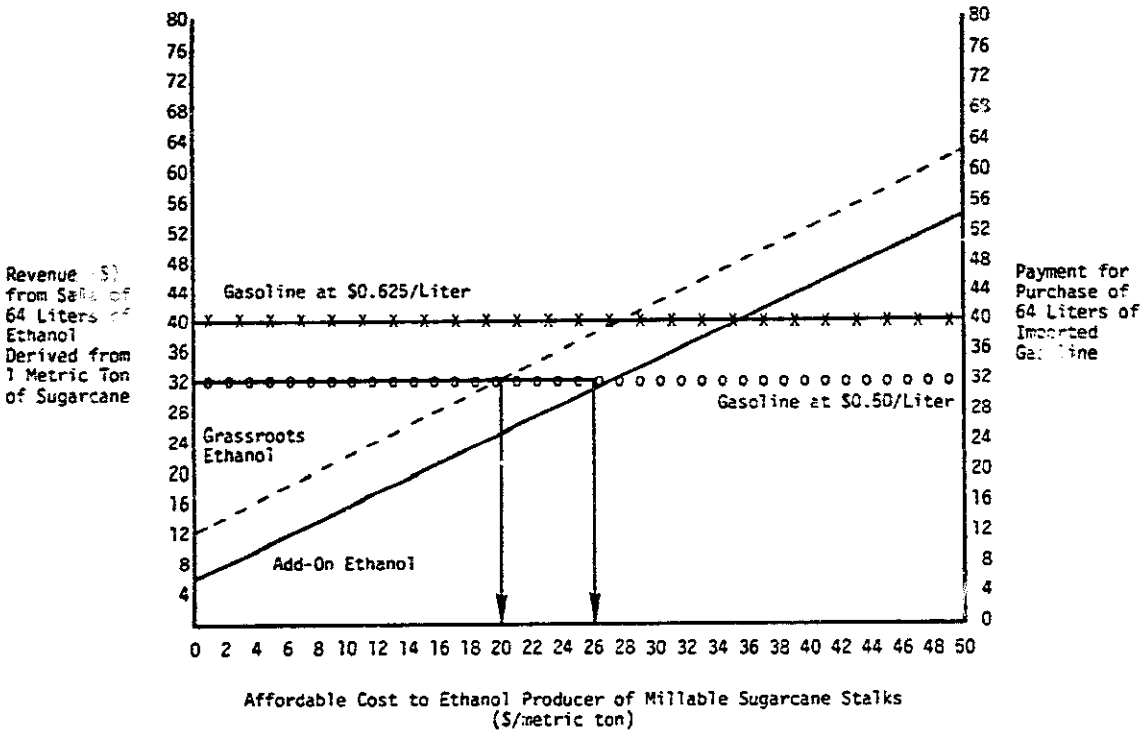
If the country used the 40,000 hectares to make raw sugar instead of ethanol, approximately 240,000 metric tons of this commodity might be produced for domestic and foreign sales. At January 1981 prices, which have not been normal for the sugar industry, this raw sugar would be worth more than $100 million. At the depressed prices that existed a few years ago, the raw sugar would have been worth $25 million. Development planners need to determine whether the production of raw sugar and/or ethanol is desirable, based on the specific circumstances that apply in each country.

The development planners of this hypothetical country observe that this tropical country has net raw sugar imports of 50,000 metric tons per year which are quite costly in foreign exchange when prices triple as they did during the last few years. The country's population of 40 million consumes relatively little sugar per capita now, but could consume approximately 800,000 tons per year when economic development reaches 80 percent that of the industrialized nations. Therefore, the development planners select a strategy in which the expansion of sugarcane land at the very minimum reduces imports of raw sugar to zero and which provides flexibility for increasing either raw sugar production or ethanol production depending on the relative cost of raw sugar and petroleum, taking into account opportunities for soft currency loans, credit terms, and similar considerations.

Tradeoff Between Options

The development planners of this country derive several graphical representations to portray the tradeoffs between ethanol production and sugar production. The planners estimate that the cost of imported gasoline will be somewhat over $0.50 per liter by the time that the new sugar conversion units could begin operations (Figure 8). A metric ton of this country's sugarcane could yield enough ethanol to replace $32 worth of gasoline. Therefore, this country could afford to construct a grassroots ethanol facility and pay $20 per ton for its sugarcane to displace this imported fuel. If sugar milling equipment were already available, the capital costs would be substantially lower. Therefore, the venture could afford to pay approximately $26 per ton for sugarcane to displace imported gasoline.

The planners consider the alternative of selling raw sugar in the international market and using the hard currency thus obtained to purchase gasoline (Figure 9). The selling price of raw sugar is set in the world commodity markets and is not a function of the cost of sugarcane in this LDC. Rather, the selling price of sugarcane paid by the mill operator is determined by a formula contract between the mill and the grower. For the sake of simplicity, the formula is assumed to be that each receives half of the revenue from the sale of the raw sugar at the world price. On this basis, when the selling price of raw sugar is $0.27 per pound (about $600 per metric ton), the sugar in one ton of sugarcane (10 percent sugar content) would sell for $60. Therefore, the grower would receive $30 per ton of sugarcane. As can be seen in Figure 9, enough hard currency is generated at all prices above $320 per ton of raw sugar to permit purchases of gasoline. This corresponds to purchase of sugarcane at about $16 per metric ton. The specific formula would vary from country to country and over time. For example, the formula does not give the mill appropriate credit for the value of the bagasse as a fuel and for production of alternative products. However, this simplified case illustrates the strategic options involved.



Assumptions

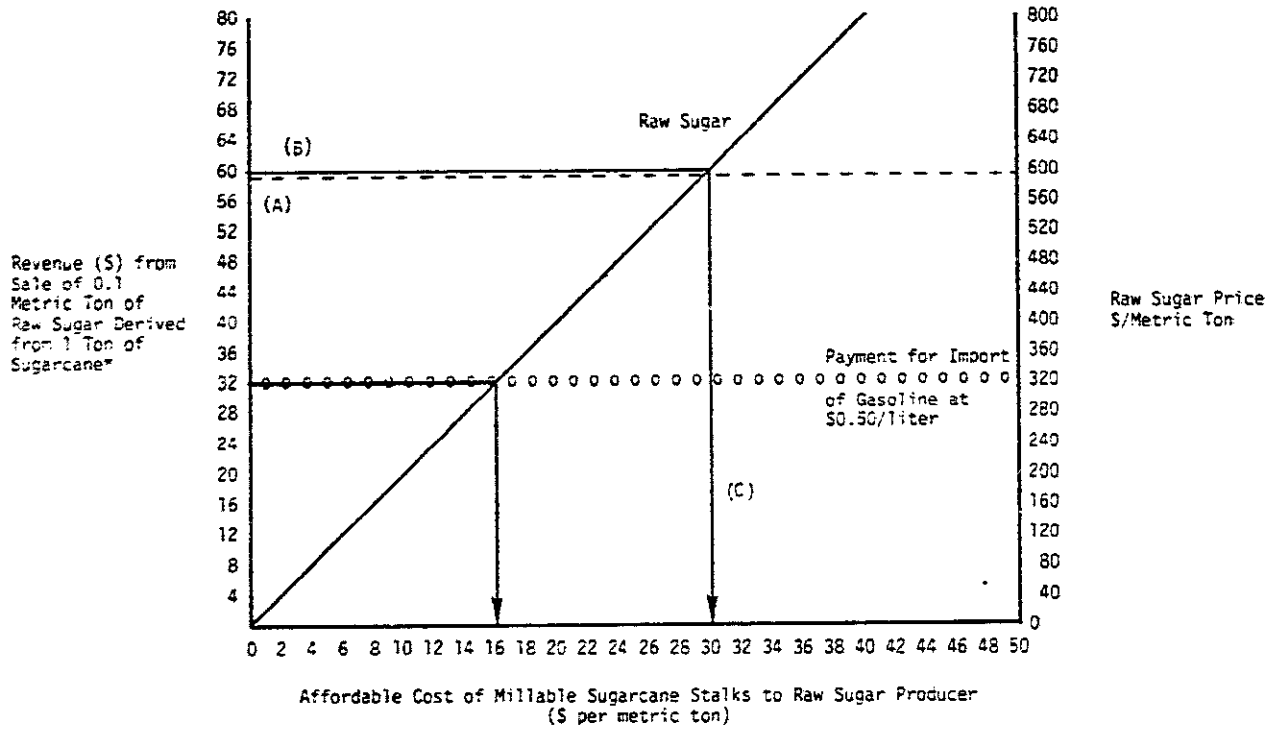
(1) Yield of ethanol is 64 liters per metric ton of sugarcane

(2) Imported gasoline and ethanol sell for $0.50/liter

(3) Add-on ethanol cost ($/liter) = grassroots cost - $0.10 ($/liter)

(4) Grassroots ethanol cost ($/liter) = $\frac{\text{millable stalk selling price (\$/metric ton)}}{\text{64 liter/ton}}$ + $0.20

FIGURE 8. COMPARISON OF REVENUE FROM ETHANOL WITH PAYMENT FOR IMPORTED GASOLINE



Assumptions

(1) Yield of raw sugar = (0.1) millable stalk weight

(2) No payment for bagasse values

(3) Raw sugar revenue requirement ($/ton) = (20) millable sugarcane selling price

To find the affordable cost of sugarcane, follow steps (A), (B), (C) in that order.

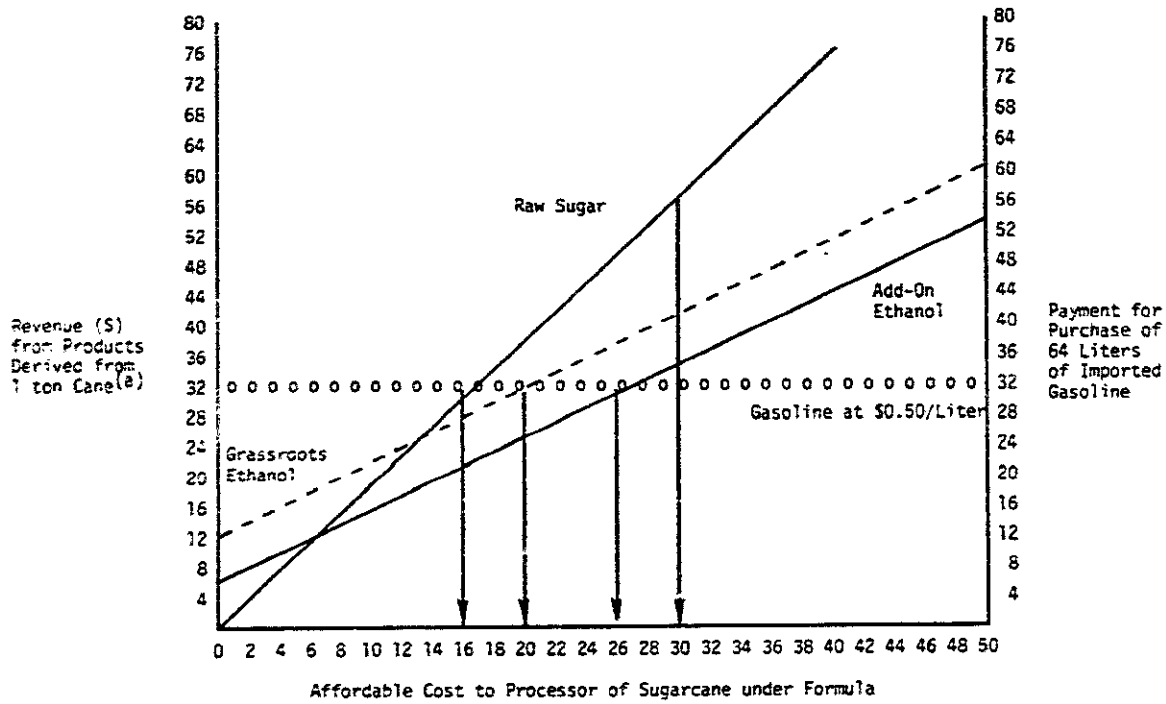
* Based on world raw sugar price

FIGURE 9. AFFORDABLE COST OF SUGARCANE AS A FUNCTION OF WORLD RAW SUGAR PRICE

Which is the better approach: ethanol production or raw sugar production? Figure 10 provides some insight into this incredibly difficult question. At low world raw sugar prices (under $320 per ton in this example), ethanol can still provide an economical substitute for imported gasoline. It can do so and pay rather generous prices for sugarcane which is good for the LDC's agricultural sector. However, sale of raw sugar outstrips ethanol by far in good times for sugar. The planners may consider that addition to raw sugar capacity is speculating on high prices for sugarcane while investment in ethanol is speculating on high petroleum prices. Viewed in this way, ethanol is a conservative investment.

In this example, the planners set the gasoline import costs at a certain static level. However, the potential selling prices are likely to increase over time and there may be periods of nonavailability. These factors would have to be taken into account in a strategic planning study.

The preceding discussion concerns the price that the raw sugar or ethanol producer could afford to pay for millable sugarcane stalks. Actual sugarcane production costs are highly site specific and vary widely from year to year as a function of the weather. Irvine[4] has reported the cost of sugarcane delivered to the nearby mill (Table 28). These costs need to be adjusted for inflation. The breakdown of these total costs into the major unit operations requires a site-specific study. The data developed through the cooperation of the USDA, various state universities, and Battelle-Columbus exemplify a format that an LDC could employ (see Table 29).



Assumptions

(1) Yield of raw sugar = (0.1) millable stalk weight

(2) No payment for bagasse values

(3) Raw sugar revenue requirement ($/ton) = (20) millable sugarcane selling price

(4) Grassroots ethanol cost ($/liter) = $\frac{\text{millable stalk selling price (\$/metric ton)}}{\text{64 liter/ton}}$ + $0.20

(5) Add-on ethanol cost ($/liter) = grassroots cost - $0.10 ($/liter)

(6) Imported gasoline and ethanol sell for $0.50/liter

(7) Yield of ethanol is 64 liters per metric ton of sugarcane

(a) Based on millable sugarcane cost for ethanol and prevailing world raw sugar price

FIGURE 10. COMPARISON OF ETHANOL AND RAW SUGAR VS GASOLINE IMPORT OPTIONS

TABLE 28. COST OF PRODUCING SUGARCANE IN SELECTED COUNTRIES AND YEARS[a]

Country	Year	Cost/m Ton at Mill	Cost/ha/yr
		$US	$US
Brazil	1977	11.17	553
Colombia	1976	8.90	1942
India	1975	12.87	644
Philippines	1975	22.54	857
Thailand	1975	14.78	627
United States:			
Florida	1977-1978	17.41	1543
Hawaii	1977-1978	19.01	4628
Louisiana	1977-1978	19.82	1247
Texas	1977-1978	18.42	1652

(a) Data for Brazil, Colombia, India, Philippines, and Thailand from "World Sugar: Capacity, Cost and Policy".

Source: Data for U.S. calculated from 1977 yields of cane and sugar for the three states, and from "Sugarbeet and Sugarcane Production Costs in the United States Projected to 1978-1979", by T. W. Little, P. L. Hoff, and L. Angelo, CED, ESCS, USDA, unpublished.

TABLE 29. ESTIMATED COSTS OF PRODUCING, HARVESTING, AND TRANSPORTING SUGARCANE IN LOUISIANA, 1978 CROP

	Dollars Per Hectare
Planting & Cultivating	
Labor	82
Seed Cane	46
Fertilizer	48
Other	60
Total	236
Harvesting & Transportation	
Labor	55
Transportation	95
Other	7
Total	157
General Overhead	
Labor	153
Lubricants	27
Insurance	45
Depreciation	77
Taxes	14
Interest on Operating Capital	30
Other Materials	146
Miscellaneous	40
Total	532
Total costs, excluding land charge	925
Land charge	210
Total costs, including land charge	1,135
Harvested yield, metric tons fresh weight	54[a]
Total costs per metric ton sugarcane	$21.02

Source: Estimated by Battelle's Columbus Division, in cooperation with U.S. Department of Agriculture and Louisiana State University: E. S. Lipinsky, et al., "Sugar Crops as a Source of Fuels, Volume I: Agricultural Research", Report No. TID-29400/1 (NTIS), July 31, 1978.

(a) Millable cane.

FUEL ETHANOL

The advantages of fuel ethanol to displace imported petroleum products and to increase octane has been thoroughly documented. However, it is desirable to review briefly the fuel properties and to present some information on the storage and safety aspects of fuel ethanol that are important but frequently overlooked. The following discussion makes use of information developed recently by the Solar Energy Research Institute (SERI) for a document entitled "A Guide to Commercial Scale Ethanol Production and Financing". Although this document pertains almost exclusively to corn grain-based ventures, it has valuable information for all contemplating entry into ethanol production.

Ethanol Properties in Automotive Fuels

As shown in Table 30, ethanol differs markedly from both gasoline and diesel fuel. Its octane rating is substantially above gasoline and it has substantial merits as an octane booster, compared with tetraethyl lead which is considered an environmental hazard.

When ethanol is distilled initially, the product contains approximately 5 percent water. The hydrated ethanol is not suitable for gasohol (approximately 10 percent ethanol — 90 percent gasoline) because phase separation would occur. Phase separation is undesirable because the engine fails to perform frequently and is subjected to corrosion. However, engines can be operated on fuel ethanol containing 1 percent to 20 percent water. Ethanol-only engines are being installed in Brazilian vehicles in a program to boost ethanol consumption beyond the gasohol level. Such major automobile manufacturers as Volkswagen, Fiat, and Ford are manufacturing such engines.

The production of anhydrous ethanol requires an additional processing step (azeotropic distillation) which is energy intensive. Azeotropic distillation also adds to the capital cost of the facility. However, the anhydrous ethanol can be blended with gasoline and used in conventional engines.

TABLE 30. COMPARISON OF ETHANOL WITH GASOLINE AND DIESEL FUELS

Property	Gasoline	Ethanol	No. 1 Diesel
Molecular Weight	-	46	-
Heating Value			
Higher (Btu/lb)	20,260	12,800	19,240
Lower (Btu/lb)	18,900	11,500	18,250
Lower (Btu/gal)	116,485	76,152	133,332
Latent Heat of Vaporization (Btu/lb)	142	361	115
Research Octane	85-94	106	
Motor Octane	77-86	89	10-30
Stoichiometric Air/Fuel Ratio	14.7	9.0	
Flammability limits (volume percent)	1.4 to 7.6	3.3 to 19	

Source: Adapted from SERI, "A Guide to Commercial Scale Ethanol Production and Financing", U.S. Government Printing Office, Washington, D.C., 1980.

Storage and Handling

Ethanol must be kept anhydrous prior to blending with gasoline, especially in humid tropical areas. Unprotected storage can undo what an expensive azeotropic distillation accomplished in a relatively short time. Then the product will give poor engine performance. In developing countries, the blending of ethanol should either be done at the ethanol facility or at a bulk gasoline storage facility either at a refinery or at a major point of importation. Although blending could occur at the gasoline service station, this appears to be a very poor point for quality control.

The cost of transporting ethanol to the point of blending is expensive, even in a country such as the United States with an excellent interstate highway system. In the United States an additional $0.05 — $0.15 per gallon are added to the plant gate cost of ethanol for the product to move approximately 120 miles to a blending point located at a bulk storage terminal.

An estimate of the capital cost of the facilities to store ethanol for blending was made in a recent SERI-sponsored study. When the storage capacity is approximately 1 million gallons, the cost is $0.19 per gallon of capacity. These are very long life facilities but their cost is by no means negligible compared with the cost of the facility to produce ethanol.

Safety Considerations

Anhydrous ethanol is stored at ambient temperature and slight positive pressure. The flash point is 55 F and the flammability limits are 3.3 to 19 volume percent. The saturated vapor/air mixture above the liquid ethanol is flammable between 50 and 110 F. Therefore, a carbon dioxide blanket should be used in ethanol storage tanks.

The hazards of an ethanol facility are greatly in access of those of a sugar factory. Protection begins with appropriate plant layout, process

safeguards, and proper education of supervisors and operators. The engineering companies that have been building ethanol plants have keen insight into the safety problems. Most of the hazards arise not in new facilities constructed on a "grassroots" basis, but where there is an existing sugar factory, the plant layout of which is not conducive to construction of a safe ethanol facility.

The codes and standards that apply in the United States for the production of fuel ethanol are shown in Table 31. Those soliciting bids from engineering companies should obtain copies of the applicable documents. This listing of codes and standards is not to be construed as providing all the necessary documents.

Process fire and explosion hazards are present during distillation and storage. Strict government regulations require seals on every pipe joint, valve, and spigot to reduce the probability of flammable liquid or vapor being released during distillation operations. Flammable liquid hazards are also present in the distilled alcohol handling areas, as well as in storage and shipment.

The colorless flame of ethanol renders it an especially great threat during fire fighting. For those accustomed to fighting bagasse or petroleum product fires, special training should be provided in ethanol fire fighting.

U.S. experience in ethanol fires and explosions are only partially relevant to fuel ethanol production in developing countries. Nevertheless, it is worth noting that most of the fires have occurred in ethanol storage, rather than in processing. The expensive fires and explosions in the distillation units have involved explosions which damaged the sprinklers that then were inoperative when needed.

TABLE 31. CODES AND STANDARDS FOR THE PRODUCTION OF FUEL-GRADE ETHANOL

Title	Code
Basic Classification of Flammable and Combustible Liquids	NFPA321
Static Electricity	NFPA77
Flammable and Combustible Liquids Code	NFPA30
Occupational Noise Exposure	OSHA191094
Machinery and Machine Guarding	OSHA Subpart O
Power Piping	ANSI B31,1
Standard for Steel Aboveground Tanks for Flammable and Combustible Liquids	UL142
Boiler and Pressure Vessel Code (B & PV)	ASME Code Section IV & VII Division I
All electrical instrumentation	NFPA70-1978
National Electric Code	Class II Division I

Source: Adapted from SERI, "A Guide to Commercial Scale Ethanol Production and Financing, U.S. Government Printing Office, Washington, D.C., 1980.

Abbreviations:		
	NFPA	National Fire Protection Association
	OSHA	Occupational Safety and Health Administration
	UL	Underwriters Laboratory
	ASME	American Society of Mechanical Engineers
	ANSI	American National Standards Institute

Distilling

Distilling operations should be separated from other buildings by at least 100 ft (30 m). Existing still-buildings that adjoin other buildings should be completely cut off by blank fire walls, parapeted above adjoining buildings. Avoid basements, pipe trenches, and other spaces beneath still-buildings.

Preferably locate distilling equipment in the open with a minimum of enclosing structure. Structures should be of damage-limiting construction. Load-bearing steel members and exposed steel equipment supports should be fire-proofed with material having a minimum two-hour fire-resistance rating. For existing buildings of substantial construction, provide explosion venting capacity through venting windows and roof panels in as high a ratio as practical.

Floor cutoffs are advisable at operating levels in high, enclosed buildings. If complete floor cutoffs are not practical, provide solid noncombustible mezzanines with curbs at levels supporting receivers or other equipment containing appreciable quantities of flammable liquids.

Unless the maximum possible spill can be extinguished by dilution while confined, provide emergency drainage facilities for the distilling area of buildings to prevent escaping liquids from exposing other areas or buildings.

Pressure vessels should be designed and constructed in accordance with applicable codes, standards, state and local laws, and regulations.

Stills should be equipped with vacuum and pressure relief devices piped to outdoors. Any condenser vents also should be piped to outdoors. Vents should be sized to discharge the maximum vapor generation possible at zero feed and maximum heating within the pressure limitations of the protected equipment. Vents should terminate at least 20 ft (6.1 m) above the ground and preferably at least 6 ft (1.8 m) above roof level and be so located that vapor will not re-enter the building. Vent terminals should be equipped with flame arresters.

Equipment should be designed and maintained to eliminate or at least minimize any liquid and vapor leaks.

Where gauges are needed, use Factory Mutual-approved gauging devices. If ordinary gauge glasses are used, both connections normally should be kept closed and provided with weight-operated, quick-closing valves. Protect the glass from mechanical injury. Where possible, tail boxes should be replaced with armored rotameters and specific gravity indicators, or with other instrumentation not subject to accidental breakage or leakage.

The steam supply for distillation should be thermostatically controlled and interlocked to shut down and sound an audible alarm on cooling-water failure. Alternately, powered standby pumps or gravity supplies of cooling water should be provided.

Stills and other large equipment containing flammable liquids should be purged with steam or an inert gas (steam will be most generally available) before opening for inspection or repair. Equipment should be washed with water following steaming.

Ventilation designed and installed to ensure air movement throughout the entire structure should be provided to prevent accumulation of explosive vapor-air concentrations within the building. The stack effect (i.e., natural ventilation) may suffice if the building is high; permanent openings are provided at grade and roof elevations; the equipment can be drained and cleared of vapors during shutdowns; and heat losses from the equipment maintain a temperature above that of the outdoors during all operating periods. If these operating conditions cannot be satisfied, or if blank walls or solid floors interfere with natural ventilation, mechanical exhaust ventilation should be designed to provide 1 cfm/sq ft (0.3 m^3/min per m^2) of floor area. Locate suction intakes near floor level to ensure a sweep of air across the area.

Electrical equipment, including wiring and lights, should be suitable for Class 1, Group D locations. Still-buildings should be considered Division 2 locations.

Distilled-Alcohol Handling

Alcohol handling areas should preferably be of fire-resistive or noncombustible construction.

Distilled-alcohol handling areas should be cut off from surrounding occupancies. Vertical cutoffs should be provided in multi-story buildings. Cutoffs should have at least a one-hour fire-resistance rating.

Provide curbs, ramps, or trapped floor drains at doorways and other openings to prevent the spread of flammable liquids to other departments. Floor drains in each distilled-alcohol handling area should be designed to handle expected sprinkler discharge unless the maximum possible spill can be extinguished by dilution while confined.

Noncombustible, vapor-tight construction should be used for all tanks containing flammable concentrations of alcohol. Tanks should be kept tightly closed except when taking samples.

Tanks should be equipped with vents of adequate size terminating outdoors. Vents should be equipped with Factory Mutual-approved flame arresters if the flashpoint of the contents is less than 100 F (38 C).

Factory Mutual-approved liquid-level gauges should be installed on tanks. If ordinary gauge glasses must be used, weight-operated, normally closed valves, should be installed at both tank connections and the glass protected against physical damage. Wherever possible, top tank connections should be provided and liquids transferred by pumping through the top rather than by gravity flow. If draw-off stations are located in the same area as the supply tank, automatically operated, emergency shut-off valves should be provided in gravity-feed lines. Flexible, metallic hose should be used on all connections to scale tanks where fire exposure would release the tank contents or expose its vapor space.

Mechanical exhaust ventilation should be provided as needed, arranged with suction near floor level to ensure air movement throughout the building. At dump troughs and similar installations, localized

intakes are desirable. Careful attention should be given to below-grade installations, windowless buildings, sumps, pipe trenches, and similar installations. Usually, 0.25 cfm of air per sq ft (0.075 m^3/min per m^2) of floor area will be adequate. The use of Factory Mutual-approved, portable flammable vapor indicators to check the need of adequacy of ventilation is recommended.

Electrical equipment, including wiring and lights, should be suitable for Class 1, Group D locations. Tank storage areas should be treated as Division 2 locations.

Fire Protection

Provide automatic sprinkler protection for distilleries.

Sprinkler control valves, dry pipe valves, and riser drains should be readily accessible at all times to plant personnel. This is particularly important for areas under direct government supervision that may be locked during non-operating periods.

Small hose with combination shutoff nozzles should be provided throughout the distillery. Hose stream demand is a minimum of 500 gpm (190 dm^3/min) for at least 60 minutes.

Suitable portable fire extinguishers should be provided throughout the distillery.

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