CEER– B-104

SYMPOSIUM PAPERS

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

CARIBE HILTON HOTEL
SAN JUAN, PUERTO RICO

SPONSORED BY

THE UPR CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
BIOMASS DIVISION

NOVEMBER 24 AND 25, 1980

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Dr. Juan A. Bonnet, Jr.

OPENING REMARKS

FUELS AND FOODSTOCKS FROM TROPICAL BIOMASS
Symposium on Alternative Domestic Energy Systems for Puerto Rico

By
Dr. Juan A. Bonnet, Jr.
Director CEER

November 24, 1980

On behalf of the Center for Energy and Environment Research and our cosponsors, the Chemical, the Electrical, and the Mechanical Institutes of the Puerto Rico Professional Society of Engineers and Surveyors, I extend a warm welcome to all of you. Good morning to all participants and to our visiting scientists. Following the order in the program, our invited speakers are:

- Dr. Donald Klass from the Institute of Gas Technology, Chicago, Illinois,
- Dr. Beverly J. Berger, Acting Director, DOE Division of Biomass Energy Systems, Washington, D.C.,
- Mr. W. O. Young, Stern-Roger Engineering Corp., Denver, Colorado,
- Mr. F. Hasselriis, Combustion Equipment Associates, Inc., New York,
- Dr. George Samuels, Agricultural Research Associates, Winter Park, Florida,
- Dr. H. Bungay, Rensselear Polytechnic Institute, Troy, New York,
- Dr. J. R. Moreira, Institute of Physics, University of Sao Paulo, Brazil,
- Dr. David Jenkins, Battelle-Columbus Division, Columbus, Ohio.

We are delighted to have you with us in this important meeting.

First of all, I must ask you to excuse Dr. Ismael Almodóvar, President of the University of Puerto Rico, for not being with us today as he had hoped to be. As many of you know, Dr. Almodóvar was the first director of this Center and one of the pioneers in promoting biomass research in Puerto Rico. Urgent business has taken him away from us today. However, allow me to welcome you on his behalf.

It is our pleasure to welcome you and to benefit from this discussion of a fundamental and urgent problem affecting the welfare of Puerto Rico and of all mankind.

In the case of Puerto Rico, where we are still almost entirely dependent on imported petroleum as our basic energy source, the escalation of petroleum prices has nearly halted our previously successful efforts to expand our economy and improve the level of living of the people of Puerto Rico.

Prior to 1973 the structure of the Puerto Rican economy and of its energy sector was based on expectations of continued availability of cheap imported petroleum. These expectations came to naught with the quadrupling of oil prices by OPEC countries in December of 1973. The repercussions in our Island economy were severe: double digit inflation, the most severe recession in the post-World War II period and a heavy burden on our balance of payments. The competitive position of Puerto Rican manufacturing suffered severely, particularly the petrochemical and refining industries.

The increase in the price of imported oil has continued. Between January 1974 and December 1978 the price of petroleum increased twenty percent. During 1979 the revolution in Iran and a consequent drop in Iranian production of oil permitted OPEC to catch up in a turbulent and rising market, causing a doubling of crude oil prices. The economic crisis of our energy sector continues unabated with crude oil prices exceeding thirty dollars a barrel in 1980. This crisis is exacerbated by the continued turbulence and uncertainly of world oil markets which are heavily affected by the political instability of the Middle East.

The crisis of increasing oil prices poses a challenge to Puerto Rico. The vital task for all of us is to achieve greater energy independence through the conservation of energy and the development of alternative energy sources.

None of us here this morning can avoid this challenge. No man of science can be indifferent to the problem.

We, as scientists and engineers, are in the business of discovering and developing new technological options. In so doing, we create the opportunity to select from among a variety of options; such as biomass, in the continuing search for technologies to serve the public good and to minimize the negative impacts of the high cost of energy. Seminars such as this one are needed in order to begin to appraise the short and the long-term impacts of the biomass option.

At the request of the Government of Puerto Rico, a major one-year study was conducted by the National Academy of Sciences to determine Puerto Rico's options for alternative energy sources. The Biomass Program presently being conducted by the CEER Biomass Division is in conformity with the National Academy of Sciences' recommendations for biomass research in Puerto Rico. Among their recommendations, we quote the following:

"Of all the alternatives discussed, biomass cropping, based on the present sugarcane industry, has probably the largest potential. It could produce a significant fraction of the Island's electricity, with bagasse as fuel, by the year 2000..."

"All in all, energy cropping may in the intermediate term be for Puerto Rico the most important renewable energy source. Given vigorous development, it might provide 10 percent or more of the Island's electricity by the year 2000. Ethanol produced as a coproduct could eliminate the Puerto Rican rum industry's dependence on imported molasses and also supplement gasoline supplies."

While we are in general agreement with this particular NAS recommendation, we welcome your observations and comment. Moreover, it is obvious that the research and analytical tools available to us in the basic and applied sciences cannot be effectively used without appropriate funding and seed money. In this matter, it is clear that meeting Puerto Rico's needs for alternative energy sources can make a substantial contribution to the solution of the similar problem faced by many other oil-dependent areas of the world. Again, I quote the NAS report:

"Puerto Rico, in dealing with its own energy problems, should grasp its opportunity to become an international energy laboratory, seeking and testing solutions especially appropriate to the oil-dependent tropical and subtropical regions of the world. The Island's geographical position and its established energy research and development facilities enhance this potential, which should be called to the attention of agencies and institutions with investments to make in accelerating development overseas."

Hopefully this Symposium will further develop and clarify the "state of the art" in different aspects of biomass utilization as an alternative energy resource. The Center for Energy and Environment Research is receptive to your ideas and will endorse and support any promising avenues towards the mitigation or solution of the energy crisis which all of us are facing.

Welcome again on behalf of the University of Puerto Rico and its Center for Energy and Environment Research.

Thank you very much.

ENERGY FROM BIOMASS AND WASTES: AN OVERVIEW

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE INSTITUTE OF GAS TECHNOLOGY
Chicago, Illinois

ENERGY FROM BIOMASS AND WASTES: AN OVERVIEW

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ENERGY FROM BIOMASS AND WASTES: AN OVERVIEW

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ABSTRACT

ENERGY from biomass and wastes already contributes about 850,000 barrels oil equivalent per day to U.S. primary consumption. Recent changes in Federal funding of energy projects are expected to stimulate commercialization of additional biomass energy systems, particularly those processes that utilize biomass and wastes for the manufacture of ethanol fuel. However, although research and development on biomass production and conversion is progressing at a rapid rate, commercialization of non-ethanol and non-combustion based processes has been minimal. Commercial plants in the United States currently include one municipal solid waste gasification plant, one manure gasification plant which was recently shut down, and eight landfill methane recovery systems.

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ENERGY FROM BIOMASS AND WASTES: AN OVERVIEW

INTRODUCTION

FEW REALIZE that the present contribution of energy from biomass and wastes to U.S. primary energy consumption is equivalent to about 850,000 bbl of oil/day (1.8 quads/yr) or slightly more than 2% of total consumption.[1] Recent projections by the Office of Technology Assessment indicate that by the year 2000, the biomass energy contribution could be as high as 12 to 17 quads,[2] which is about 11 to 15% of projected energy consumption, assuming that it will be about 95 quads (excluding biomass) in 1995.[3] Thus, energy from biomass and wastes is already a major commercial energy resource for the United States and is expected to exhibit substantial growth.

Recent research and commercialization efforts in the United States are briefly reviewed in this paper to provide an overview of the state of the technology. Because of the multitude of projects now in progress, this review is necessarily selective and all projects are not discussed. But each major category of activity is summarized by using certain projects as examples.

FUNDING

Over the last several months, changes in the Federal funding of energy projects have occurred that directly affect biomass energy development. The Energy Security Act (Public Law 96-294), which created the Synthetic Fuels Corporation (SFC), was signed into law on June 30, 1980 by President Carter. The government-backed SFC may commit up to $88 billion by 1992 to achieve production goals of 500,000 barrels of oil or its equivalent per day by 1987 and 2 million bbl/day by 1992. Title II of this act is called the Biomass Energy and Alcohol Fuels Act of 1980. On October 1, 1980, it made available for biomass energy projects $1.27 billion for financial assistance; $15 million for demonstration, educational, and technical assistance; and $12 million for research and development. This latter figure is independent of the U.S. Department of Energy research programs on biomass and wastes which are summarized in Tables 1 and 2.

The $1.27 billion in Title II for biomass energy is allocated over a two-year period beginning October 1, 1980 as follows: $525 million to the USDA for loans, loan guarantees, price guarantees, and purchase agreements for biomass energy plants that have an annual production capacity less than 15 million gallons of alcohol or its equivalent; $525 million to the USDOE for loan guarantees, price guarantees, and purchase agreements for biomass energy plants that have an annual production capacity of at least 15 million gallons of alcohol or its equivalent; and $220 million to USDOE for loans, loan guarantees, price support loans, and price guarantees for municipal waste-to-energy projects.

Another source of funding for biomass energy projects is the Alternative Fuels Production Program created in November 1979 by Public Law 96-126. Ninety-nine feasibility studies and 11 cooperative agreement awards totaling about $200 million were made by USDOE out of 971 proposals on July 9, 1980. Tables 3 and 4 present some of the details of the awards that were made on projects concerned with biomass and wastes. Interestingly, about one-third of the awards made on a dollar basis were on biomass and waste projects which comprised about two-thirds of the total number of awards.

Still another source of funding for which biomass energy projects are eligible is the Supplemental Appropriations and Recision Act of 1980 (Public Law 96-304) which President Carter signed in July 1980. This act provides $100 million for feasibility studies and $200 million for cooperative agreements. The awards are expected to be announced near the end of this year. Three billion dollars are also provided by Public Law 93-304 to stimulate domestic commercial production of alternative fuels via purchase commitments, price guarantees, and loan guarantees.

Overall, Federal support of biomass energy projects has increased substantially and is expected to have great impact on commercialization.

BIOMASS PRODUCTION

Much of the research currently in progress on the selection and growth of suitable biomass species for energy applications is limited to laboratory studies and small-scale test plots. No commercial fully-integrated biomass production, harvesting, and conversion systems of any significant scale in which biomass is grown specifically for energy applications have yet been placed in operation in the United States, and most of the test programs on biomass growth for energy have only recently been started. This is an important factor to keep in mind because low-cost biomass is needed to make biomass fuels competitive. For example, at a cost of $15.00/dry ton of biomass, the energy cost contained in the biomass is about \$1.00 to \$1.25 per million BTU.

Tree Growth

Intensively managed growth and short-rotation tree production methods are being evaluated for energy applications in all sections of the country and it is expected that valuable data will be generated for the selection of suitable high-yield species as these tests progress. Some of the species of particular interest are red alder, black cottonwood, Douglas fir, and ponderosa pine in the Northwest; *Eucalyptus*, mesquite, Chinese tallow, and the leucaena in the West and Southwest; sycamore, eastern cottonwood, black locust, catalpa, sugar maple, poplar, and conifers in the Midwest; sycamore, sweetgum, European black alder, and loblolly pine in the Southwest; and sycamore, poplar, and sugar maple in the East. Generally, tree growth on test plots is studied in terms of soil type and the requirements for planting density, irrigation, fertilization, weed control, disease control, and nutrients. Harvesting methods are also important, especially in the case of coppice growth for short-rotation hardwoods. Although tree species native to the region are usually included in the experimental design, non-native and hybrid species are often tested too. Considering the large number of new plots now under test, it is estimated that the results will start to be publicized in volume in the early 1980's. Real cost data for short-rotation hardwoods, the preferred tree production method for energy applications, should result from this work.

Non-Woody Herbaceous Plants

Considerable work is in progress to screen and select non-woody herbaceous plants as candidates for biomass energy farms. Some of the projects are aimed at the screening of plants that are mainly unexploited in the continental United States; others are concentrating on cash crops such as sugarcane and sweet sorghum; and still others emphasize tropical grasses. A comprehensive screening program generated a list of 280 promising species from which up to 20 species were recommended for field experiments in each region of the country. The four highest yielding species recommended for further tests in each region are listed in Table 5.[7] Since many of the plants in the original list of 280 species had not been grown for commercial use, the production costs were estimated as shown in Table 6 for the various classes of herbaceous species and used in conjunction with yield and other data to develop the recommendations in Table 5.

Based on the results of small-scale test plots using cultivars and higher-than-normal planting densities (Table 7), sweet sorghum has apparently been selected as a prime energy candidate for expanded field tests in North Dakota, Kansas, Nebraska, Illinois, Iowa, and Ohio.[7] Sweet sorghum and its sugar yields were increased by 40 to 100% by narrow interrow spacing. For example, when the rows were 1.5 ft. apart instead of 3 ft. apart, the yields were nearly doubled in the Bell Glade, Florida test plot.

In greenhouse, small-plot, and field-scale tests conducted to screen tropical grasses, three categories have emerged based on the time required to maximize dry matter yields: short-rotation species (2-3 months), intermediate-rotation species (4-6 moths), and long-rotation species (12-18 months).[7] A sorghum-sudan grass hybrid (Sordan 70A), the forage grass napier grass, and sugarcane were outstanding candidates in these categories, respectively. Minimum tillage grasses that produce moderate yields with little attention were wild *Saccharum* clones and Johnson grass in a fourth category. The maximum yield observed to date is 27.5 dry ton/ac-yr for sugarcane propagated at narrow row centers over a time of 12 months. The estimated maximum yield is of the order of 50 dry ton/ac-yr using new generations of sugarcane and the propagation of ratoon (regrowth) plants for several years after a given crop is planted.

Overall, the work in progress on the evaluation of non-woody herbaceous biomass shows that a broad range of plant species may ultimately be prime energy crops.

Aquatic Biomass

Aquatic biomass, particularly micro- and macroalgae, are more efficient at converting incident solar radiation to chemical energy than most other biomass species. For this reason and the fact that most aquatic plants do not have commercial markets, experimental work has been performed for the last several years to evaluate several species as energy crops. Recent reports for freshwater macrophytes grown in cultural units show yields for common duckweed, water hyacinth, and *Hydrilla verticillata* of 5.4, 35.3 and 6.1 dry ton/ac-yr.[7] For the first time, a single clone of the red seaweed, *Gracilaria tikvahiae*, was grown continuously in controlled culture over 1 year without replacement to give projected dry matter yields of 31 ton/ac-yr.[7] Large-scale experiments will be carried out with hyacinth and the red seaweed in units up to one quarter acre in size to demonstrate mass culture systems and to permit realistic cost-benefit analyses.

In related experimental work, it has been shown that freshwater green algae such as *Chlorella vulgaris* can be grown on bicarbonate carbon alone.[7] This interesting observation suggests that the method might be used to maximize algal yield because, normally, the transport of carbon dioxide from the atmosphere cannot keep pace with algal assimilation of carbon dioxide. The experimental results support the conclusion that for both freshwater and marine microalgae, bicarbonate is a suitable carbon source provided the pH is controlled; carbon utilization under these conditions is virtually 100%.

In studies on marine biomass production, most of the work has been concentrated on the giant brown kelp, *Macrocystis pyrifera.* One of the key results to-date is that nutrient-rich seawater from more than 1,000 ft. deep is superior to enriched surface water in supporting kelp growth.[7] A larger scale test farm to confirm this with upwelled deep water was constructed off the Southern California Coast late in November and early December 1978, but because of unanticipated operational difficulties, the program has been delayed.[7] An interesting observation made after loss of the protective curtain and 103 adult transplants on the farm due to storms was that after strong upwelling occurred there locally in the spring of 1979, juvenile plants began to develop on the solid structures of the test farm from spores liberated by the adult transplants. This growth is now being monitored.

CONVERSION

Combustion

Direct wood burning for the production of steam and electric power by the forest products industries and for heating in residential wood stoves provided 1.8 quads of energy in the private sector in 1977.[7] Some of the recently announced plants in the final design, construction, or operating stages include a $13 million wood-waste cogeneration plant to generate 4 MW of electric power and 68,000 lb/hr of steam at an overall thermal efficiency of 64-65% in Anderson, California by the Simpson Paper Company.[7] This plant is designed around a wood-waste fueled combustor and an indirectly fired turbine, is expected to have a 3-year payback, and is projected to save $1.6 million to $2.2 million per year in fuel at today's prices.

Larger wood-powered systems in the 40 to 50 MW range, the designs for which were recently completed, seem to have been placed on hold. One of the largest plants, a 50-MW cogeneration plant for steam and electric production for Westbrook, Maine, has been designed, but the project has not as yet been continued.[7] In this proposed plant, wood harvested over a 50-mile radius of the site will supply the fuel for the plant at the rate of 1,000 oven dry tons equivalent/day. Under average conditions, about 258,000 lb/hr of steam and 20 MW of power will be sold. The total investment and operating costs for the plant are estimated to be $64.5 million and $12.8 million/yr (wood at about $25.00/ton).

Raw MSW and RDF combustion is the second major source of energy generation by combustion. Commercial resource recovery coupled with energy recovery continues to grow as a substitute for waste disposal only, although not without problems. The 200-ton/day Ames, Iowa plant for recovery and sale of iron, aluminum, and RDF, one of the first commercial plants of its type, is still operating after going on stream in 1975. In contrast, the $25 million, 1,000-ton/day, Chicago, Illinois plant for recovery of ferrous metal and RDF for co-combustion with coal has only operated in spurts for a variety of reasons since it was dedicated in 1976.[7] Also, the $43 million, 1,500-ton/day plant in Saugus, Massachusetts for direct combustion of raw MSW and steam production processed its one millionth ton of refuse in March 1979; the plant was started in October 1976.[7] This is perhaps the best record of any of the plants in operation in the U.S.A.

Currently, there are 23 operating plants in the United States for the production of steam or electric power via combustion of MSW or RDF: 12 more plants are under construction, and 21 are in the advanced planning stage.[7] The total design capacities for processing refuse in these plants is 15,163 ton/day (operating), 13,146 ton/day (under construction), and 23,506 ton/day (advanced planning). The corresponding equivalent barrels of oil assuming 100% utilization of the refuse heating value and a heating value of 9×10^6 Btu/ton of refuse, are 23,528, 20,399 and 35,777 bbl/day, or a total of about 80,000 bbl/day. This does not include the energy conserved by recycling the iron, aluminum, and glass because of the displacement of virgin materials. Obviously, it would be quite beneficial to operate these refuse processing plants near their design capacities.

Gasification

Research, development, and demonstration activities on the production of low-, medium-, and high-Btu gas (500, 500-900, and 900 Btu/SCF) by anaerobic digestion and thermochemical gasification processes have continued to advance, especially at the PDU and pilot scales. Commercial utilization of the resulting information is, however, proceeding at a slow rate in the United States. Small-scale gasification units and package systems are commercially available and have been placed in operation for some processes, but few large-scale systems are in the construction or operational stages. For anaerobic digestion, small-scale farm digesters for manure and methane-recovery systems from landfills comprise the thrust of new commercialization ventures. For thermo-chemical gasification, most of the new commercialization ventures are concentrated on small-scale air-blown gasifiers for production of low-Btu gas. Only one large-scale pyrolysis plant is currently in operation in the U.S.A. for low-Btu gas manufacture. The highlights of these efforts are presented in this section.

Anaerobic Digestion

Basic research on the anaerobic digestion of biomass has provided a better understanding of the mechanism and kinetics of the biological gasification process, but the improvements in digestion efficiencies in terms of methane yield and volatile solids reduction have been slow to evolve from this knowledge. The plateau of about 50% volatile solids destruction efficiencies and 50-60% energy recovery efficiencies pointed out previously,[8] seems to be holding. Typical methane yields and volatile solids reductions observed under standard high-rate conditions are shown in Table 8.[7] Longer detention times will increase the values of these parameters, such as a methane yield of 4.79 SCF/lb VS added and a volatile solids destruction efficiency of 53.9% for giant brown kelp at a detention time of 18 days instead of the corresponding values of 3.87 and 43.7 at 12 days under standard high rate contitions.[7] However, improvements might be desirable in the reverse direction; i.e., at shorter detention times.

Digestion system configurations that have shown advantages over standard high-rate digestion are two-phase, fed-film, and plug-flow digestion.[10] Considerable laboratory work is in progress to evaluate feedstock suitability and to develop pre- and post-digestion treatments that improve biodegradability. Innovative designs in which thermochemical and biological gasification are combined and in which anaerobic digestion is used to generate in-plant fuel from fermentation alcohol residuals are under development. Demonstration projects are in progress with waste feeds, but none has yet been started with biomass. The only commercial large-scale digestion plant for methane production in the U.S.A. uses cattle manure feedstock, but it has been shut down because of operating difficulties.[10]

Methane recovery from sanitary landfills in the form of medium- or high-Btu gas is now commercial technology as shown by the listing of eight commercial systems in Table 9. Several new methane recovery systems, notably those in New York and Chicago, are expected to be operated on a commercial basis in the near future.

Thermochemical Gasification

Extensive research and pilot studies are in progress to develop thermal processes for biomass conversion to fuel gas and synthesis gas. Basic studies of the effects of various catalysts and operating conditions are underway in the laboratory and PDU scale on steam and steam-air gasification, and on hydrogasification. Other work on the rapid pyrolysis of biomass is in the laboratory and PDU scale.

The largest commercial pyrolysis plant in the United States now in operation with MSW is located in Baltimore, Maryland.[7] This $24 million plant was originally based on Monsanto's Landgard design.[7] It is sized to process 1,000 ton/day of shredded MSW in a refractory-lined inclined rotary kiln. A portion of the waste is combusted with air to supply the heat needed for pyrolysis. The pyrolysis gas has a heating value of about 120 Btu/SCF and is combusted on-site to generate steam. When the plant was first started in January 1975, considerable operating and emissions problems were encountered. The City of Baltimore took over the plant, made several major modifications, and returned it to service in May 1979.[7] About 520 ton/day of refuse is now processed in the plant, and the steam is sold to generate revenues of about $120,000-$140,000/mth.[7] Further plant modifications are in progress to permit operation at higher through-put rates.

Commercialization of other developed pyrolysis processes such as the Andco-Torrax slagging process for non-sorted MSW, and the Purox process which uses partial oxidation with oxygen in a three-zoned shaft furnace for pyrolysis of coarsely shredded MSW under slagging conditions, have still not occurred in the United States.[7,8] Several large-scale Andco-Torrax plants have been placed in operation in Europe, and construction of a 100-ton/day plant is underway at Disney World.

Recent steam gasification studies with cellulose have shown that gas-phase steam cracking reactions dominate the chemistry of biomass gasification.[7] High heating rates and short residence times with gas-phase temperatures exceeding 650°C were found to produce hydrocarbon-rich gases containing commercially interesting amounts of ethylene and propylene.

Studies on the gasification of wood in the presence of steam and hydrogen showed that steam gasification proceeds at a much higher rate than hydrogasification.[7] Carbon conversions 30 to 40% higher than those achieved with hydrogen can be achieved with steam at comparable residence times. It was concluded that steam/wood weight ratios up to 0.45 promote increased carbon conversion but have little effect on methane concentration. Other recent work shows that potassium carbonate-catalyzed steam gasification of wood in combination with commercial methanation and cracking catalysts can yield gas mixtures containing essentially equal volumes of methane and carbon dioxide at steam/wood weight ratios below 0.25 and atmospheric pressure and temperatures near 700°C.[7] Other catalyst combinations were found to produce high yields of product gas containing about 2:1 hydrogen/carbon monoxide and little methane at steam/wood weight ratios of about 0.75 and temperature of 750°C. Typical results for both of these studies are shown in Table 10. These reports establish that the steam/wood ratios and the catalysts used can have major effects on the product gas compositions. The composition of the product gas can also be manipulated depending on whether a synthesis gas or a fuel gas is desired.

Preliminary studies at IGT on the hydroconversion of biomass have led to a conceptual process called RENUGAS for producing SNG.[9] In this process, biomass is converted in a single-stage, fluidized-bed, noncatalytic reactor operating at about 300 psig, 800°C, and residence times of a few minutes with steam-oxygen injection. About 95% carbon conversion is anticipated to produce a medium-Btu gas which is subjected to the shift reaction, scrubbing, and methanation to form SNG. The cold gas thermal efficiencies are estimated to be about 60%.

LIQUEFACTION

Research on the development of liquefaction methods for biomass and wastes has increased in recent months. The effort is still small compared to gasification research, but several potentially practical liquefaction methods have been reported. There are essentially four basic types of liquefaction processes: fermentation, direct thermochemical, indirect thermochemical, and natural. Highlights of on-going work in each of these categories are summarized in this section.

Fermentation[7]

Much work is in progress on the development of suitable fermentation conditions and on organism selection for the production of carboxylic acids, alcohols, glycols, and ketones. Some of the work is concentrated on chemical production while other projects are directed to fuel applications. The greatest effort is devoted to improved ethanol processes because of the intense interest in gasohol.* Projects are also underway to develop a total biomass utilization scheme in which wood chips are extracted with hot aqueous butanol to yield an enzyme-degradable cellulose fraction for ethanol production, a partially degraded hemicellulose fraction for butanol production, a butanol-lignin extract for use as fuel, and a polymer-grade lignin fraction; to study the conversion of pentoses from corn stalk-derived hemicellulose hydrolysate to butanediol, ketones, and other products; and to produce carboxylic acids from aquatic and terrestrial biomass by acid-phase anaerobic digestion, after which the acids are subjected to Kolbe electrolysis to form aliphatic hydrocarbons or ketones on pyrolysis of the calcium salts of the acids. These projects are in the laboratory stage of development.

Direct Thermochemical[7]

There has been a dearth of information on hydroliquefaction of biomass, but one report has appeared on the direct hydrogenation of wood chips by treatment at 100 atm and 340-350°C with water and Raney nickel catalyst. The wood is completely converted to an oily liquid, methane, and other hydrocarbon gases. Batch reaction times of 4 hrs. give oil yields of about 35 wt % of the feed;

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* Ethanol is discussed in more detail in a separate section.

the oil contains about 12 wt % oxygen and has a heating value of about 16,000 Btu/lb. Distillation yields a major fraction that boils in the same range as diesel fuel and is completely miscible with it.

A modification of the PERC process has been tested under continuous liquefaction conditions in DOE's Albany, Oregon pilot plant using Douglas fir wood chips. The original PERC process consisted of a sequence of steps; drying and grinding the wood chips to a fine powder, mixing the powder with recycled oil (30% powder to 60% oil), blending the mixture with water containing sodium carbonate, and treatment of the slurry with synthesis gas at about 4,000 psig and 700°F. The Lawrence Berkeley modification consists of partially hydrolyzing the wood in slightly acid water and treating the water slurry containing dissolved sugars and about 20% solids with synthesis gas and sodium carbonate at 4,000 psig and 700°F on a once-through basis. The resulting oil product yield is about 1 bbl/900 lb. of chips and is roughly equivalent to No. 6 grade boiler fuel. It contains about 50% phenolics, 18% high boiling alcohols, 18% hydrocarbons, and 10% water. An economic analysis of the process by SRI and Rust Engineering Co. indicates the oil can be manufactured for about $\$6/10^6$ Btu. Further tests are in progress. It should be pointed out that this type of product, although referred to as an oil in the literature, cannot be upgraded to refined products by conventional refinery practice.

Pyrolysis of biomass and wastes produces gaseous, liquid, and char products. Short residence time pyrolysis, sometimes referred to as flash pyrolysis, affords higher liquid yields. The largest plant in the United States for the purpose of producing liquid fuels (oil) by flash pyrolysis is the 200-ton/day system in El Cajon, California. This plant uses shredding and air classification of MSW to produce a fluffy material for pyrolysis, magnetic separation of ferrous metals, screening and froth flotation to recover a glass cullet, and an aluminum magnet for aluminum recovery. The pyrolysis section of the plant originally involved high-speed transport of a blend of recycled char and organic material through the reactor. The plant was placed in operation in May 1977; several thousand gallons of oil were produced. However, because of operating problems in the pyrolysis section of the plant and the cyclone separation units downstream of the pyrolysis reactor, the plant was shut down in June 1978 and mothballed in September 1978. Currently, Occidental Research Corporation is negotiating with San Diego County to continue to develop the pyrolysis design. As in the case of the PERC process, the oil product was proposed as a replacement for No. 6 fuel oil. The oil could not be refined by conventional means because of its relatively high oxygen and nitrogen contents.

Work just getting underway based on IGT's HYFLEX™ process utilizes a hydrogen atmosphere at moderate to high pressures and temperatures in the 700°C range for only a few seconds to convert biomass to hydrocarbons.[10] Short residence times promote maximum liquid yields, and it is believed that the product can be converted to a gasoline blending stock. The product produced by these hydropyrolysis conditions should have a higher intrinsic value than the heavy flash pyrolysis products described above.

Indirect Liquefaction[7]

The conversion of synthesis gas to paraffins and olefins via Fischer-Tropsch processes and to methanol is established chemistry. Synthesis gas from biomass provides the same product spectrum. The integrated production of synthesis gas by pyrolysis, catalytic conversion to hydrocarbons and low-molecular weight alcohols, and isomerization of the hydrocarbons to gasoline has now been developed in PDU equipment operated continuously at feed rates of about 25 lb/hr. Feedstocks under investigation include RDF and agricultural residues. The pyrolysis system consists of a dual fluidized-bed unit (pyrolyzer and combustor). Typical feedstock-to-gas yields are 75-85%; reactor temperatures of 500-1,000°C and pressures of 0-5 psig have been studied. Subsequent conversion to liquids in a fluidized bed catalytic reactor gave liquid yields of about 20-100 gal/ton of pyrolysis feed. Passage of the hydrocarbon product through a fixed-bed catalytic reactor gave 50 vol % yields of liquid product per volume of liquid feed; the product at 300-500°C and 400-600 psig has an 80-100 octane rating. It was concluded from this work that liquid fuels equivalent to commercial products can be produced by the use of biomass feeds.

Another indirect route to liquid fuels from biomass involves the coupling of pyrolysis of organic wastes to yield gases high in light olefins, compression and purification of the olefins, and polymerization to yield gasoline. The conditions found to be optimum for RDF were about 750°C with steam dilution for pyrolysis times of less than one second. Slightly more than half of the energy contained in the waste can be recovered in the gasoline precursors. Using temperatures of about 400-500°C and pressures of about 700-1,000 psig, the purified olefin mixture is polymerized to yield a product 90% of which boils in the gasoline range. The estimated overall yield is about 1.8 bbl/ton RDF (MAF) at a 50% efficiency in energy recovery. Preliminary economic analysis indicates that polymer gasoline is currently competitive with petroleum-derived gasoline.

An indirect route to biomass liquids that has received much attention is Mobil's process in which methanol is converted to hydrocarbons over zeolite catalysts. The New Zealand Government has approved Mobil's technology as the heart of a 13,000-bbl/day synthetic gasoline plant designed to meet one-third of the nation's needs in the mid 1980's. Negotiations are in progress. The methanol for this plant will be made from natural gas, but it could be made from biomass.

Another zeolite catalyst application was recently reported by Mobil which provides another indirect route to hydrocarbon liquids from biomass. In this process, biomass-derived oils such as corn, castor, peanut, and jojoba oils as well as Hevea latex are converted in high yields to gasoline by passage over zeolite catalysts at 400-500°C. In addition to gasoline, which is the major product, fuel gas (C_1–C_2), liquid petroleum gas (C_3–C_4), and light distillate are formed. The product mix is similar to that obtained from methanol, and constitutes a high-grade gasoline with an unleaded research octane number of 90 to 96. Product distributions for methanol, corn oil, and Hevea latex are summarized in Table 11. Experimental results show that when isoprene or dipentene, the decomposition products of latex rubber in the reactor without catalyst, is passed over the zeolite catalyst, the same product spectrum as that formed by the latex is produced. It was therefore suggested that polyisoprene rubber first depolymerizes to lower molecular weight units which then interact with catalyst.

Natural Processes[7]

Natural production of polyisoprene by biomass has been recognized for many years; it formed the basis of commercial production of natural rubber on *Hevea braziliensis* plantations. Recently, new screening studies of over 300 plant species have shown that about 30 species may serve as useful sources of hydrocarbons. Most are vigorous perennial species relatively rich in oils and hydrocarbons and adapted to wide areas of North America. A most interesting species, *Copaifera langsdorfii*, is a tree which grows wild in the Amazon. Mature trees are about 1 m in diameter and 30 m high. A 1-1/2 in. bung hole yields about 10 to 20*l* of oil/yr from four such holes and that the tree can be grown at a density of 100 trees/ac. This corresponds to about 15,000 *l*/ac-yr (94 bbl/ac-yr). It is believed that the tree can grow in a few places in the United States such as Florida.

Alcohol Fuels

Ethanol

It appears that more controversy has occurred among energy specialists on ethanol as a motor fuel than any other synthetic fuel. Nevertheless, it is commercially marketed now in the United States on a large scale as gasohol (10 vol % ethanol – 90 vol % unleaded gasoline) and of all the possible biomass- and waste-derived fuels, it has been given the most Federal support. As indicated in Tables 3 and 4, 43 projects on ethanol out of 76 projects on energy from biomass and wastes were chosen for feasibility study and cooperative agreement awards under Public Law 96-126. The breakdown is shown in Table 12; the dollar awards ($53,971,000) are about 78% of the total dollar awards given to projects on energy from biomass and wastes under this law. About $378 million in loan guarantees have also been awarded by the U.S. Department of Agriculture for ethanol fuel plants as shown in Table 13, and the U.S. Department of Energy is negotiating loan guarantees for 7 other plants as shown in Table 14. Presuming that all of the plants listed in Tables 12, 13, and 14 are built, the total alcohol production would be about 1,726 million gallons per year, or about 1.5% of U.S. gasoline consumption in 1979.

Ethanol Research

Much of today's research on ethanol has been concentrated on improving cellulose hydrolysis processes, increasing ethanol yields, reducing fermentation times, and achieving higher net energy production efficiencies. Significant experimental data have been reported on improved-enzyme-catalyzed hydrolysis of low-grade cellulosics and on the continuous hydrolysis of cellulosics to glucose via flash hydrolysis using dilute sulfuric acid. For example, hydrolysis of water slurries of newsprint with 1% sulfuric acid in the range 235-240°C at a residence time of 0.22 min afforded 50 to 55% of the theoretical glucose yields in a plug flow reactor.[7] These results are believed to be of commercial interest. Another short-residence time sulfuric acid hydrolysis process feeds a hydropulped slurry of newsprint or sawdust into a twin-screw extruder device which expresses water from the slurry.[7] The resulting high-solids cellulose plug is then hydrolyzed with acid which is injected into the feeder. The residence time-temperature-glucose yield relationships are about the same as those of the plug flow reactor experiments. The EPA, the sponsor of this work, estimates that ethanol might be produced by this process for \$0.85-\$1.00/gal – \$0.60/gal for hydrolysis, and \$0.30-\$0.40 for fermentation and distillation.[7]

Recent approaches to improving the alcoholic fermentation process itself include the use of bacteria instead of yeasts to shorten fermentation times; continuous fermentation techniques to shorten fermentation times; simultaneous saccharification and fermentation of low-grade cellulosics with enzymes and yeasts; thermophilic anaerobes for the one-step hydrolysis and fermentation of cellulosics; packed columns containing live, immobilized yeast cells, or both enzymes and yeast cells through which glucose solutions are passed; and recombinant-DNA techniques to develop new yeast strains for rapid conversion of starch to sugar.[7] For example, packed columns of live saccharomyces yeast cells entrapped in carrageenan gel are reported to convert 20% aqueous glucose solutions containing nutrients to 12.8 vol % ethanol solutions in 2.5 hr.[7] Biomass not normally used for alcohol production, such as pineapple, has also been evaluated for alcoholic fermentation.[7] This plant species, which requires much less water than sugarcane or cassava for growth, was projected to yield ethanol quantities per unit growth area higher than those of sugarcane or cassava.

Since distillation of the fermentation broth to separate the ethanol consumes relatively large amounts of energy, several methods are being studied to try to improve post-fermentation processing. Drying of the partially concentrated alcohol solution with dehydrating agents including corn and corn derivatives is reported to be effective for producing nearly anhydrous alcohol; the energy content of the ethanol is ten times that needed for dehydration.[7] Other techniques for reducing energy consumption use azeotropic agents, low-energy distillation, and membrane filters. Another possible route to anhydrous ethanol is to use a solvent for direct extraction of ethanol from the aqueous solution; little data seems to be available on the potential energy consumption benefits of this method which could, in theory, produce gasohol directly without distillation. A few projects are underway to develop this technique.

No recent reports could be found on the thermochemical production of ethanol via hydration of ethylene derived from biomass. But an interesting non-biological method has been reported on the conversion of furfural from rice hulls, corn cobs, and material from the southern pine forest to ethanol. Furfural undergoes ring cleavage and reduction in the presence of lithium metal and alkyl amine solvent to form ethanol.[7] The use of less expensive lithium salts in amine solvents bombarded with gamma rays may also promote the same reaction.[7] These reactions are under laboratory study.

Methanol

Methanol is a suitable fuel for internal combustion engines too, although it does have several advantages and disadvantages when compared with ethanol. Biomass-derived methanol has also not been receiving near the attention that has been given to ethanol. For example, only one of the 71 projects in Table 3 is directed to methanol from biomass. The current emphasis for future methanol fuel plants is concentrated on coal-based processes. Interestingly, even though such processes are relatively well established from a technological standpoint, none is on-line in the United States. Natural gas is the prime raw material.

Methanol has not been produced in any appreciable yield by fermentation. Currently, most of it is manufactured by conversion of synthesis gas, usually by the so-called low-pressure process developed by Imperial Chemical Industries in the 1960's. Subsequent research to develop new methanol processes has usually been patterned after the ICI method which uses heterogeneous copper oxide catalysts to reduce carbon monoxide.

Recently, homogeneously catalyzed reduction of carbon monoxide to methanol and methyl formate at 1300 atm and 225° to 275°C in the presence of solutions of ruthenium complexes was discovered.[7] This observation could be the forerunner of new catalytic systems for methanol manufacture.

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Table 1. SUMMARY OF U.S. DEPARTMENT OF ENERGY BUDGET FOR BIOMASS ENERGY SYSTEMS R&D*

Program Element	Selected Activities	Appropriation in Fiscal 1980	Requested in Fiscal 1981
Technology Support			
Combustion	Wood and wood residues for process and residential heat and electricity; demonstrations; retrofit units; biomass availability studies; near-term low-Btu gasification.		
Alcohol Production	Improved fermentation efficiency; use of higher-yield sugar crops; sweet sorghum growth.		
On-Farm	Anaerobic digestion of farm residues; alcohol fermentation (via USDA).		
		$16,000,000	$22,000,000
Production Systems			
Silvicultural	Species screening; regional farms; harvester development.		
Herbaceous	Species screening; fermentable crops and tropcial grasses.		
Aquatic	Ocean-based test farm off California.		
		$ 5,700,000	$11,600,000
Conversion			
Biochemical	Anaerobic digestion and fermentation of lignocellulosics and aquatic biomass (via SERI).		
Thermochemical	Gasification and liquefaction PDU's.		
		$24,500,000	$11,500,000
Research & Exploratory Development			
Innovative Conversion	Biochemical conversion; chemicals; new conversion technology.		
Advanced Feedstocks	Identifying promising species, products, and markets; multi-use crops; yield-increasing methods.		
Aquatic Systems	Fresh and brackish water biomass production and conversion.		
		$ 8,300,000	$14,400,000
Support and Other	Analyses and environmental assessments.		
		$ 1,500,000	$ 3,500,000
	Total:	$56,000,000	$63,000,000
Operating Expenses	--	$53,500,000	$57,750,000
Capital Equipment	--	500,000	750,000
Construction	--	2,000,000	4,500,000
	Total:	$56,000,000	$63,000,000

*Table adapted from Reference 4. Figures do not include project funding in other DOE departments on municipal, industrial, or sewage wastes, and on relevant basic research. Fiscal 1981 figures are prior to congressional action.

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Table 2. SUMMARY OF U.S. DEPARTMENT OF ENERGY BUDGET FOR URBAN WASTE-TO-ENERGY SYSTEMS

Program Element	Selected Activities	Appropriation in Fiscal 1980	Requested in Fiscal 1981
Urban Waste	RefCOM (Pompano Beach, Florida); enzymatic hydrolysis (U.S. Army, Natick, Mass.); landfill methane; 50,000 gal/day Anflow digestion unit (Knoxville, TN); Disney World sewage treatment and energy production system via water hyacinth; Disney World 75-ton/day solid waste pyrolysis plant; manuals, handbooks, and workshops; mobile RDF production unit.		
	Total:	$13,000,000	$10,900,000
Operating Expenses			
Develop Options	--	--	$ 4,300,000
Develop Small-Scale Systems	--	--	2,500,000
Wastewater Treatment	--	--	3,300,000
Capital Equipment			
RDF Unit	--	--	800,000
	Total:	$13,000,000	$10,900,000

*Table adapted from Reference 5. Fiscal 1981 figures are prior to congressional action. The House Committee added $10,000,000 for demonstration projects to the fiscal 1981 DOE request, but final appropriations have not yet been made.

Table 3. PROPOSED ALTERNATIVE FUELS FEASIBILITY STUDY AWARDS ON BIOMASS AND WASTES UNDER PUBLIC LAW 96-126[a] (Announced July 9, 1980)

Fuel Type	Number of Studies		Requested From DOE, $		Barrels Oil Equivalent/Day	
	Biomass[c]	Wastes[f]	Biomass[c]	Wastes[f]	Biomass[c]	Wastes[f]
Ethanol	39[d]	2	19,055,500	115,500	71,850	222
Non-Ethanol Liquid	2	0	851,500	0	8,923	0
Gas	2[e]	15	1,652,000	2,942,151	1,328	12,931
Solid	9	2	2,189,700	4,579,520	374	15,660
Subtotal:	52	19	23,748,700	7,637,171	82,475	28,813
Total:	71		$ 31,385,871		111,288	
Total Feasibility Studies[b]	99		$100,803,054		549,168	

[a] Adapted from Reference 6.

[b] Includes all feasibility studies in addition to those using biomass and wastes.

[c] Includes land-based vegetation, corn and other grains, milo, sugar beets, potatoes, wood and wood chips, molasses, sugarcane, and sorghum.

[d] One project in this category uses corn and livestock entrails as feeds.

[e] One project in this category is on gaseous and liquid hydrocarbon production.

[f] Includes MSW, RDF, wood wastes, sewage, manure, industrial wastes, rice hulls, and cheese whey.

Table 4. PROPOSED COOPERATIVE AGREEMENT AWARDS FOR BIOMASS AND WASTES UNDER PUBLIC LAW 96-126
(Announced July 9, 1980)[a]

Fuel Type	Number of Studies		Requested From DOE, $		Barrels Oil Equivalent/Day	
	Biomass	Wastes	Biomass	Wastes	Biomass	Wastes
Ethanol	2[c]	0	34,800,000	0	5,284	0
Non-Ethanol Liquid	0	0	0	0	0	0
Gas	0	2[e]	0	2,414,800	0	43[g]
Solid	1[d]	0	950,000	0	500	0
Subtotal:	3	2	35,750,000	2,414,800	5,784	43
Total:	5		$ 38,164,800		5,827	
Total Cooperative Agreements:[b]	11		$103,209,300[f]		119,027[h]	

[a] Adapted from Reference 6.

[b] Includes all cooperative agreements in addition to biomass and wastes.

[c] Corn feedstock.

[d] Wood feedstock.

[e] MSW feedstock.

[f] Proposers will contribute $120 million.

[g] Does not includes one award for MSW gasification; information not reported.

[h] Does not include three coal projects; information not reported.

Table 5. REPORTED MAXIMUM PRODUCTIVITIES FOR RECOMMENDED HERBACEOUS PLANTS[a]

Region[b]	Species	Yield, dry ton/ac-yr
Southeastern Prairie Delta and Coast	Kenaf	13
	Napiergrass	12.7
	Bermuda Grass	12
	Forage Sorghum	12
General Farm and North Atlantic	Kenaf	8.3
	Sorghum Hybrid	8.2
	Bermuda Grass	7.1
	Smooth Bromegrass	6.2
Central	Forage Sorghum	11.4
	Hybrid Sorghum	8.5
	Reed Canary Grass	7.6
	Tall Fescue	7.0
Lake States and Northeast	Jerusalem Artichoke	14.3
	Sunflower	8.9
	Reed Canary Grass	6.1
	Common Milkweed	5.5
Central and Southwestern Plains and Plateaus	Kenaf	14.7
	Colorado River Hemp	11.2
	Switchgrass	10.0
	Sunn Hemp	9.5
Northern and Western Great Plains	Jerusalem Artichoke	14.3
	Sunchoke	12.7
	Sunflower	8.8
	Milkvetch	7.2
Western Range	Alfalfa	8.0
	Blue Panic Grass	8.0
	Cane Bluestem	4.8
	Buffalo Gourd	4.5

Table 5, Cont. REPORTED MAXIMUM PRODUCTIVITIES FOR RECOMMENDED HERBACEOUS PLANTS[a]

Northwestern/Rocky Mountain	Milkvetch	5.4
	Kochia	4.9
	Russian Thistle	4.5
	Alfalfa	3.6
California Subtropical	Sudan Grass	16.0
	Sudan-Sorghum Hybrid	14.1
	Forage Sorghum	12.9
	Alfalfa	8.5

[a] Four highest yielding species in recommended species list reported for each region.

[b] As defined by U.S. Department of Agriculture, Agriculture Handbook 296, March 1972; excludes Alaska and Hawaii.

Table 6. AVERAGE PRODUCTION COSTS FOR HERBACEOUS PLANTS[a]

Plant Groups	Model Crop Used	Type	Whole Plant Yield, dry ton/ac-yr	Cost/Ton, $
Tall Grasses	Corn	A	7.7	21
Short Grasses	Wheat	A	4.4	19
Tall Broadleaves	Sunflower	A	6.7	14
Short Broadleaves	Sugar Beet	A	6.2	85
Legumes	Alfalfa	P	6.1	23
Tubers	Potatoes	A	4.1	150

[a] See Reference 7.

[b] A denotes annual, P denotes perennial.

Table 7. TEST PLOT YIELDS OF SWEET SORGHUM USING NARROW INTERROW SPACING[a]

Location	Cultivar[b]	Maximum Biomass Yield	Maximum Total Sugar Yield
		ton/ac	
Belle Glade, Fl	Wray	12.7	3.9
Weslaco, Tx	Sart	13.4	4.0
Baton Rouge, La	Wray	12.8	3.8
Meridian, Ms	MN 1500	9.99	3.4[c]
Columbus, Oh	Wray	9.90	2.9

[a] From Reference 25.

[b] Specially bred varieties.

[c] Cultivar MER 60-2.

Table 8. COMPARISON OF DIGESTION PERFORMANCE UNDER HIGH-MESOPHILIC CONDITIONS[a]

	Giant Brown Kelp[b]	Coastal Bermuda Grass[c]	Kentucky Bluegrass	Biomass-Waste Blend[d]	Primary Sewage Sludge
Gas Production Rate, vol/vol-day	0.66	0.59	0.55	0.55	0.78
Methane Yield, SCF/lb VS added	3.87	3.51	2.54	3.40	5.3
Methane Concentration, mol %	58.4	55.9	60.4	62.0	68.5
Volatile Solids Reduction, %	43.7	37.5	25.1	33.3	41.5
Feed Energy Recovered as Methane, %	49.1	41.2	27.6	38.3	46.2

[a] Conditions were 35°C, daily feeding, continuous mechanical agitation, 12-day detention time, 0.10 lb VS/ft^3-day loading rate; Reference 7.

[b] Loading rate of 0.13 lb VS/ft^3-day.

[c] Supplemented with nitrogen to overcome deficiency.

[d] Feed blend consisted of water-hyacinth, Coastal Bermuda grass, RDF, and mixed activated-primary sewage sludge on a VS basis of 32.3:32.3:32.3:3.1.

Table 9. LANDFILLS USED FOR COMMERCIAL METHANE RECOVERY[a]

Location	Well Type[b]	Product Gas[c]	Production, 10^6 ft^3/day	System Cost, \$ 10^6	Start-Up Time	Operator	Gas Use
Azuza, CA	D	MBG	0.75	1.2	1978	Azuza Land Reclamation Co.	Sold to Reichold Chemical Co.
Cinnaminson, NJ	--	MBG	0.3	--	1979	Public Service Electric & Gas Co.	Industrial sales
Industry, CA	S	MBG	0.7	0.4	1978	SCS Engineers	Boiler fuel
Los Angeles, CA	D	MBG	2.6	1.75	1979	City	City electric power
Monterey Park, CA	D	SNG	4	--	1979	Getty Synthetic Fuels, Inc.	Sold to Southern California Gas Co.
Mountain View, CA	S	MBG	0.7	0.84	1978	Pacific Gas & Electric Co.	Blended into natural gas
Palos Verdes, CA	D	SNG	0.75	--	1975	Getty Synthetic Fuels, Inc.	Sold to Southern California Gas Co.
Wilmington, CA	S	MBG	1.5	--	1978	Watson Energy Systems	Sold to Shell Oil refinery

[a] Source: U.S. Environmental Protection Agency and Getty Synthetic Fuels, Inc.

[b] S, shallow, less than 100 ft; D, deep, more than 100 ft.

[c] MBG, medium-Btu gas; SNG, high-Btu gas.

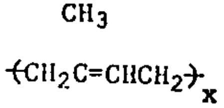
Table 10. TYPICAL PRODUCT GASES FROM STEAM GASIFICATION OF WOOD

Reference	55[a]	55[a]	54[b]	54[b]
Reactor Temperature, °C	740	750	696	762
Pressure, psig	0	0	18.7	23.1
Primary Catalyst	K_2CO_3	K_2CO_3	None	Wood Ash
Secondary Catalyst	Ni:SiAl	SiAl	None	None
Steam:Wood Wt Ratio	0.25	0.75	0.24	0.56
Gas Composition, mol %				
H_2	0	53	29	50
CH_4	52	4	15	17
CO_2	48	12	17	11
CO	0	30	34	17
Carbon Conversion to Gas, %	64	77	68	52
Feed Energy in Gas, %	76	78	--	--
Heating Value of Gas, Btu/SCF	526	309	424	450

[a] Laboratory results with unspecified wood.

[b] PDU results with unspecified hardwood.

Table 11. PRODUCT DISTRIBUTION FROM MOBIL PROCESS[a]
HZSM-5 Catalyst
Atmospheric Pressure

	Feedstock[b]		
	Methanol	Corn Oil	Hevea Latex
Formula	CH_3OH	$C_{57}H_{104}O_6$[c]	 $\left(CH_2\overset{CH_3}{C}=CHCH_2\right)_x$
Temperature, °C	450	450	482
Weight-Hourly Space Velocity	0.67	2.4	0.6
Coke Yield, %	0	3	26
Product Distribution, %			
C_1-C_2	8	3	12
C_3-C_4	42	24	21
Gasoline	48	58	67
Distillate	2	15	0

[a] Estimated from bar graphs in Reference 12.

[b] Also includes hydrogen at 300 ml/hr over 2 ml of 14-30 mesh catalyst.

[c] Triglyceride with $C_{17}H_{33}CO_2$-groups.

Table 12. FEASIBILITY STUDY AND COOPERATIVE AGREEMENT AWARDS BY USDOE FOR ETHANOL FUEL PLANTS

State	Company	Capacity, 10^6 gal/yr	Requested From DOE	Feedstock	Distillery Fuels
Alabama	Grasp, Inc.	40	$ 1,200,000	Corn, Milo	--
Arizona	Arizona Grain, Inc.	12.5	188,300	Corn, Grain, Barley	--
Arkansas	Arkansas Grain Fuels, Inc.	35	50,400	Milo	--
California	Ultrasystems, Inc.	20	223,200	Sugar Beets, Potatoes, Wheat, Grain	Geothermal
California	Western Concentrates, Inc.	132	860,000	Corn	--
Colorado	Grand American, Inc.	10	179,700	Grains	--
Georgia	Cafpro, Inc.	2	40,100	Corn	--
Georgia	Nuclear Assurance Corp.	25	430,500	Wood	--
Hawaii	Hilo Coast Processing	23.5	900,00	Molasses	--
Idaho	Clearwater Palouse Energy Co-op	20	102,000	Wheat, Barley	--
Illinois	Rochelle Energy Development	1.5	25,000	Corn	--
Indiana	Agri Answer, Inc.	21	653,900	Corn	Coal
Indiana	New Energy Corp. of Indiana	50	1,952,000	Corn	--
Iowa	Agri Grain Power, Inc.	50	99,700	Corn	--
Kansas	Planning Design & Development, Inc.	10	335,800	Grain	--
Kentucky	American Farmers Marketing Co-op	10	486,000	Corn	--
Louisiana	Apex Oil Co.	33	318,300	Several	--
Louisiana	Independence Energy Co.	20	2,060,400	Sugarcane, Sorghum, Molasses, Corn	--
Maine	D. W. Small & Sons, Inc.	25	156,400	Corn, Cull Potatoes	--
Maryland	Americol Ltd.	10	570,000	Local	--
Massachusetts	Belcher New England, Inc.	25	893,900	Corn, Grain, Cull Potatoes, Cellulose	--
Michigan	U.S. Ethanol Industries	40	597,100	Corn	--
Minnesota	CBA, Inc.	24.5	436,500	Corn	--
Mississippi	Alcohol Fuels of Mississippi	1	150,000	Wood Chips	--
Missouri	Missouri Farmers Assoc.	5	100,000	Wood	--
Montana	Infinity Oil Co., Inc.	5	115,600	Wheat, Barley	--
Nebraska	Nebraska Alcohol Fuels Conversion	50	1,180,000	Corn	--
Nevada	Geothermal Food Processors, Inc.	5	68,600	Corn	Geothermal
New York	Andco Environmental Processes	15	246,900	Corn	Coal
North Carolina	Diversified Fuels, Inc.	30-50	183,200	Corn	--
North Dakota	Dawn Enterprises, Inc.	50	225,200	Wheat, Potatoes	Lignite
Oklahoma	Fulton Energy Corp.	25	622,800	Corn, Milo	Coal
Oregon	Morrow Ag Energy Corp.	20	240,000	Corn, Wheat, Sugar Beet, Potatoes	--
Pennsylvania	Lavco, Inc.	20	799,200	Corn	--
South Carolina	Energy Conversion Corp.	20	185,900	Corn	--
South Dakota	Sodak Resources, Ltd.	20	118,400	Corn	--
Vermont	Alternative Concepts of Energy	1.4	95,700	Cheeze Whey	--
Virginia	A. Smith Bowman Distillery	20-40	466,000	Corn	--
Washington	Omega Fuels	50	1,517,900	Corn	--
Wisconsin	Dvorak Farms	2	19,800	Corn, Entrails	--
Wisconsin	Wisconsin Agri Energy Corp.	20	76,600	Corn	Coal
			$19,171,000		
Kentucky**	James R. Wade	21	9,800,000	Corn	Coal
Ohio**	Publicker Industries, Inc.	60	25,000,000	Corn	Coal
		~1,100	~$53,971,000		

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[*] Adapted from Reference 6.

[**] Cooperative agreement; all others are feasibility study awards; capital cost and most of distillery fuels not stated.

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Table 13. FEDERAL LOAN GUARANTEES AWARDED BY USDA FOR ETHANOL FUEL PLANTS*

State	Company	Capacity, 10^6 gal/yr	Capital Cost	Loan Guarantee	Feedstock	Distillery Fuel
Alabama	Alaynol, Inc.	6	$ 10,800,000	$ 6,900,000	Corn, Sorghum	Natural Gas, Coal
Arkansas	Gasohol One, Inc.	0.65	1,400,000	1,000,000	Milo	Natural Gas
Arkansas	E. J. McGuire	4.6	8,400,000	7,017,470	Corn, Sorghum	Natural Gas
Arkansas	Big D&W Refining & Solvents Co., Inc.	2.7	3,300,000	3,000,000	Corn	Natural Gas
Florida	Florida Ethanol, Inc.	5	12,000,000	10,000,000	Corn, Milo	Wood
Georgia	Southeast Energy Group, Ltd.	10	27,600,000	19,000,000	Corn	Purchased Steam
Georgia	Syncorp, Inc.	2.2	4,000,000	2,500,000	Corn	Wood Chips
Idaho	Power Alcohol, Inc.	5	12,000,000	8,700,000	Barley, Potatoes, Wheat	Coal
Idaho	Idaho Fuels	0.133	591,000	475,000	Barley, Potatoes	Electricity
Illinois	Ethanol Motor Fuel Associates	14.3	25,000,000	20,000,000	Corn	Coal
Iowa	Farm-Fuel Products Corp.	2.3	4,200,000	3,800,000	Corn	Natural Gas
Iowa	Consolidated Energy Group, Ltd.	10	35,900,000	25,157,000	Corn	Coal
Iowa	The Agrifuel Corp	5.4	6,000,000	5,600,000	Corn	Coal
Kentucky	Kentucky Agricultural Energy Co.	21	51,000,000	35,200,000	Corn	Coal
Kentucky	Bardstown Fuel Alcohol Co.	3.5-4	3,200,000	2,500,000	Corn	Coal
Louisiana	Goodwill Agri-Fuels, Inc.	3.3	5,200,000	4,220,000	Corn, Grain, Sorghum	Crop Residues
Michigan	Enerhol Limited	10	19,000,000	19,000,000	Corn	Purchased Steam
Michigan	Michigan Agri-Fuels, Inc.	8	9,300,000	2,905,000	Corn	Flare Gas
Minnesota	Agri-Energy, Inc.	4	9,800,000	6,300,000	Barley, Wheat	Coal
Montana	Montana Agri Processors, Inc.	1	2,200,000	2,150,000	Barley	Coal
Nebraska	Boucher Rural Products	0.25	350,000	280,000	Corn	Wood
Nebraska	Agri-Hol, Inc.	3	5,600,000	4,480,000	Corn	Natural Gas
North Carolina	Continental Alcohol Fuels Corp.	25	67,000,000	50,000,000	Corn	Coal
Ohio	South Point Gasohol, Inc.	60	66,000,000	32,000,000	Corn	Coal
South Carolina	Carolina Alcohol Corp.	0.6	566,000	352,000	Corn, Milo	Wood
South Dakota	Coburn Enterprises, Inc.	0.75	950,000	750,000	Corn	Fuel Oil
South Dakota	SEPCO, Inc.	0.876	483,000	150,000	Corn	Propane
Tennessee	Tiger Tail Distillery, Inc.	50	90,000,000	66,850,000	Corn, Milo, Wheat	Sawdust
Texas	Mapco Alcohol Fuel, Inc.	22	52,000,000	37,260,000	Milo	Coal
		~282	$533,840,000	$377,746,470		

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*Adapted from References 13 and 14.

Table 14. FEDERAL LOAN GUARANTEES AWARDED BY USDOE FOR ETHANOL FUEL PLANTS*

State	Company	Capacity, 10^6 gal/yr	Capital Cost	Feedstock	Distillery Fuel
Indiana	New Energy Co.	50	$141,000,000	Corn	Coal
Kansas	Circle Energies Corp.	18	22,000,000	Corn	Stover, Manure
Louisiana	U.S. Ethanol Corp.	120	220,000,000	Corn	Coal
Michigan	Michigan Sugar Co.	20	33,200,000	Corn	Coal
Minnesota	Minnesota Alcohol Producers	15	45,000,000	Corn	Coal
Pennsylvania	Grain Fuels Inc.	20	61,600,000	Corn	Coal
South Carolina	Energy Conversion Corp.	20	63,000,000	Corn	Wood Waste
		263	$585,800,000		

*Adapted from References 15 and 16. Amount of loan guarantee to be negotiated.

BIOMASS ENERGY SYSTEMS: AN OVERVIEW

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

The Biomass Energy Systems Division
U.S. Department of Energy
Washington, D.C.

BIOMASS ENERGY SYSTEMS: AN OVERVIEW

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Biomass Energy Systems: An Overview*

Dr. Beverly J. Berger, Acting Director
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INTRODUCTION

DURING the early 1970's, it became apparent to the Congress that renewable energy sources should be developed to reduce the Nation's growing dependence on foreign oil and the dwindling domestic supplies of oil and natural gas. In 1974, the Energy Reorganization Act (P.L. 93-438) and the Solar Energy Research, Development and Demonstration Act (P.L. 93-473) established the Energy Research and Development Administration (ERDA) as the responsible Federal agency in solar energy RD&D.

The Biomass Energy Systems Program (BES) was originally organized under the name "Fuels From Biomass Program" in ERDA's Division of Solar Energy. The Department of Energy Organization Act of 1977 (P.L. 95-97), consolidated the energy functions of the Federal Energy Administration, ERDA and other Federal agencies into the Department of Energy on October 1, 1977. At that time, BES was placed in the Division of Distributed Solar Technology and in the 1980 reorganization it became a Division within the Office of Solar Applications for Industry.

In fiscal year 1977, $6 million were, for the first time, appropriated for ERDA to develop fuels from biomass. The budget authority has increased nearly ten-fold since that time. The fiscal 1980 budget for BES has grown to $55.5 million of which $22 million was used to initiate the Office of Alcohol Fuels. This dramatic increase in funding reflects the expectation of biomass to be the largest energy contributor of all solar technologies in this century.

The Biomass Energy Systems Program was reoriented in FY 1980 from primarily technology and engineering development to include commercialization activities as well. The overall strategy is to balance the near term, midterm, and long term energy options. The present emphasis is on those technologies which can make an energy contribution in the next five years. At the same time,

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* Presented by Marilyn Ripin.

support is being given for the development of production and conversion technologies which will begin to contribute to our energy supplies after 1985, and long term R&D is being initiated on those concepts with high technical and financial risks but potential for high payoff after the year 2000.

PROGRAM FOCUS

Within each of the major activity areas there are barriers which must be eliminated or engineering problems to be solved for a particular biomass technology to become a viable alternative energy option. In every case, efforts are supported to reduce the financial risk to industry of developing and commercializing biomass technologies. In addition, the majority of activities, particularly those involved with technology development, are aimed at reducing the manufacturing costs to accelerate market penetration. Some of the more specific barriers and problems are enumerated below with examples of activities aimed at removing these impediments.

Commercialization

Commercialization activities are being conducted to accelerate the use of wood as fuel in the near term. Direct combustion technologies are being considered for the generation of industrial process heat/steam, the generation of electricity, the cogeneration of process heat and electricity, and the production of space heat for residential applications.

There are several issues or barriers which must be addressed before the potential of wood as a fuel will be realized. First, in order to develop regional wood utilization plans, an accurate estimate of the total above ground biomass must be made. Current national estimates include only the merchantable volumes of trees and exclude the tops, branches and small or defective trees. The methodology needed to estimate total biomass will be developed and implemented on a national and regional basis in conjunction with the U.S. Forest Service. Assessments will also be made to determine the regional market potential for wood fuel to provide a focus for the regional utilization plans.

The lack of an identifiable and reliable wood supply infrastructure is currently inhibiting its use. Evaluations are being made of land ownership patterns, transportation systems and costs of delivering wood. Cost-shared site specific feasibility studies will be conducted to determine the wood available to potential industrial and utility users. For the residential sector, two retail wood outlets have been established in the Southeast to demonstrate the reliability of stick wood fuel supplies.

Another potential deterrent to wood burning is the increasing concern about emissions and their effect on health and the environment. BES is currently funding studies to quantify and reduce the emissions from stoves and furnaces and will fund research in cooperation with EPA on the potential health effects caused by wood combustion. There is also a need to provide up-to-date technical and economic data on the use of wood to potential producers, suppliers and users. Cost-shared demonstrations of direct combustion systems are planned to encourage the acceptance of this technology by non-forest products industries and utilities. In addition, a technical assistance team has been established in the Northeast to provide information and direction to interested industrial/utility concerns, as well as those interested in residential wood burning.

Commercialization activities will also be directed at the agricultural sector. In cooperation with the Science and Education Administration (SFA) of the U.S. Department of Agriculture, BES will conduct a program aimed at achieving greater on-farm energy production and use through the anaerobic digestion of animal manures, the direct combustion and low Btu gasification of agricultural residues and the processing and use of vegetable oils as a substitute for petroleum-based diesel fuel. Farm energy needs include space and process heat, electricity and shaft power. There is a need to match the energy requirements with the available feedstocks and appropriate conversion technology.

The major problem surrounding the anaerobic digestion of animal manure is informational in nature. The agricultural sector has not been convinced that this technology is both technically and economically feasible under appropriate circumstances. Plans are to construct and demonstrate a number of on-farm digestion systems to encourage wider user acceptance. Direct combustion and low Btu gasification systems designed to use crop residues will be constructed and demonstrated for several applications including crop drying and shaft power for irrigation. Concurrently, these systems will be fine tuned to alleviate material handling and storage problems.

Several issues are currently unresolved concerning the substitution of vegetable oils for diesel fuel. Tests will be conducted to determine if available processing equipment for oil seed crops is cost and energy effective when used on-farm. Similarly, the performance of vegetable oils in farm equipment engines will be evaluated as well as the need for modifications to provide for efficient operation. In addition, research on the chemistry of these oils will be directed at identifying useful by-products and quantifying combustion characteristics.

Technology Development

A wide ranging program is being pursued for the development of biomass production and conversion systems. The production research is aimed at increasing the biomass resource base, through silvicultural, herbaceous and aquatic crop development. Activities involve not only developing production systems, but also the harvesting, processing and delivery technologies needed to supply the biomass to a conversion facility.

Silvicultural research activities are concentrating on filling gaps in information and developing the technologies needed for growing and harvesting woody biomass both on energy plantations and from natural stands. Species are being identified, regionally, for cultivation on short-rotation energy farms on a variety of sites, including arid and semi-arid land. Tied closely to the species screening efforts is the quantification of the cultural techniques, energy inputs and costs of increasing yields. Various schemes will also be tested for increasing the fuelwood output from natural stands during commercial harvests. Currently available harvesting equipment has been designed, principally, for the handling of large and relatively uniform logs. Delivering small and defective trees, tops, and irregular pieces from logging sites and short-rotation plantation material with this equipment is inefficient and costly. Improvements and specialized equipment and systems will be designed and tested to harvest such materials and process it into a uniform size for transport and use. Fquipment will also be designed or modified to effectively handle these materials on a wide variety of terrain such as steep slopes, wetlands and small wood lots.

The herbaceous species production program is in the early stages of development and deals with non-woody plants which are not traditionally cultivated. A regional approach will be used to determine the extent to which systems will be practical based upon land availability and potential end use applications. Natural stands as well as those under cultivation will be evaluated. As the cultivation and harvesting techniques are quantified, efforts will also concentrate on matching the biomass with the appropriate conversion technology to produce the desired energy product(s).

The aquatic species program includes four categories of aquatic plants: microalgae, macroalgae, floating plants, and emergent plants. All are capable of rapid growth and can provide biomass yields that surpass those of terrestrial plants.

Microalgae, which can be grown in saline, brackish and wastewater can supply up to 85 percent of their mass in easily extractable hydrocarbons. Land-based systems are under development that maintain a circulation of nutrients and carbon dioxide as well as stabilize the pH and temperature. A special problem area under investigation is defining those environmental conditions which enhance lipid and hydrocarbon production.

Macroalgae, such as giant kelp and other seaweeds, have the capacity to produce and store proportionately large amounts of carbohydrates. The engineering problems associated with the development of land based and nearshore systems for macroalgae are similar to those for microalgae. Nutrients must be supplied to maintain yields sufficient to support the operating and structural costs of the system and stable environmental conditions must be provided.

Floating aquatic plants, particularly water hyacinth, have been shown to be highly productive as well as effective wastewater purifiers. Advantage of both factors is being taken into account through the integration of wastewater treatment with biomass production and conversion systems. Major limitations associated with this concept are the restricted geographical range of water hyacinth and the high rates of water loss through transpiration. These problems are currently under investigation.

A major problem area common to microalgae, macroalgae, and floating plant systems is harvesting. In each case, large amounts of water must be processed in proportion to the biomass recovered.

Emergent aquatic plants, such as reeds, cattails, and bulrushes represent a potentially significant feedstock resource. The U.S. has extensive marsh land which has been estimated to be greater than 42 million acres. However, information must be developed with respect to the cultivation, management, and harvesting of these species. In addition, since marsh ecosystems are very sensitive to disruption, numerous environmental issues will be carefully analyzed during the development of these species.

Complimenting the production systems research is the development of biomass conversion technologies. These include the medium Btu gasification, the direct liquefaction and the anaerobic digestion of cellulosic feedstocks.

BES is currently testing a variety of high performance gasification systems to determine which are technically and economically feasible. The major challenge, currently being addressed by the gasification research, is the production of medium Btu gas and synthesis gas without the addition of pure oxygen. Medium Btu gas and synthesis gas have several advantages over low Btu gas. First, unlike low Btu gas, medium Btu gas can be piped a considerable distance and second, synthesis gas can be upgraded to substitute natural gas and reformed into liquid fuels, such as methanol and other higher alcohols. Novel heat transfer techniques are being incorporated in the design of biomass gasifiers to eliminate the costly oxygen units used in coal gasification processes. Catalysts are also being employed to direct processes toward a desired gas composition and eliminate tars and heavy hydrocarbons.

Many reactors require that the biomass be fairly uniform in size and shape for proper feeding and gasification. Processing equipment will be evaluated and modified, if necessary, to produce suitable feedstocks from a variety of biomass types including forest and agricultural residues.

The direct liquefaction of biomass produces a biocrude oil. The feedstock is made into a slurry with a carrier fluid, usually oil or water, before entering the reactor. Once the biocrude oil is produced, it is separated and the carrier recycled. The major issue in direct liquefaction is the need to reduce the energy lost in heating and cooling of the carrier fluid. Extrusion feeding devices are being developed to increase the concentration of biomass in the carrier fluid. It is expected that increasing the ratio of biomass to carrier fluid will improve not only the energy balance, but the manufacturing costs as well.

The anaerobic digestion research is aimed at gaining a more complete understanding of the biochemistry of methane production from crop residues. Comparisons are being made between thermophyllic and mesophyllic bacterial systems. A major drawback to anaerobic digestion is the long retention times necessary to convert the cellulosic feedstocks. Various pretreatment schemes are being tested to enhance the overall process. In addition, economic uses of the digester effluent are being sought, including cattle feed and fertilizer, to eliminate disposal costs.

Exploratory Research

Exploratory research is being conducted to support the activities of the entire program. Longer term projects, such as the development of terrestrial plants which produce hydrocarbons and the photobiological, photoelectrolytic, and photochemical production of hydrogen are included. A fundamental understanding of these renewable energy options must be gained before full scale engineering development is warranted.

Research has been initiated on developing hydrocarbon bearing plants for semi-arid and arid regions. Species screening activities are attempting to determine those species with the greatest potential to synthesize desired hydrocarbons. Another problem area is the extraction and characterization of these fluids. Work is underway on the development of chemical process techniques for the extraction of plant materials after harvest. Potential market applications are also being identified and will be evaluated to determine the most suitable energy end use of the hydrocarbons.

The demand for hydrogen as a chemical feedstock in the U.S. is growing steadily and expected to continue in view of the attention being given to synthetic fuels. Low cost hydrogen production systems will be needed to compliment this emerging industry. Several approaches are being investigated to produce hydrogen photobiologically. Basic research is being conducted primarily on the biochemistry of hydrogen production by photosynthetic bacteria, algae and cell free or *in vitro* systems. Photoelectrolysis is closely related to photovoltaic hydrogen production except the photoactive semiconductor material becomes not only the solar collector but the electrode as well. Semiconductor materials are being developed which possess a suitable wavelength threshold and also resist corrosion. Research efforts in photochemical hydrogen production systems are focused on increasing the solar conversion efficiencies of promising processes.

CONCLUSION

In summary, the Biomass Energy Systems Program is pursuing numerous combinations of feedstock, conversion process and end-product which have the potential to contribute to our energy needs. Specific barriers and problems have been and will continue to be identified and solutions will be sought to ameliorate them.

The commercialization efforts are expected to accelerate the acceptance of biomass technologies by industry in the near term and lead to significant energy contributions by the year 2000. Furthermore, DOE will continue to play a key role in supporting the research and development of promising technologies.

HERBACEOUS LAND PLANTS AS A RENEWABLE ENERGY SOURCE FOR PUERTO RICO

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE UPR CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
Biomass Division, Río Piedras, Puerto Rico

HERBACEOUS LAND PLANTS AS A RENEWABLE ENERGY SOURCE FOR PUERTO RICO

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Herbaceous Land Plants As A Renewable Energy Source For Puerto Rico

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ABSTRACT

HERBACEOUS tropical plants are a renewable energy source of major importance to many tropical nations. They convert the radiant energy of sunlight to chemical energy, which is stored in plant tissues (cellulose, hemicellulose, lignin) and fermentable solids (sugars, starches). Because all tropical plants do this—even those commonly regarded as "weeds"—they constitute an inexpensive, renewable, and domestic alternative to foreign fossil energy.

The vast majority of herbaceous tropical plants have never been cultivated for food, fiber, or energy. A major screening program would be needed to identify superior species and the most effective roles they can play in a domestic energy industry. Other herbaceous plants, such as sugarcane and tropical forage grasses, have been cultivated for centuries as agricultural commodities. As energy crops, important revisions in management will be needed to maximize their energy yield.

Two broad groups of herbaceous plants are seen to have an immediate potential for reducing Puerto Rico's reliance on imported fossil fuels: The tropical grasses (of which sugarcane is the dominant member) and the tropical legumes. Managed for its maximum growth potential, sugarcane is an excellent source of boiler fuel, fermentation substrates, cellulosic feedstocks, and the sweetener sucrose. Other tropical grasses store relatively little extractable sugar while equaling or moderately surpassing sugarcane in yield of cellulosic dry matter. The latter might soon become an economical source of fermentation substrates. Certain legume species are also very effective producers of biomass. Herbaceous tropical legumes are perceived as a potential source of biological nitrogen for energy crops unable to utilize nitrogen from the atmosphere.

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Herbaceous Land Plants As A Renewable Energy Source For Puerto Rico

INTRODUCTION

1. Herbaceous Plants In Perspective

FOR this presentation the term "herbaceous" refers to nonwoody plants having some potential as renewable energy sources. Ordinarily, a herbaceous plant will complete its life cycle in one growing season or one year. It is comprised of relatively succulent tissues as opposed to the drier and more fibrous tissues of woody perennial species.

This distinction between succulent and woody species becomes much less clear in the tropics. Herbaceous plants may grow continuously rather than seasonally, and some species will do so for many years. For example, a 6-months old stem of napier grass can be far more "woody" than most forest trees of equal age. Similarly, an 18-month "gran cultura" crop of sugarcane, though still "herbaceous," can yield more fiber/acre than virtually any form of higher plant in a comparable period of time.

Literally thousands of terrestrial plant species can be regarded as potential energy sources. A majority of these are herbaceous seed plants which complete their growth and reproductive processes within a single growing season of a few months duration. They are widely distributed from arctic regions to the tropics (1,2,3). They are equally diverse with respect to their growth and anatomical characteristics, their cultural requirements, and their physiological and biochemical processes (2-9). Yet, all have the capacity to convert sunlight to chemical energy and to store this energy in the form of biomass. An oven-dry ton of herbaceous biomass represents about 15×10^6 BTU's of stored energy. The direct firing of one such ton, in a stoker furnace with high-pressure boiler having a 70% conversion efficiency, would displace about two barrels of fuel oil. Alternatively, as cellulosic materials (10), much of the dry biomass could be converted to fermentable sugars, alcohol, and a range of chemical feedstocks (Figure 1).

In addition to their fibrous tissues, some species also produce sugar or starch in sufficient quantities to warrant extraction and conversion to alcohol. The total soluble sugars of sugarcane comprise roughly 1/3 of the whole plant, or about 40% of the millable cane stem (11). The "Irish" potato (*Solanum tuberosum*) is frequently used as a fermentation substrate during periods of low market value. Other species store energy in the form of natural hydrocarbons (12,13).

A majority of herbaceous land plants have never been cultivated for food or fiber. In warm climates, wild grasses such as *Sorghum halepense* (Johnson grass), *Arundo donax* (Japanese cane), and *Bambusa* species are borderline cases where occasional use has been made of their high productivity of dry matter. In cooler climates, self-seeding plants such as reed canarygrass, cattail, wild oats, and orchard grass may be viewed with mixed feeling by landowners unable to cultivate more valuable food or forage crops. Plants such as ragweed, redroot pigweed, and lambsquarters are recognized for their persistent growth habits while otherwise regarded as common pests. However, the value of such species could rise dramatically as biomass assumes a future role as a renewable, non-fossil energy resource.

2. Prior Studies With Herbaceous Plants

While it is not correct to say that herbaceous land plants have been overlooked as a domestic energy resource, only a small number have been examined closely for this purpose. Among the latter are tropical grass species of *Zea, Sorghum, Saccharum,* and *Pennisetum* which were recognized for their high yields of fiber and fermentable solids long before the oil embargo of 1973. Throughout their history as cultivated crops, plants such as corn, sweet sorghum, sugarcane, and napier grass have evolved extensive technologies for their cultivation, harvest, post-harvest transport and storage, and for their processing and marketing. Other tropical plants, some with very fine botanical or agronomic attributes and confirmed histories as excellent biomass producers, have been generally ignored as energy resources. Pineapple, cassava, plantain, and papaya are examples of underutilized tropical biomass species (4,8,14).

Aside from sugarcane and "allied" tropical grasses (5,6,7,11,15,16,17), relatively little attention has been given to herbaceous land plants specifically as sources of fuels and chemical feedstocks. Studies were initiated recently at Battelle-Columbus Laboratories on common grasses and weeds as potential substitutes for fossil energy (18). Plants showing promise as boiler fuels include perennial ryegrass, reed canarygrass, sudangrass, orchardgrass, bromegrass, Kentucky 31 fescue, lambsquarters, and others. A range of species have indicated some potential as sources of oil, fats, protein, dyes, alkaloids, and rubber. Such plants include giant ragweed, alfalfa, jimsonweed, crambe, redroot pigweed, dogbane, milkweed, and pokeweed.

In 1978 the U.S. Department of Energy issued an RFP for herbaceous plant screening as a means to close the information gap in this area of biomass energy development (19). The DOE objective has two phases: First, to identify promising species for whole-plant biomass production in at least six different regions of the U.S., and second, to perform field evaluations on at least 20 species per region, with a view toward identifying those most suitable for cropping on terrestrial energy plantations. Arthur D. Little, Inc. was selected to conduct Phase I (2).

Six regions were designated on the basis of climatic characteristics, land availability, and land resource data provided by the U.S. Soil Conservation Service. A list of 280 potential species was prepared on the basis of published literature and personal interviews. These were screened in accordance with botanical and economic characteristics, with emphasis on previously uncultivated species. Certain agricultural plants were also considered.

Factors such as yield potential, cultural requirements, tolerances to physiological stress, production costs, and land availability were considered in ranking the candidate species of each region (2). Plants with yields less than 2.2 tons/acre (5 metric tons/hectare) were eliminated. For the potential energy crop species comparisons were drawn with six categories of economic plants, including tall and short broadleaves, tall and short grasses, legumes, and tubers. Some 70 species were recommended for consideration in the program's second phase (field screening). Some of these plants (redroot pigweed, lambsquarters, Colorado river hemp, ragweed) have no prior history as cultivated crops and their cultural needs remain obscure. Other species (Bermuda grass, Kanaf, reed canarygrass, sudangrass) have been improved and cultivated for decades.

HERBACEOUS TROPICAL PLANTS

The initial steps taken by DOE to evaluate herbaceous land plants will help to clarify their value as a renewable energy source for the U.S. mainland. No comparable effort has been undertaken for the species of Puerto Rico or for tropical regions in general. The remainder of this presentation concerns two broad categories of tropical plants common to Puerto Rico, ie, the tropical grasses and the herbaceous tropical legumes. Intentionally or otherwise, much experience has been gained with each group over a period of many decades.

1. Botanical Considerations

The correct selection and management of tropical herbaceous plants is aided by an understanding of their function as botanical entities. Above all, the biomass energy worker must recognize four decisive characteristics: (a) That each species is a living solar collector of potential value, but operating for its own benefit rather than that of man; (b) an ability to utilize effectively a limited or irregular water supply; (c) an ability to harvest solar energy on a year-round basis, if correctly managed for this purpose; and (d) the biomass-producing potential of each species is a function of two discrete growth phases, ie, tissue expansion and tissue maturation.

(a) *Photosynthetic Energy Conversion:* Although not an efficient process, photosynthesis is the only system of solar energy conversion on earth that has operated at any appreciable magnitude, with any appreciable economy, for any appreciable period of time. The earth's plants store annually about 10 times more energy than is utilized by man, and about 200 times more than is consumed as food (20).

SOLAR ENERGY CONVERSION TO BIOMASS

$$CO_2 + H_2O \xrightarrow[\text{Chl}]{\text{light}} [CH_2O] + O_2$$

Energy Storage = 114 KCal/Mole CO_2

Photosynthesis consists of two phases: (a) Energy capture, yielding chemical energy and reducing power; and (b) the reduction or "assimilation" of atmospheric CO_2. The carbon reduction phase is accomplished by three distinct pathways (C_3, C_4, and CAM). Each pathway is found among tropical herbaceous plants, but the C_3 pathway is probably the most widely distributed. CAM plants, which assimilate carbon at night, are relatively less important even though their utilization of water is generally more efficient than for C_3 species. The C_4 pathway was at first thought to reside only in sugarcane and related tropical grasses (21,22,23). It was soon found in temperate plants such as *Zea, Sorghum,* and *Amaranthus* (34-38). The C_4 species constitute a kind of apex in photosynthetic proficiency (5,9,23), aided to some extent by attributes such as a low CO_2 compensation point, a "lack" of photorespiration, and a capability to utilize both lower and higher light intensities than do C_3 and CAM species (Table 1).

An important aspect of photosynthetic energy conversion often overlooked in higher plants is their "spectral proficiency," that is, their ability to convert different regions of the sun's spectral energy distribution. Ironically, more than 60 percent of incoming solar energy is received at wavelengths shorter than 550 nm, while (apparently) most plants are photosynthetically active at wavelengths longer than 600 nm. There is some evidence that *Saccharum* species have major photosynthesis activity in the blue-violet to blue-green region (25,26). Photosynthetic action spectra have been determined for approximately 30 agricultural plants, but a vast majority of herbaceous land plants have not been examined in this context.

(b) *Energy Conversion vs Water Utilization Efficiency:* Tropical herbaceous plants such as sugarcane, corn, and sweet sorghum require about six inches of water per month to sustain maximum growth (27,28,9). Most tropical plants will not receive that quantity of water as rainfall nor are they likely to be given this quantity as irrigated crops. Their water utilization efficiency will be influenced markedly by the specific pathway of carbon reduction. C_4 species should tend to reduce more carbon per unit of water transpired than C_3 species but less than plants using the CAM pathway. C_4 plants such as sugarcane (4,27,Chap. 4) have a lower mesophyll resistance (r_m) than C_3 plants, favoring in turn a steeper CO_2 gradient between the atmosphere and photosynthetic reaction sites in the leaf. CAM plants have an r_m comparable to C_4 plants, but they assimilate carbon at night when transpirational water loss is at a minimum. The CAM pathway in effect is a plant water conserving mechanism.

(c) *Year-Round Growth Potential:* To produce maximum biomass on a per annum basis one would ideally select a year-round growing season and propagate species that grow on a year-round basis. Certain grasses (sugarcane, napier grass, Johnson grass, bamboo) do this nicely if planted in the tropics. Some of their members produce well also in sub-tropical or even temperate regions, but they will realize only part of their full yield potential when growth is constrained for several months by cool temperatures and reduced daylength. At the risk of offending mainland sugarcane planters, it must be said that there is no region of the continental U.S. really suited to tropical grasses production in this context. Even in Puerto Rico, located only 18 degrees north latitude, a very definite "winter" effect is exerted on the growth rates of sugarcane and napier grass (Table 2).

It is important to recognize also that growth is a 24-hour process as well as a 12-month process. The photosynthetic and tissue-expansion systems that operate each day are fully dependent on the noctural transport and mobilization of growth-supporting compounds. For this reason the tropics are again favored by their warm nights for biomass production (27).

Possibly the most desirable growth characteristic of all for herbaceous species is the ability to produce new shoots continually throughout the year, year after year, from an established crown. This is a predominant characteristic of sugarcane and certain other tropical grasses both related and unrelated to *Saccharum* species. Such plants do not require the periodic dormancy and rest intervals so important to most temperate species. Nor is this compensated by the intensive flush of May-June growth by temperate plants. Over the course of a year, the slower-growing tropical forms will out-produce them by a factor of three or four.

A less obvious but utterly critical feature of the perennial crown is its continual underground contribution of decaying organic matter to the soil. This process proceeds concurrently with the continuous renewal of underground crown and root tissues. For this reason the long-term harvest and removal of above-ground stems, together with the burning off of "trash," does not have an adverse effect on sugarcane lands. There are soils in Puerto Rico that have produced sugarcane more or less continually for four centuries without destruction of their physical properties or nutrient-supplying capability. On the other hand, seasonal crops such as field corn and grain sorghum do not develop a perennial crown. For these plants a good case can be made against the removal of above-ground residues from the cropping site.

(d) *Tissue Expansion vs Maturation:* A common misconception holds that biomass growth involves mainly a visible increase of size, and that per acre tonnages of green matter are a reasonably accurate indicator of a plant's yield potential. It is also frequently assumed that the moisture content of plant tissues is essentially constant at around 75 percent, and that dry matter yields can be calculated rather closely from green weight data. These assumptions are not correct in any case but are particularly erroneous with respect to herbaceous tropical species.

In virtually all herbaceous tropical plants, "growth" consists of discrete, diphasic processes of tissue expansion followed by maturation. The tissue expansion phase produces visible but succulent growth consisting mainly of water (in the order of 88-92 percent moisture). The maturation phase corresponds to physiological aging and senescence, that is, to flowering and seed production, slackening of visible growth, yellowing and loss of foliage, and hardening of the formerly succulent tissues. During this period the dry matter content will increase by a factor of two to four in a time interval that may be shorter than that of the tissue-expansion phase. An excellent example of this is the hybrid forage grass Sordan 70A, which more than doubles its dry matter yield in a time-span of only two weeks (29, ie, during weeks 8 to 10 in a 10-week growth and reproduction cycle) (Figure 2). For this reason the optimal period of harvest must be determined with care for each candidate species.

For most herbaceous tropical plants the production of dry matter can be plotted as an S-shaped curve, as shown schematically in Figure 3. Dry matter content will not ordinarily exceed 10 to 12 percent during the period of rapid tissue expansion but will begin to rise dramatically at some point in time that is characteristic of the individual species. Dry matter will rarely increase beyond 40 percent in herbaceous plants. Attempts to hasten this rise (by withholding water) or to delay it (by use of growth stimulants) have met with limited success in tropical grasses (30).

2. Management As Energy Crops

Certain characteristics of a promising tropical plant as a biomass energy resource were described in the preceding sections. In translating such plants to a well-managed, energy-plantation scenario, some straight-forward steps must be taken to assure maximum returns from production expenditures. These will include: (a) Correct land preparation, including land leveling and planing where needed; (b) correct design and installation of the irrigation system; (c) correct seedbed preparation; (d) careful selection and treatment of seed; (e) correct seeding (relative to depth, density or row spacing, and season); (f) reseeding of vacant space when necessary; (g) correct pest control programs (including administration of control on weekends and holidays when required); (h) maintenance of correct irrigation, fertilization, and cultivation programs; (i) correct timing and synchronization of harvest operations; (j) correct selection and use of harvest equipment; (k) post-harvest maintenance of land and machinery.

For most biomass crops the costs of these measures will accrue whether they are performed correctly or not. The decisive factor will be the skill and motivation of the operation's field managers. In the author's opinion, good management can best be assured for Puerto Rico when production is retained in the context of privately owned plantations that are operated for personal profit.

(a) *Harvest Frequency:* Of all management operations, the correct harvest period for herbaceous tropical plants is probably the least understood. It is here that prior experience with a given species can lead one astray when trying to maximize its energy potential.

Once the diphasic nature of biomass growth and maturation is recognized (Figure), the importance of harvest frequency is also underscored. The optimal period for harvest in the maturation curve of one species will differ enormously from the optimal harvest period of another–even among varieties within the same genus and species. For this reason it has been convenient to group candidate tropical grasses into distinct categories based on the time interval that must elapse after planting to maximize dry matter yield (30). The management and harvest requirements of each group will also vary. On this basis the tropical grasses were organized into "short-, intermediate-, and long-rotation" categories (30).

As illustrated in Figure 4, the schematic maturation curves for type species of each category vary greatly over a time-course of 12 months. Hence, to harvest sugarcane at the 10-week intervals favorable to Sordan 70A would yield little dry matter. Similarly, any delay of the Sordan harvest beyond 12 weeks is a waste of time and production resources. Napier grass, an "intermediate rotation" species, is more than a match for sugarcane at two- and four-months of age, and will nearly equal sugarcane yields at six months, but thereafter sugarcane will easily out-produce napier grass. In this context a short-rotation species should be harvested four or five times per year, an intermediate-rotation species two or three times per year, and a long-rotation species no more than once per year. This need for careful attention to the maturation profiles of candidate species is underscored by yield data for sugarcane and napier grass harvested at variable intervals over a time-course of 12 months (Table 3).

It is also evident that, while Sordan and napier grass attain rather level plateaus for dry matter, sugarcane continues to increase dry matter beyond 12 months (Figure 4). Sucrose accumulation profiles are very similar for sugarcane. For many years sugar planters have taken advantage of this feature by extending the cane harvest interval beyond 12 months. Hence, the Puerto Rico sugar industry harvests two crops—the "gran cultura" (16 to 18 months between harvests) and the "primavera" (10 to 12 months between harvests). In Hawaii sugarcane is commonly harvested at 20 to 24 month intervals.

(b) *Energy Crop Rotations:* From Figure 4 one would surmise that the energy plantation manager should plant a herbaceous species such as sugarcane and leave it there—up to 18 months if possible—before harvest. In addition to maximum fiber he would also harvest fermentable solids as a salable by-product. This reasoning would probably be correct in a tropical ecosystem suited to *Saccharum* species and where a regional tradition exists for sugar planting. However, these circumstances do not exist in many countries having an otherwise good potential for growing biomass. For example, there is no region of the U.S. mainland suited for 12- to 18-month cropping of sugarcane, although there are vast regions there suited to some form of tropical grasses. Hence, a future energy planter in Florida, Louisiana, southern California, or southern Texas might seriously consider whether he should harvest a 6 to 8 month crop of sugarcane per annum or two crops of napier grass in the same time-frame.

Equally important is the fact that some countries will not be able to afford a land occupation of 18 months by a single energy crop. This is especially true of densely populated, developing tropical nations having an urgent need for domestic food production (32). In such cases a short-rotation species such as Sordan may be the popular choice for energy planting since it can be sown as a stop-gap between the harvest of one food crop and the planting of another. In this capacity it would also prevent soil erosion and weed growth while acting as a scavenger for residual nutrients left over from the prior food crop.

Seasonal climate changes will also be a factor in the rotation of biomass energy species with conventional food and fiber crops. Short-rotation tropical grasses such as Sordan are ideally suited to the tropics—but they can be grown on a seasonal basis during the heat of summer in most temperate regions. Such plants could be propagated to maturity in a mid-June to mid-August time frame. In a given year the same site could produce a cool season food crop (a *Brassica* species, spinach) or a cool season forage (ryegrass, fall barley) both preceding and following the biomass energy crop.

(c) *Solar Drying, Compaction, And Delivery:* A perceptive observer of mainland biomass conferences will recognize a consistent weakness in harvest equipment and harvest technologies for maximized crops of biomass. This is most evident in woody biomass scenarios where conventional forest harvesting technology is either not applicable or simply doesn't exist in the context of silviculture energy plantations. The outlook for harvesting herbaceous tropical plants is considerably better, but a good deal of research remains on harvest and post-harvest technology, together with equipment redesign and modification.

The vast majority of herbaceous tropical land plants will have relatively low density stands at harvest (less than 10 green tons/acre) and can be mowed adequately with a conventional sickle-bar mower. Aside from low plant densities its chief limitations are: (a) A requirement for dry, upright stems (it has difficulty with wet, lodged material), and (b) its cutting process is confined to a single slice near the base of upright stems. In other words, it is essentially a mechanized sickle for severing stems rather than conditioning them for drying. A more suitable harvest implement is the "rotary-scythe conditioner," a machine which "mows" herbaceous plants by shattering the stems at 3- to 5-inch intervals. This implement has been totally effective on mature napier grass stands of about 40 green tons/acre (16,31). It functions nearly as well in lodged material as in upright stems. An added advantage is its relatively trouble-free operation. The number of parts subject to malfunction have been reduced to an absolute minimum.

The solar drying of herbaceous energy crops would be very similar to conventional hay-making operations. For light materials the same rake and tedder designs used in hay making will be quite adequate. Drying tests with mature napier grass indicate that an added one to two days drying time will be needed owing to the thickness of the plant stems (17,31). Such relatively heavy materials have not been handled well by conventional forage rakes operating from the tractor's PTO system.

However, it is expected that a different rake design, ie, the "wheel" rake, will perform adequately under these conditions (31).

The baling, or compaction, of light herbaceous materials similarly should pose no serious difficulties. The standard hay baler today is actually a compactor. It produces conveniently-sized cubes having a controlled density range of roughly 12 to 20 pounds/cubic foot. A typical bale would be a rectangular cube weighing 60 to 70 pounds and easily handled by one man in transport and storage operations or in feeding cattle.

A baling machine of more recent design is the "round" or "bulk" baler which performs as a windrow wrapper rather than a compactor. It produces large cylindrical bales weighing up to 1500 pounds each (33,34). Since no appreciable compaction is involved the mass density is relatively low—in the order of 10 to 12 pounds/cubic foot. More recent modifications enable this machine to produce cube-shaped bales which are more economical of space during transport and storage. The round baler has given very good performance with solar-dried Sordan, and with solar-dried napier grass aged up to six months at the time of harvest (17,31). Both front- and rear-end loaders suitable for handling these bales are marketed as conventional tractor attachments.

There are two types of balers for sugarcane bagasse: The baling press and the briquetting press (35). The first type is a hydraulic press employing the same compaction principle used for hay. The bagasse is baled in a semi-green state and the formed cubes are tied with twine or wires to prevent them from reexpanding. Their density will range from 25 to 40 pounds per cubic foot. Bales of this type must be stacked carefully to prevent spontaneous combustion, that is, with sufficient space between them to allow air circulation. The briquetting press operates with dry bagasse having a moisture content of 8 to 15 percent. This press provides high pressures in the order of 5,000 to 15,000 psi. Under these conditions extremely compact cubes are produced which retain their form without the use of twine or wires.

For herbaceous biomass that has been solar-dried and baled, it should be possible to deliver it to processing or storage sites without appreciable difficulty with existing equipment. Ordinarily such materials would be loaded directly in the field on a low-bed truck. Standard bales (60-80 pounds) can be loaded manually or with mechanical loaders requiring only one laborer on the truck for final positioning of the bales. Bulk bales would be stacked two layers deep on the truck bed with tractor-mounted loaders. The same truck would transport the biomass to a final processing or storage facility without intermediate transshipment operations. In the case of sugarcane, the harvested whole stalks or stem billets are hauled in carts to the adjacent mill. The same materials are sometimes carted to an intermediate reloading point for truck delivery to more distant sugar mills.

Delivery costs will vary considerably with the individual biomass production operation. As a general feature, a 30-ton, low-bed truck with driver can be hired for about $200 per 24-hour day. Loading equipment with operators must be stationed at each end of the delivery run. In an ideal biomass production operation, ie, one managed by a private farmer for profit, the land owner would probably own and help operate the truck and accessory equipment. An estimated delivery cost for solar-dried biomass on a 20-mile run would be $6.00 to $8.00 per ton.

(d) *Obtaining Correct Cost Data:* A seriously misleading trend is to base the production costs of a herbaceous biomass candidate on its published yield performance as a conventional food or fiber crop. Yet, this is done routinely by otherwise highly qualified analysts (36,37,38,39). Sugarcane is an appropriate example. In Puerto Rico, sugarcane managed for sucrose yields 25 to 30 millable tons per acre year at a cost of about $600.00/acre (41). As an energy crop it can yield 80 to 90 tons per acre year with only moderate increases in production costs (40,41). Napier grass data are similarly misleading. There is a wealth of printed matter on the yields of napier grass managed as a tropical forage crop, that is, when harvested repeatedly at five- or six-week intervals at moisture contents approaching 90 percent. As an energy crop, napier grass produces roughly two to three times more dry matter per annum at less cost than the cattle forage (16,40).

The concept of an "energy plantation," especially as applied to herbaceous plants, raises the spectre of intensive production operations, a continual forcing of lush green plants to production levels beyond their usual means, and a frequent coming and going of assorted machines, all with sinister implications for the land and environment. Our own experience with tropical species indicates that just the opposite will happen (16,31,40,41). The decisive factor is the acceptance of herbaceous species as sources of dry matter rather than as food or forage commodities. This means that the plants' maturation phases rather than human activities will be the main source of increased yield. The increased inputs of water and nutrients are actually *extensive* rather than *intensive* factors; a disproportionately greater time lapse is allowed for these to be assimilated in growth and maturation processes. The presence of heavy equipment will be reduced by more than half. Expenditures for transportation, fuel, labor, pesticides, seed, and seedbed preparation will also be lowered by a significant fraction. Land rentals, plus pre- and post-harvest land maintenance costs, will be about equal to conventional food- and forage-cropping operations. There is no point in the herbaceous energy plantation scenario where one can perceive clearly the producer *doing* more; there are many points where he is doing less. Again, it is largely the plants' inherent capacity to make dry matter, and the grower's good sense in allowing them to do so, that validate the energy plantation as a correct and profitable enterprise.

TROPICAL LEGUMES

1. The Need For Alternative Nitrogen Sources

Cost and energy balance data for tropical grasses managed as energy crops underscore an imperative need to lower inputs of chemical fertilizers, particularly nitrogen-bearing fertilizers (16,40,41). A characteristic feature of the tropical grasses is their need for a significant input of nitrogen (N) to maximize yield (40,42,43). For sugarcane, fully half of the total energy expenditure in optimizing dry matter can be traced to elemental N (41). Unfortunately, Puerto Rico must import her nitrogen in the form of nitrates, ammonium sulfate, and urea, at a time when both the manufacturing and importation costs of these sources are mounting drastically. Since the early 1960's the local sugarcane industry has been underutilizing mineral N owing to high fertilizer costs. Since 1974 these charges have become all but prohibitive for adequate field management of the cane plant.

The option of developing tropical legumes as a local N source was an attractive concept for Puerto Rico more than 25 years ago (44-48). Little was done by way of investigating the co-production of legumes and tropical grasses, although some work was done on soybean intercropping with food crops (46,49,50). A rather extensive range of wild, hardy, and highly-adaptive legumes was almost entirely overlooked as potential N resources. Even today some of the most productive herbaceous legumes on the Island (*Phaseolus* spp.) are widely regarded as weeds and are destroyed by pre- and post-emergence herbicides.

2. An Underexploited Tropical Resource

The number and diversity of wild tropical legumes seems surprisingly large even to experienced plant taxonomists. This is the consensus of a recent study by the U.S. National Academy of Sciences (51). An initial NAS listing of 150 "promising" species was quickly expanded to 400 species when brought to the attention of plant scientists throughout the world. As the study progressed, an additional 200 species were nominated as potentially valuable resources for developing nations. From a total of over 600 candidate legumes nearly half received top ranking by at least one plant scientist. This is a clear reflection of legume adaptability to the variations of soil, rainfall, temperature, and sunlight found in the ecological life zones of the world's tropics (51,52,53).

3. Puerto Rico's Native And Imported Legumes

A large number of legume species–both herbaceous and woody–are found in Puerto Rico but their modern taxonomy remains obscure. In part this relates to an inherent difficulty in distinguishing clearly between species at the genus level. Moreover, while individual scientists have shown periodic interest in the wild legumes there has been no concerted effort by Island research institutions to evaluate this family as an agricultural resource (54,44).

The earliest systematic survey of PR legumes dates back 75 years. It was published by J. R. Perkins as a Contribution to the U.S. National Herbarium (55), and is based on collected specimens retained by the Royal Botanical Museum of Berlin. Perkins also used materials collected by Urban. She generally followed the nomenclature of Watt, Urban, Cook, Collins, and other reliable authorities of that period, but did not work with specimens in the field. Significantly, the editors of the "Contributions" series initially delayed publication of this work in anticipation of a complementary study on "agricultural relations" of Puerto Rico legumes. The latter did not appear and Perkin's work was published as a separate account.

Perkins described 67 genera and 141 species of legumes in Puerto Rico. An apparent lack of endemic species was noted. Only one genus (*Stahlia*), with eight species, was considered native to

Puerto Rico. Most were common to the Antilles, Central America, and South America. In 1974, Woodbury and coworkers (56) compiled a list of indigenous Puerto Rican legumes consisting of three sub-families, 24 genera, and about 50 species (Table 4). Nodulation was extensive in both acidic and neutral soils. Nearly all of these species were thought to have potential agricultural value (56).

The entry of new legumes into Puerto Rico probably dates to the inter-island movements of pre-Columbian times. The Caribs are thought to have used plant materials for food, shelter, utensils and clothing (57). The process was definitely accelerated by the steady arrival of Europeans in the sixteenth century. In nature, a discrete species could be confined to a single hill, or require many centuries to spread even to its preferential habitats on the Island (57). This process was also speeded up by the advent of roads and human commerce throughout Puerto Rico. In recent decades the entry and dispersal of new species could have occurred in a matter of hours. This is particularly true of small-seeded forms accompanying farm produce as "weeds," or as totally unnoticed occupants of highway vehicular traffic. For example, the species *Phaseolus lathyroides* is quickly. discernable along roadsides and refuse areas in virtually every Puerto Rican town and district.

4. Potential Co-Production With Tropical Grasses

An immediately attractive concept for tropical legume exploitation is their use as biological N sources for tropical grasses. Certain legume species would contribute an appreciable quantity of cellulosic biomass as well. Alternatively, some biomass potential in tropical grasses could be sacrificed in selecting candidates especially well suited for coproduction with legumes.

From prior observation there appear to be at least 80 to 100 wild legumes having some potential for either coproduction or intercropping with tropical grasses. The real number is probably much larger. Some of the more obvious legume candidates include species of the genera *Glycine, Phaseolus, Sesbania, Desmodium, Lespedeza, Vigna, Leucaena, Acacia, Pueraria,* and *Cassia* (Table 5). These range in size from small vines and bushes to semidwarf trees. All would be *managed* as herbaceous N sources, including woody species in their juvenile growth period. Each category has a potential contribution to make in the production of short-, intermediate-, or long-rotation tropical grasses (Table 5).

Many additional legumes could be imported for evaluation as energy crops. As many as half of the 600 species identified by NAS (51) are potential candidates. Examples of these include *Medicago, Lathyrus, Coronilla, Cajanus, Crotalaria, Sesbania,* and *Vicia.* Some are only partially represented on the Island, while others, such as the "Colorado River Hemp" (*Sesbania exaltata*) have only recently come to the attention of local biomass researchers. Certain legumes not ordinarily classified as "tropical" would be fully accepted if they serve the needs of tropical grasses.

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Table 1

PHYSIOLOGICAL ATTRIBUTES OF SACCHARUM AND ALLIED GENERA

- C_4 PATHWAY
- LOW CO_2 COMPENSATION POINT
- HIGH LIGHT SATURATION
- LOW PHOTORESPIRATION
- 24-hr. SOURCE-SINK OPERATION
- SUCROSE PHOTOSYNTHATE

Table 2

SEASONAL INFLUENCE ON DRY MATTER YIELD 1/

Period	% Of Total Yield, For — Sugarcane	% Of Total Yield, For — Napier Grass
July 15—Nov. 15	47.0	36.6
Nov. 15—Mar. 15	18.0	22.8
Mar. 15—July 15	34.9	40.7

1/ Mean of two ratoon crops.

Table 3

DRY MATTER YIELD vs HARVEST FREQUENCY

Interval (Months)	No. Of Harvests	DM (Tons/Acre Yr) For [1]	
		Napier Grass	Sugarcane
2	6	11.4	3.6
4	3	23.4	9.7
6	2	27.1	15.9
12	1	21.5	29.0

[1] Average of three crop years (31).

Table 4

TROPICAL LEGUMES CLASSIFIED AS INDIGENOUS TO PUERTO RICO (1974)

Genus	No. Of Species	Nodulation	Growth Habit
Abrus	1	Moderate	Vigorous, Climbing Vine
Aeschynomene	3	Abundant to Rare	Vigorous Shrubs To Vines
Cassia	4	Abundant To Rare	Erect Shrubs To Vines
Desmanthus	2	Abundant To Moderate	Erect To Low Stems
Alysicarpus	1	Few	Prostrate Matted Vine
Cracca	1	Few	Erect Shrub
Canavalia	1	Moderate	Creeping Beach Vine
Calopogonium	1	Rare	Short Prostrate Vine
Centrosema	2	Abundant To Rare	Slender Twining Vine
Clitoria	2	Moderate To Few	Sparse Elongated Vine
Crotalaria	3	Moderate To Rare	Small Herbaceous Shrub
Dalbergia	1	Few	Extensive Woody Vine
Desmodium	10	Abundant To Rare	Low Vines To Shrubs
Galactia	2	Few To Rare	Slender Twining Vine
Indigofera	1	Few	Large Shrub
Phaseolus	3	Abundant To Rare	Twining Vine To Shrub
Vigna	3	Moderate To Few	Creeping Vine
Rhynchosia	2	Few To Rare	Vigorous Vine
Sesbania	1	Abundante	Annual, Erect Shrub
Stylosanthes	1	Moderate	Low Shrub
Tephrosia	2	Moderate To Few	Low Shrub To Vine
Teramnus	2	Moderate To Few	Slender Twining Vine
Zornia	1	Moderate	Low Bush

Table 5

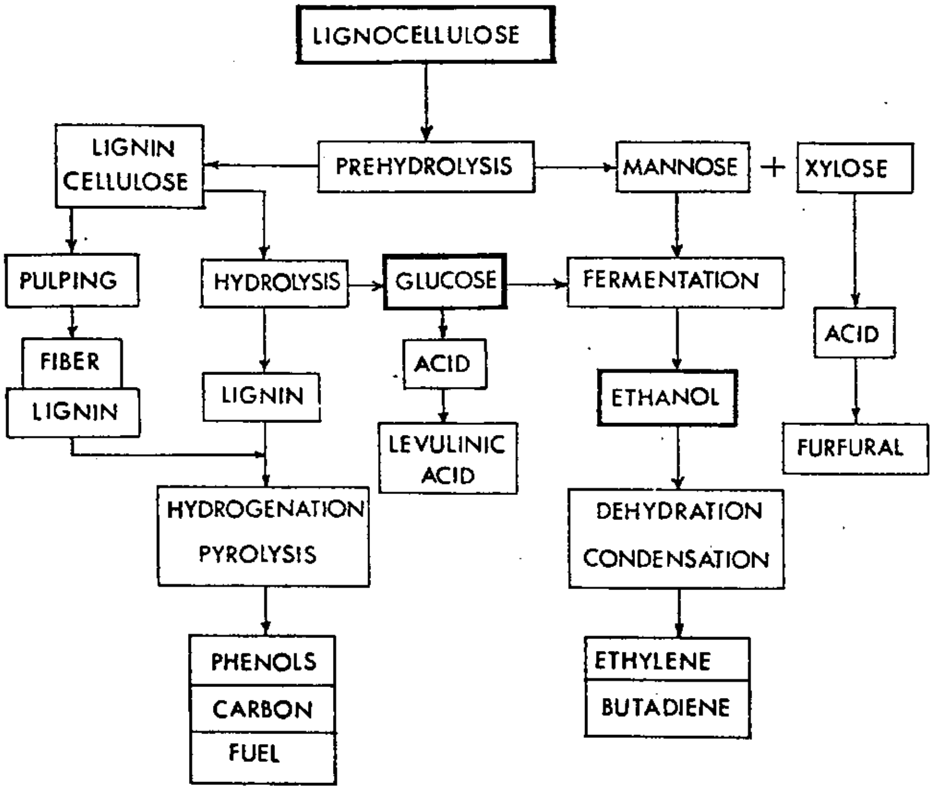
TROPICAL GRASS CATEGORIES AND CHARACTERISTICS, AND POTENTIAL LEGUMES FOR CO-PRODUCTION AS ENERGY CROPS

		Crop Characteristics, At Harvest —				Legume Candidates For —	
Category	Type Species	Age (Weeks)	Height (Feet)	Yield (Tons/Acre)	N Requirement	Co-production	Intercropping
Short Rotation	**Johnson Grass**	7-10	5-6	2-4	Low	*Sesbania sericea* *Sesbania exaltata* *Stylosanthes erecta*	*Phaseolus lathyroides* *Phaseolus* spp. *Desmodium* spp. *Lespedeza* spp. *Pueraria javanica*
	Sordan 77	9-12	6-8	3-5	High		
Intermediate Rotation	**Napier (Merker)**	12-24	8-14	6-12	Very High	*Sesbania* spp. *Stylosanthes* spp. *Sesbania* (?) *Stylosanthes* (?)	*Medicago* spp. *Phaseolus* *Desmodium* *Lespedeza* *Vigna* spp. *Cassia* spp. *Pueraria*
	Napier Hybrid	12-24	10-15 1/	7-14	Very High		
	Saccharum Spp.	18-24	12-16 1/	6-12	Intermediate		
Long Rotation	**(Cane, Primavera)**	40-52	10-15 2/	28-32	High	*Sesbania* (?) *Stylosanthes* (?) *Phaseolus adananthus* (?)	*Medicago* *Phaseolus* *Desmodium* *Lespedeza* *Vigna* *Cassia* *Leucaena* *Pueraria*
	(Cane, Gran Cultura)	66-78	12-16 2/	35-40	High		
Minimum Tillage	**_Pennisetum_ Spp.**	26-52	14-16 2/	10-15	Intermediate	*Sesbania* (?) *Phaseolus adananthus* (?) *Stylosanthes* (?)	*Phaseolus* *Desmodium* *Medicago* *Leucaena*
	Saccharum Spp.	52-78	14-16 2/	15-20	Low		

1/ Some lodging probable.

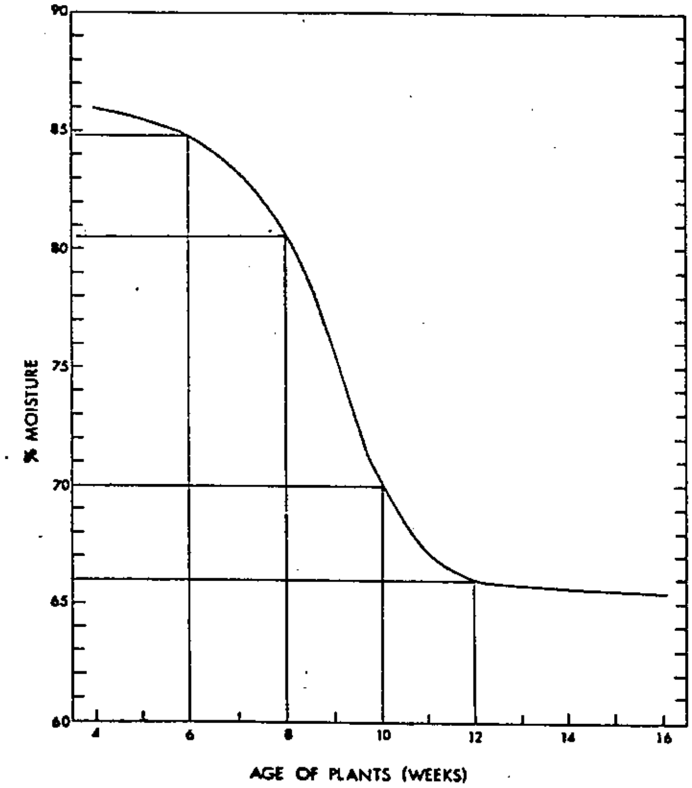
2/ Extensive lodging probable.

Figure 1



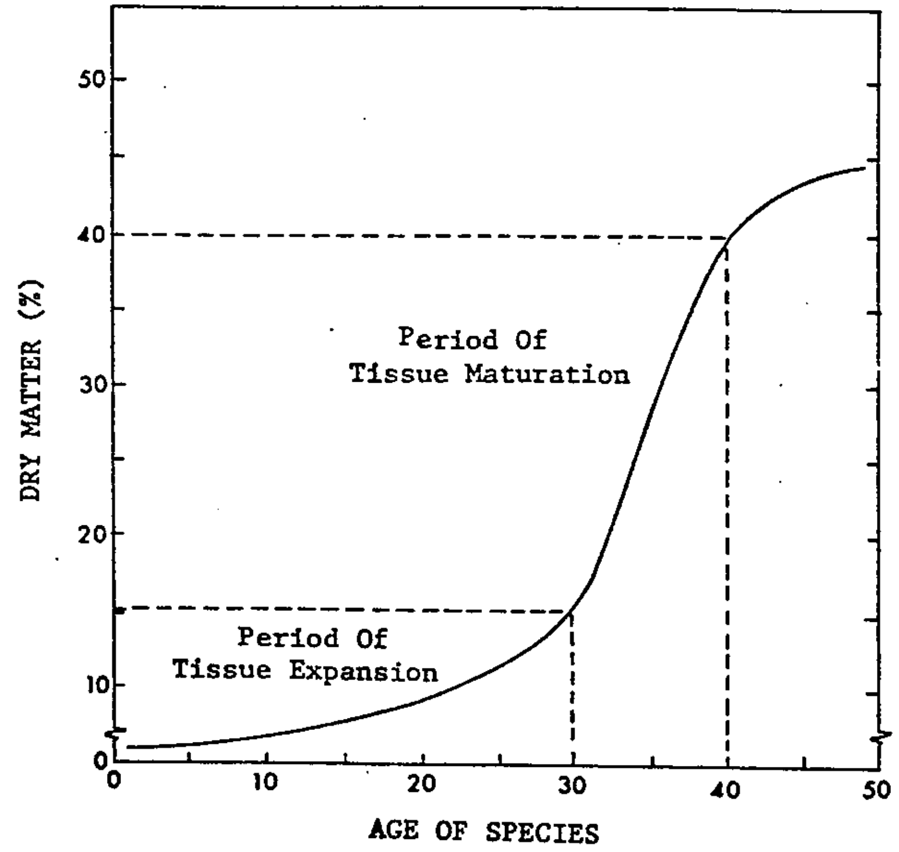
FLOW DIAGRAM OF A LIGNOCELLULOSIC CHEMICAL PLANT

Figure 2



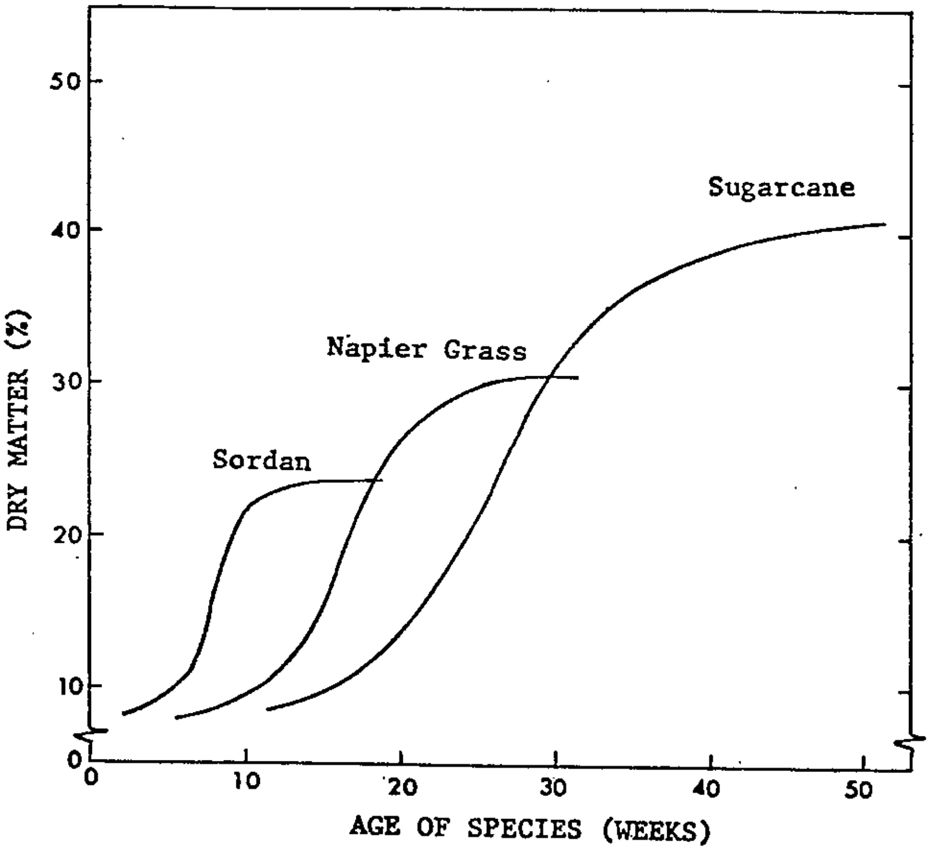
MATURATION CURVE FOR SORDAN 70A. WEEKS 8 TO 10 ARE CRITICAL FOR DRY MATTER.

Figure 3



A schematic representation of the maturation profile of herbaceous plant species. With the visible growth phase (tissue expansion) essentially complete, the energy planter will gain much more dry matter by allowing a brief additional time interval to elapse before harvest.

FIGURE 4



Relative maturation profiles for Sordan 70A, napier grass, and sugarcane over a time-course of one year. These plants are representative of the short-, intermediate-, and long-rotation cropping categories, respectively.

TROPICAL FORESTS AS A PUERTO RICAN ENERGY SOURCE

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
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TROPICAL FORESTS AS A PUERTO RICAN ENERGY SOURCE

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TROPICAL FORESTS AS A PUERTO RICAN ENERGY SOURCE

INTRODUCTION

THE RATE at which ecosystems produce and store organic matter is dependent upon environmental conditions. In tropical environments with adequate moisture and fertile soils, production of organic matter and storage of biomass are both high. Higher storages of organic matter but slower rates of production are characteristic of very wet environments. In arid environments both storage and production of organic matter are low. Brown and Lugo (1981) have described these patterns which are summarized here in Figs. 1 and 2. Figure 1 shows the patterns of organic matter storage according to Life Zone designation, and Figure 2 shows the pattern of organic matter production in terms of rates of litter production according to Life Zone. Due to the close relationship of these parameters with Life Zone, it follows that the Life Zone composition of a country is an important factor in determining the potential biomass yield for energy purposes of its natural ecosystems.

Humans can alter the rates of production and storage of organic matter of forest ecosystems within certain limits by using a variety of management techniques. For example, by selecting the proper species and overcoming environmental limiting factors, rates of organic matter production can be accelerated. Thus, irrigation makes up for the lack of rain in arid environments and fertilization may help overcome the poor fertility of leached soils in wet environments. The higher yields thus obtained are not free and they must be considered in relation to the costs associated with overcoming environmental limitations. This is particularly true for energy procuring systems which must be proven to yield net energy.

In Puerto Rico we have forests representative of 6 of the 30 forested tropical and subtropical Life Zones (Ewel and Whitmore 1973). The distribution of these Life Zones sets an upper limit on the potential production and storage of organic matter that the Puerto Rican forest stands can produce and sustain. Within each Life Zone there is a great diversity of plant associations and successional stages that further modify what the island forests can, and actually do, produce in terms of organic matter. The fact that we have 164 separate soil series (Lugo-López and Rivera

1977) represented in the 880 thousand hectares (ha) of the island, provides an idea of the potential diversity of forest types in Puerto Rico. It is not our objective in this paper to analyze this diversity of forest types but, instead, to calculate the amount of organic matter now stored and being produced by the forests of Puerto Rico, to look at the changes in organic matter storage that have occurred in our history as a result of changes in land uses, and to determine the feasibility of using forests for biomass energy production.

CURRENT RATES OF STORAGE AND PRODUCTION OF ORGANIC MATTER IN PUERTO RICAN FORESTS

From the work of Ewel and Whitmore (1973) we know the Life Zone distribution on the island (Table 1). The most recent forest inventory (1973) by the Department of Natural Resources shows that forests cover 375.8 thousand ha or 41.5% of the island. We do not know the Life Zone distribution of these forested areas. However, we assumed that: the very wet Life Zones (Rain, Lower Montane Rain, and Lower Montane Wet) are completely forested, and that the remaining forested areas are distributed by the same proportions that the Life Zones are distributed (i.e. 61% Moist Forest, 25% Wet Forest and 14% Dry Forest). The resulting distribution of forest areas in Puerto Rico is given in Table 1.

Using the regression equations in Fig. 1 and areas of forests in Table 1, we arrive at the estimates of storage of organic matter in Table 2. The results show that the moist and wet forests store the largest amount of organic matter with the Moist Forest Life Zone storing almost twice as much organic matter as the Wet Forest Life Zone and more than half of the total storage for the island. Within a given Life Zone the soil may store from almost as much organic matter as the vegetation to about less than half as much. For the island as a whole, the organic matter storage in the soil is 33% of the total.

Using Table 1 we multiplied forest area estimates by rates of organic matter production in order to estimate the potential organic matter production of the forests in Puerto Rico. Two calculations were made (Table 3). The maximum production possible, or gross primary production, was calculated from data reported in three studies done in Puerto Rico which used CO_2 gas exchange methods (Dugger 1978, Lugo et al. 1978, Odum 1970). Net primary production, equivalent to the actual amount of organic matter stored by plants after all their respiratory demands have been met, was estimated by assuming that net primary production was twice litter production (Brown and Lugo 1981). Litter production was obtained from Dugger (1978) and Fig. 2.

Gross primary production on a unit area basis peaks in the Rain Forest Life Zone and is lowest in the Dry Forest Life Zone. On an island-wide basis, the Wet Forest Life Zone contributes the most gross primary production (52%). The Moist Forest Life Zone is second and the other Life Zones exhibit negligible amounts. The rates of net primary production are an order of magnitude lower than gross primary productivity. This is a reflection of the high respiration of tropical vegetation. The Moist and Wet Forest Life Zones account for almost all (90%) of the net primary production of the island's forests. However, on a unit area basis, the differences among Life Zones are small (the range is 10-14 tons per hectare per year–t/ha.yr) with the exception of the Lower Rain Forest and Dry Forest Life Zones which exhibit much lower rates of net primary production (about 4.5 t/ha.yr).

PAST RATES OF PRODUCTION AND STORAGE OF ORGANIC MATTER BY PUERTO RICAN FORESTS

In Table 4 we reconstruct the known history of forest cover in Puerto Rico. This is necessary to estimate past rates of storage and net production of organic matter by our forests. The highest estimates are for the period prior to the discovery when the island was nearly all forested. The maximum potential of storage (208 x 10^6 t) and net production (8.5 x 10^6 t/yr) of organic matter that can be expected from the island's natural forests occurred at the time of the island's discovery. The lowest estimates occurred early in the century when Puerto Rico was highly dependent upon the land for food and energy. Since then, forest storage and net production of organic matter has approximately doubled with much of this recovery of forests occurring during the last 20 years or so.

FEASIBILITY OF USING NATURAL FORESTS FOR ENERGY PRODUCTION

As a starting point of this discussion we will use the present (1973) net organic matter production potential of 3.8 x 10^6 t/yr and an organic matter storage of 94 x 10^6 t for the island (Table 4). Because Dry Forests are slow to recover from any disturbance and very wet forests on slopes are difficult to harvest physically and economically, we will reduce the storage and net organic matter production values to 84 x 10^6 t and 3.4 x 10^6 t/yr, respectively. However, the net production value includes leaves and roots which we estimate represent 60% of the net production, leaving 1.4 x 10^6 t/yr available for use in the form of wood.

In previous analyses of forestry potential in Puerto Rico, Wadsworth (personal comm.) has suggested that 344 x 10^3 ha of land in Puerto Rico is suitable for pine (*Pinus caribaea* var. *hondurensis*) production. These forest lands are located in the Subtropical Moist and Wet Life Zones. Assuming all these lands were available for pine plantations, annual wood production would be 6.1 x 10^6 t/yr (Table 5). However, 56% of these lands are now forested, leaving 153 x 10^3 ha available for reforestation with pine. These would yield 2.7 x 10^6 t/yr (Table 5), if they were covered with pine plantations.

The energy consumption in Puerto Rico was 88.6 x 10^{12} kcal of fossil fuels in 1973 (Sánchez-Cárdona et. al., 1975) and 90.2 x 10^{12} kcal of fossil fuels in 1979 (Office of Energy, personal comm.). Using the island's 1979 energy consumption and the forest production values shown in Table 6, one finds that in terms of heat equivalents, the best we could expect from the forests would be 30% of today's total energy consumption. To achieve this rate of energy production (30% of the total), much of the island would have to be planted with pine or with any species that produced organic matter at a similar rate (Table 4). If the energy production through forest biomass is corrected for quality, in order to get a better idea of the capacity of the fuel to do work, we could expect 15% of the total island's energy demand to be satisfied by plantations. Natural forests could yield 4% of today's total energy demand (in fossil fuel equivalents) and a combination of natural forest and plantations could yield 10% of the fossil fuel equivalents used today in Puerto Rico.

The above calculations may appear conservative because we have not used all available forest lands to produce biomass for energy. Yet, lands that were not included are not suitable for fast biomass production because they are too dry or too wet. We have also not included leaves and roots in the calculations because these should be left behind to maintain site fertility through decomposition. Their use to generate energy would be questionable anyway. Also, we have only used the net energy production of the forest lands in the calculations and have not included the standing crop of biomass energy stored in the forests. It is very important that Puerto Ricans do not depend on the standing stock of wood in the forests, but rather adjust demand to the forest's annual net production. The standing crop of wood (about 75% of total biomass in vegetation) now present in the forests amounts of a fossil fuel equivalence of 159 x 10^{12} kcal or enough to supply current energy demand for 1.8 years. However, once destroyed, this standing crop could not be replaced for another 20-50 years during which time the island would be deforested and without the use of its forests. To avoid this catastrophe, the energy demands on the forests of the island must be proportional to the rate of annual production by the forest, and its standing crop of biomass must be protected.

If the analysis of energy need vs. forest production of potential energy is based on electric demand alone, a brighter scenario can be predicted. The justification for such an approach is that a significant fraction of the total energy consumption in Puerto Rico is in forms that would be hard to satisfy using wood (e.g. gasoline for vehicles). However, the use of wood for electric generation is a more realistic use of the resource. The approximate total electric consumption in Puerto Rico in 1978 was 11 x 10^{12} kcal of electricity or 44 x 10^{12} kcal of fossil fuel equivalents (about half of the total energy consumption of the island). Using results from Table 6 we find that plantations could satisfy 31% of this demand in terms of fossil fuel equivalents and the combination of natural forests and plantations could supply 21% of the electricity demand (also in fossil fuel equivalents).

When the island turns again to forests for energy, we will have to decide on the use of plantations vs. the use of natural forests. We will not address in this paper which alternative is the best. However, one advantage of plantations is the rapid rotation which allows for the production of significant amounts of wood in a short time (10-12 years). Natural forests also produce high amounts of biomass in a short time (13-15 t/ha.yr in the first 6 years, see Brown and Lugo 1981), but not as much in the form of wood. Ultimately the decision will have to be made based on such criteria as the net energy yield of each alternative and implicit in the net energy yield calculation, the environmental cost of maintaining productive plantations year after year. Our ability to make an adequate calculation along these lines at this time is nil.

CONCLUSION

In summary, the energy future of Puerto Rico is bleak, particularly in light of the current high rate of fossil fuel consumption on the island and the expected increases in the price of oil. Earlier in history the island was dependent upon its forests and lands for food and energy. We can learn much from the energy use strategy of the island at this time.

In Table 7 we summarize the energy use and energy sources of Puerto Rico in 1910 when the island had a population density of 125 people/km^2 or 3-4 times lower than today. At that time, the energy use of Puerto Rico was 70 times lower than today's and the energy source was solar in contrast with the predominance of fossil fuels of today. By comparing the energy use of 1910 (Table 7) with the energy production potential of our forests in Table 6, it is clear that with adequate forest management, the forests of Puerto Rico could have supplied all the energy demands of the island. Table 6 shows that the forests of the island have the capacity to meet all this demand. However, at the time of Murphy's study, the forests were being cut three times faster than they were growing. At the time, the island imported about 50% of its wood demand. By 1916 (Table 4) the island had lost 79% of its forest resources.

What we learn from this historic record is that without management, and in spite of a low population density (relative to today's), natural forests can disappear very quickly (in less than 15 years, according to Murphy 1916). This loss occurred because demands on the land exceeded the land's capacity to convert solar energy. One hopes that we learned a lesson in land management and that the degraded conditions caused by senseless use of the land do not return to Puerto Rico in the future. However, the small amount of energy that can be concentrated via forests relative to the current uses of fossil fuels means that standards of living must decline when fossil fuels disappear from the market. As this happens, there will be efforts to maintain an abnormally high intensity of energy use by harvesting standing forests. But, to avoid serious long-term harm to society, forest cover must be protected and only the annual rate of organic matter production, not the storage, should be used. This annual rate of production adds up to a maximum of 15% of the 1979 energy demand and 31% of the electrical demand (both in fossil fuel equivalents). Since these calculations are based on high yields obtained in experimental plantations, it is likely that actual values are much lower.

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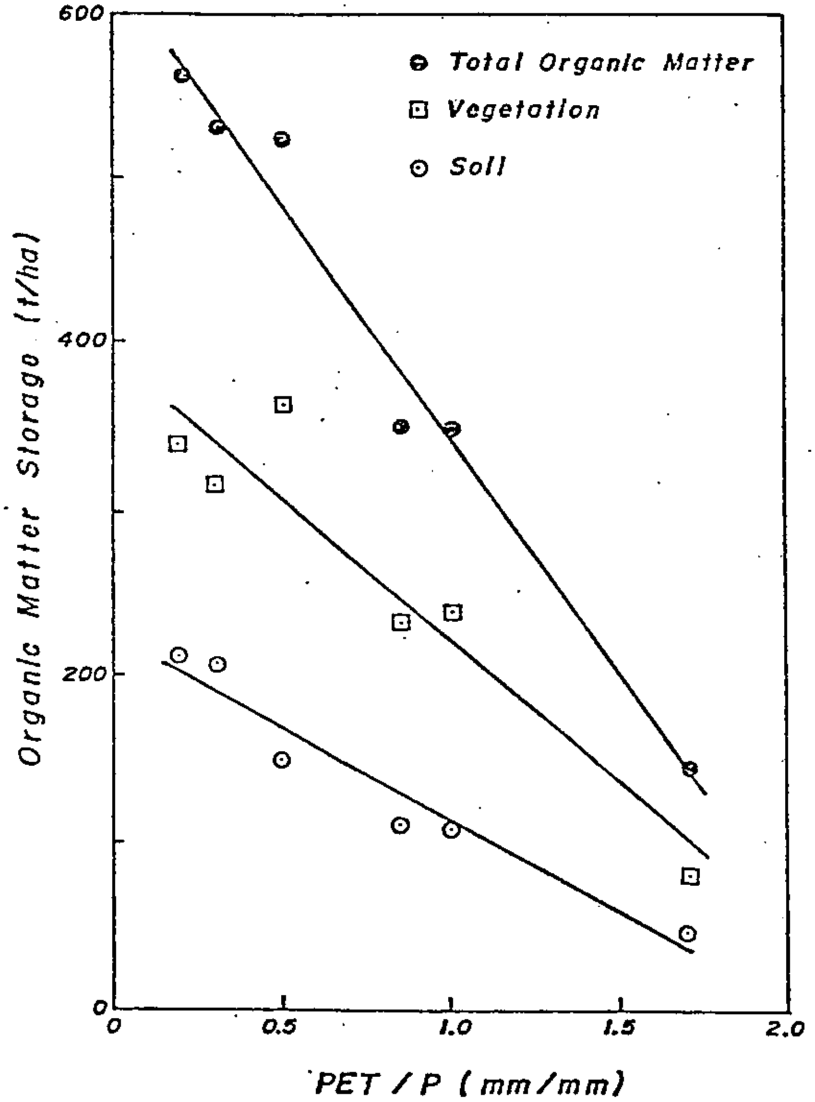

Fig.1. Relationship between total organic matter storage and organic matter storage in vegetation and in soils grouped into six Life Zone groupings, and potential evapotranspiration to precipitation ratio (PET/P). The equations describing the relationships are significant ($p = 0.05$) and are: total organic matter storage (t/ha) = 625 - 281 x PET/P ($r^2 = 0.97$), organic matter storage in vegetation (t/ha) = 392 - 169 x PET/P ($r^2 = 0.90$), and organic matter storage in soil (t/ha) = 224 - 111 x PET/P ($r^2 = 0.94$). From Brown and Lugo 1981.

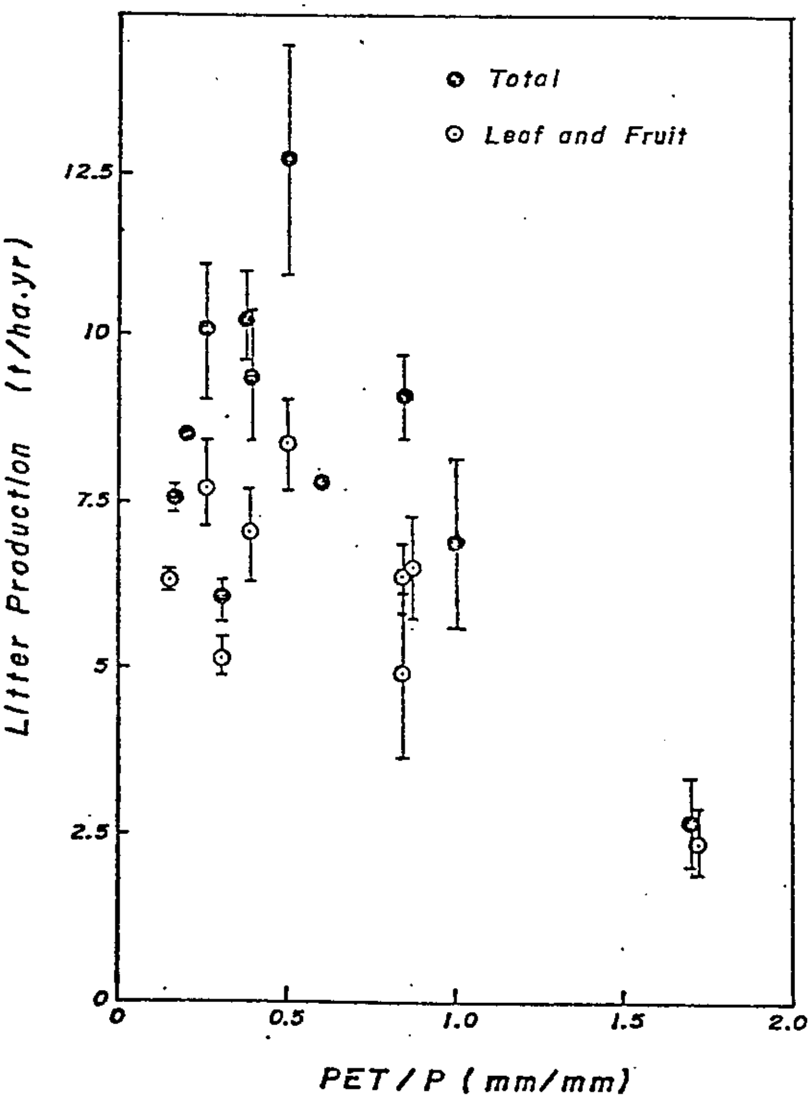

Fig. 2. Relationship between total litter production and leaf litter production and potential evapotranspiration to precipitation ratios (PET/P). From Brown and Lugo 1981.

Table 1. Areas of Life Zones and forests in mainland Puerto Rico, 1973

Life Zone [a]	Area [b] (10^3 ha)	Forested Area (10^3 ha)
Dry Forest	121.64	50.85
Moist Forest	532.61	222.66
Wet Forest	212.48	88.83
Rain Forest	1.32	1.32
Lower Montane Wet Forest	10.91	10.91
Lower Montane Rain Forest	1.23	1.23
TOTAL	880.19	375.8

[a] All are subtropical.

[b] From Ewel and Whitmore (1973).

Table 2. Storage of organic matter in Puerto Rican Forests

Life Zone and Average PET/P[a]	Organic Matter[b] in: Vegetation (10^6 t)	Soils (10^6 t)	Total Storage of Organic Matter[b] (10^6 t)
Dry Forest (1.77)	5.3	1.8	7.5
Moist Forest (0.85)	55.3	29.0	85.9
Wet Forest (0.39)	29.0	16.1	45.8
Rain Forest (0.21)	0.5	0.3	0.8
Lower Montane Wet Forest (0.30)	3.7	2.1	5.9
Lower Montane Rain Forest (0.16)	0.4	0.3	0.7
TOTAL	94.2	49.6	146.6

[a] PET/P = Potential evapotranspiration to precipitation ratio for the mid-biotemperature and precipitation values of a Life Zone (c.f. Brown and Lugo 1980 for details).

[b] From regressions in Fig. 1.

Table 3. Production of Puerto Rican Forests.

Life Zone	Gross Primary Production		Net Primary Production [a]	
	(t/ha.yr)	(10^6t)	(t/ha.yr)	(10^6t)
Dry Forest	19.0[b]	2.3	4.8	0.24
Moist Forest	36.1[c]	19.2	9.8	2.18
Wet Forest	119.7[d]	25.4	14.0	1.24
Rain Forest	140[e]	0.2	14.0	0.02
Lower Montane Wet Forest	130[e]	1.4	10.4	0.11
Lower Montane Rain Forest	32.0[c]	-	4.4	-
TOTAL		48.5		3.79

[a] Estimated as 2 x leaf litter production (Brown and Lugo 1981); litter production data are from Dugger (1978) and Brown and Lugo (1981).

[b] Lugo et al. (1978).

[c] Dugger (1978).

[d] Odum (1970).

[e] Extrapolated (by eye) from relationship between PET/P ratio and gross primary production of the 4 other Life Zones.

Table 4. Historical trends in the storage and production of organic matter in Puerto Rican Forests.

Date	Forest Area[a] (10^3 ha)	Storage in Vegetation[b] (10^6 t)	Net Primary Production (10^6 t/yr)
1493	836.2[d]	208.0	8.5
1916	178.7[e]	45.5	1.8
1950	235.2[f]	54.9	2.4
1973	375.8	94.2	3.8

[a] We assumed very wet Life Zones (Rain, Lower Montane Rain, Lower Montane Wet) were always forested and the remaining forested areas were distributed by the same proportions the Life Zones were distributed.

[b] From PET/P ratios in Table 2 and regression in Fig. 1.

[c] From net primary production estimates (t/ha) in Table 2.

[d] Assumes 95% of the island forested and deforested area was in Moist Forest Life Zone.

[e] Zon and Sparkhawk (1923).

[f] Puerto Rico's Department of Natural Resources Inventory Program.

Table 5. Potential production of pine (*Pinus caribaea* var. *hondurensis*) plantations in Subtropical Moist and Wet Forest Life Zones in Puerto Rico (Wadsworth, pers. comm.).

Soil Conditions	Area[a] (10^3 ha)	Wood Production[b] (10^6 t/yr)
Total Land:		
Deep clays	164	3.20
Deep sands and shallow clay loams	180	2.88
TOTAL	344	6.08
Presently non-forested:		
Deep clays	73	1.42
Deep sands and shallow clay loams	80	1.28
TOTAL	153	2.70

---

[a] Excludes prime agricultural land.

[b] Using 19.5 t dry weight/ha.yr for deep clays and 16 t dry weight/ha.yr for sandy and shallow loams (not including bark).

Table 6. Energy content of biomass production in forests of Puerto Rico.

Forest Type	Area (10^3 ha)	Useable Wood Production (10^6t/yr)	Heat Equivalents[a]	Fossil Fuel Equivalents[b]
			(10^{12} kcal/yr)	
(a) Natural forests	376	1.4	6.3	3.2
(b) All commercial land suitable for pine	344	6.1	27.5	13.7
(c) Non-forested commercial land suitable for pine	153	2.7	12.2	6.1
(d) Natural forests plus reforested land (pine) (a) + (c)	529	4.1	18.5	9.3

[a] 1 g organic matter = 4.5 kcal.

[b] 1 kcal heat equivalent = 0.5 kcal fossil fuel equivalents (Odum and Brown, 1975).

Table 7. Energy consumption and types of energy sources used in Puerto Rico in 1909. Data are from Murphy, 1916.

Type of Energy Source	Heat Equivalents kcal X 10^6	Fossil Fuel Equivalents[a] kcal X 10^6
Fossil Fuels		
Anthracite coal	6,055	6,055
Bituminous coal	275,021	275,021
Coke	2,411	2,411
Oil	0.41	0.41
Other[b]	3,014	3,014
Total Fossil Fuels	286,501.4	286,501.4
Solar Fuels		
Wood		
for commercial use	496,859	248,429
for domestic use	1,321,468	660,734
Total Solar Fuels	1,818,327	909,163
Total Energy Consumption:	1.20 X 10^{12} kcal fossil fuel equivalents.	
Solar Fuel/Fossil Fuel	6.35	3.17

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[a] Used 1.0 kcal heat equivalent of wood = 0.5 kcal of fossil fuel (Odum and Brown, 1975).

[b] Assumed to be fossil fuels with heat equivalence of 6.385 X 10^6 kcal/t.

Keynote Address

POTENTIAL COSTS AND BENEFITS OF A PUERTO RICAN CANE INDUSTRY ORIENTED TO FUELS AND ALCOHOL

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

Dr. Gary D. Martin, Director
OFFICE OF ECONOMIC RESEARCH, ECONOMIC DEVELOPMENT ADMINISTRATION
San Juan, Puerto Rico

"The sugar fields of the Caribbean are worth more than all the gold in Peru." This observation was made in the 17th century. Since that time gold has risen greatly in esteem while sugar has been on the decline. Nowhere has that decline been as steep as in Puerto Rico in recent years where the area planted has dropped from over 390,000 cuerdas (.97 acre) in 1952 to less than 90,000 cuerdas at present. One doesn't have to project the trend line very far to see the end of sugar in Puerto Rico, especially considering the losses that the Sugar Corporation has rung up through the years. It seems to be just a matter of pulling the plug on its life support system.

There are many who will welcome its passing for reasons other than elimination of the red ink. Like King Cotton in the southern states, sugar never matched in human terms its contribution in economic terms. Because of the nature of its introduction, cultivation, and processing, very few of the people most closely associated with its production were ever able to live a good life on account of sugar. From the beginning it depended upon large amounts of involuntary labor or the labor of very desperate people. Cutting cane by hand was—and still is—a very unpleasant task and those who did it were assured of an income only a few months of the year. Worst of all for the general welfare, the income went mainly to those who owned the land and others who owned the sugar after it left the land.

The expression "sugar island" has connoted an overpopulated, poverty-stricken, racially mixed up, socially uprooted, politically explosive society dominated by a few powerful figures from within and without. Seldom has the wealth generated by sugar served as a springboard, or what the economics call an "export base," for genuine economic development. The Virgin Islands, whose European and African settlement was predicated upon sugar, have now abandoned the crop completely with hardly a regretful look back. National leaders from Cuba to Barbados have vowed to purge the captivating weed from their islands, but sugar keeps hanging on and coming back.

Sugar comes back because demand for it continues to grow around the world causing the price to soar every time there is a temporary supply setback in some important sugar producing area. In this, it is hardly different from all commodities, whether they be rice, beans, coffee, cocoa, cinnamon or sow bellies. Right now we are on one of those upward spirals as the price of sugar has risen from 8 cents to 42 cents per pound in the last 17 months. But this very volatility of price ultimately constitutes just another page in the catalog of the ills of sugar. Small national economies heavily dependent on this one commodity ride the same kind of prosperity-poverty cycle over long periods that the sugar worker experiences every year.

Sugar also hangs on because of the miraculous quality of the crop itself. In the words of Dr. Alex Alexander, "Sugarcane (Genus Saccharum) is the finest living collector of solar energy which functions on a year round basis to store this energy in forms of fermentable solids and fiber." This remarkable ability of sugar to collect and store solar energy in huge quantities per acre of land has been at the root of its success as a luxury human consumption crop, and this property portends extremely favorably for its continued success in the world and its revival in Puerto Rico. Translating the amazing biological productivity of sugar cane into economic terms, Erich Zimmerman made an estimate in the 1940's that the proceeds of the sale of Puerto Rican sugar extracted from the cane grown on one acre bought in terms of corn, oats, rice, wheat, dried beans, and potatoes, the products of 8.2 acres in the continental United States. At today's sugar price, the ratio might well be higher.

For a host of reasons–I'm sure I will not be able to list them all–Puerto Rico in the 1980's is the right place at the right time for sugar, not for sweetness, but for fuel. Going down the list of sugar's ills, one can see that they would not or need not apply if the crop is grown for fuel.

First, as a fuel, sugar would free itself of the curse of commodities, the rising and falling of price on the world market. At least for the foreseeable future the price of energy is going only one way, up. This would be an excellent way for an oil-less island such as Puerto Rico to hitch a ride on OPEC's wagon.

Next, whatever happens to sugar's price, the island economy has grown too big for sugar ever to be as dominant at it has been in the past. There is no reason for it to become an export crop again. Using Combustion Equipment's estimates of energy output in its proposed 15,000 acre project, even if we could plant the acreage of 1952 again, we could replace only 20% of our total petroleum imports in 1978. The domestic market is more than big enough to absorb all that could be produced.

Alternatively, as the Center for Energy and Environment Research envisions, the liquid portion of the cane could be used to satisfy the needs of the local rum industry, which are significant, and again the output is tied to a product whose price is not subject to the vagaries of world commodity markets. Either way the product is used, it becomes an integral part of our modern economy rather than an anachronistic appendage standing in the way of development.

Perhaps the most welcome departure from the past offered by an energy cane regime is the possibility of operating the sugar mill throughout the year. In the year just completed the average grinding period for the 7 mills still operating was 112 days with an average time lost of 42 days for a final effective average of 70 days out of the 365. In a society geared to year-round work and the 40-hour week one must wonder what our 3,000 sugar mill workers do the remainder of the year, or if anyone could afford to keep them on the payroll for 365 days.

With regard to another of sugar's traditional evils, Puerto Rico has already recognized the bad social consequences of too great a concentration of ownership of the land, and this has been dealt with. There are legal safeguards against the re-emergence of massive corporate control of the Puerto Rican patrimony. In any energy cane project, we must be sure that they are adhered to.

Continuing on the positive side of the ledger, alternative fuels of this type are very high on the national agenda in the United States, the idea being to lessen dependence on imported oil. The 1.6 billion dollars that Puerto Rico spends annually on foreign oil weakens the dollar and lowers U.S. living standards every bit as much as would the same purchases by the state of Kansas. Electoral votes aside, there is just as good a reason for the United States Department of Energy to support energy self-reliance in Puerto Rico as in the mainland. Perhaps, with Puerto Rico's growing strategic importance in the Caribbean, there is even more reason.

The recent agricultural emphasis in Puerto Rico has been upon food production to substitute for imports. Given the high level of local food purchasing power and the high cost of transportation of many food items, this policy makes a great deal of economic sense. Where freshness is of paramount consideration it also makes sense to produce some items that can be imported more cheaply. The fact that 56 percent of agricultural income in Puerto Rico in 1979 was made in the import-substituting commodities of meat and dairy products is an altogether healthy development. We can apply the same logic and make similar inroads into the vegetable and fruit produce section of the supermarkets.

But we should also recognize the limits of any food-import-substituting policy. Unless the people are willing to accept a drastic change—one might say reduction—in their standard of living, Puerto Rico will continue to import most of its food. One need only take a stroll through the local supermarket and ask himself as he goes through, "Could that product be made here? If so, should it be made here? If it were made here, how much would it cost to persuade people to buy it?" Product by product the would-be Puerto Rican producer finds himself up against companies which, for a wide variety of reasons, have risen to the top in a tough game of survival of the fittest. The two main advantages most of these companies have over the would-be Puerto Rican producer are economies of large scale production and superior resources for product design and marketing. The first advantage stems from the relative proximity of abundant land, well suited for certain temperate zone food crops, on which very capital intensive techniques can be used. The second advantage is a function of the wealth and experience of the companies. We can match neither of these in the foreseeable future.

As a substitute for imports, fuel from sugarcane would have some definite advantages over food. We would continue to cultivate a proven tropical crop. We could then sell the final product in a cartel-inflated market. The food market is far more competitive. Fuel would not be faced with the brand-name identification problem. Suitably priced, it will sell. And the need to substitute for fuel imports is even greater than for food. In 1979 we imported $1.78 billion in fuel versus $1.20 billion in food.

Biomass for energy has also been compared unfavorably with food on moral grounds and on employment grounds. Addressing the moral question first, we must admit that a great deal of the energy created would be wasted. Working in buildings whose design necessitates heavy air conditioning expense and simmering in traffic jams reminds us constantly of the squandering of energy. But at the same time, energy is an important part of all our necessities, our vital transportation, our shelter, our clothing, and, indeed, our food.

We should be reminded, furthermore, that not one of the big three money crops in Puerto Rican history could be regarded as a necessity, those being sugarcane, coffee, and tobacco. The widespread cultivation of grains for animal feed in the United States is also an extremely wasteful use of land, nutritionally speaking. And a recent news report stated that the premier agricultural state in the United States, California, may now count as its principal money crop marijuana. From a moral standpoint, people can do, and have done, a lot worse things with their land than producing energy.

On the employment question, I think we must face the fact that no modern agricultural project will generate the same level of employment per acre as did traditional agriculture, nor will it create the same number of jobs per acre as does sugar production currently. The only way that could be done would be for us to turn back the clock in wages and living standards, or for the government to provide massive subsidies as it is currently doing through the Sugar Corporation. Even with considerably less employment per acre, total sugar related employment could be increased over time, as land that had been in sugar before is put back into sugar. Of equal importance is the fact that the jobs would be year-round and, if the project is basically sound, the jobs would be much more secure and better paying than are most agricultural jobs at present. Our main consideration in the revitalization of agriculture should be restoring productivity in economically sound projects, not the number of jobs we can sustain per acre of cultivation.

We arrive, then, at the basic question to be answered, "Is the growing of sugarcane for the purposes of energy economically sound? Will it yield a sufficient return on investment to be worthwhile for a private company?"

I don't think anyone can answer that question with complete assurance at this time. We won't really know until it is tried on a commercial scale in Puerto Rico. The numbers I have seen tell me that such a project would have a very good chance to succeed. If biomass for energy makes sense anywhere in the United States, then sugarcane in Puerto Rico does. It is the most energy-efficient crop yet tested and Puerto Rico is the best place under the U.S. flag to grow it. If its time has not yet come, it soon will, as fuel prices continue in their inexorable upward course.

Finally, we must recognize the very large stakes in the world energy game. Our supplies of food, mainly from the United States, are relatively secure. One need only open today's newspaper to be reminded that our supplies of fuel are not. We are still experiencing an energy crisis even though the word is no longer in vogue. Puerto Rico is accustomed to looking to the United States for leadership in time of crisis. We now have the opportunity, with a successful biomass-to-energy project, to provide leadership for the United States. We should not pass up that opportunity.

THE DECLINE OF SUGAR REFINING IN PUERTO RICO: HISTORY AND PRESENT OUTLOOK

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

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DECLINE OF SUGAR REFINING IN PUERTO RICO: HISTORY AND PRESENT OUTLOOK

Mariano A. Romaguera[1]
Mechanical Engineer, and Consultant
PR Sugar Corporation

OVER a period of years, output of the Sugar Industry in Puerto Rico has experienced a decline–from a peak of 1,310,000 tons of raw sugar produced in 1953 to a production level in 1980 that was slightly over 176,000 tons. Major factors in this decline have been:

- Lack of agricultural labor caused in part by the migration of workers to the continental U.S.
- Forced field mechanization without a logical transitional period.
- Deterioration in the performance of cane varieties resulting in lower yields in tons cane/cuerda and in sucrose content in the cane. This deterioration has been accelerated by the forced field mechanization.

Although production of raw and refined sugar usually go hand in hand in the sugarcane industry, this has not been the case in Puerto Rico. Refined sugar production was linked directly to the capability of selling the refined product to the mainland and this capability was restricted; the federal government set limits on the amount of refined sugar that was permitted to be sold to the continental U.S. in order to assure a large market share to mainland refiners. Even at the time of peak raw sugar production, Puerto Rico refined a maximum of slightly over 240,000 tons, and although raw sugar production has plummeted to roughly 15% of its former level, refined sugar output has only decreased to about 40%.

In 1943 there were six refineries producing refined sugar, some utilizing the Sucro Blanc process, others using activated carbon. At present, there are two refineries operating with ample capacity to produce over 160,000 tons of refined sugar.

PROBLEMS OF PUERTO RICAN REFINERIES

The decline of raw sugar production indirectly affected the operation of the existing refineries.

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The intermittent grinding, due in part to field mechanization problems and the necessity of continuous operation in refining, caused excessive consumption of fuel.

Due to agricultural problems, the quality of the raw sugar left much to be desired. We have been plagued by low filtrability, raw sugar of very high colors, high ash content, and poor overall performance. Since our existing refineries are tied up to our raw sugar houses, we are forced to accept this low quality prime material.

Our local refineries, contrary to those in the Continental U.S.A., make only one grade of sugar. This means that our refineries cannot get by with second grade liquors that can be utilized by various industries. This places an added burden on our existing facilities.

PRESENT OUTLOOK

Whether we like it or not, the problems analyzed here will not pass away. The sugar industry outlook as a whole is one of restraint. Our Government is embarked on an agricultural diversification program that allocates enough land for cultivation of sugarcane to produce roughly the same amount of raw sugar we produced this year. The main purpose will be to supply our basic needs plus a small reserve, and the present production fits all right. Refined sugar will tend to maintain its present position, that is, a production level of around 110,000 to 130,000 tons of refined sugar, which is ample for our present needs.

The world market's latest projections indicate a sustained low production for the next two to three years. The cost of producing raw and refined sugar has increased three-fold in third world countries. This means that the present world market price for raw sugar, around 40 cents per pound, will not come down as it did in 1975 after the 63 cents per pound peak. Puerto Rico experienced her greatest cost increases in the decade of 1970 to 1980. It is expected that this cost, although not stable, will rise proportionally at a lower rate than that of the rest of the world.

Unless our local Department of Agriculture has a change of priorities, refined sugar production in Puerto Rico will maintain its present level. It is expected that, at present, changes in the refineries will improve somewhat; sugar could be produced in a single refinery, depending on the availability of sugarcane in the specific area.

Although the present outlook is one of a very limited nature, present projections do not envision an increase in production. Statistical curves on production of raw and refined sugar have bottomed out. It is expected that this low plateau will maintain a stable, even line for the immediate future.

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4) Personal Records of Consultant.

5) P.R. Department of Agriculture, Santurce, P.R.

6) U.S. Department of Agriculture, San Juan, P.R.

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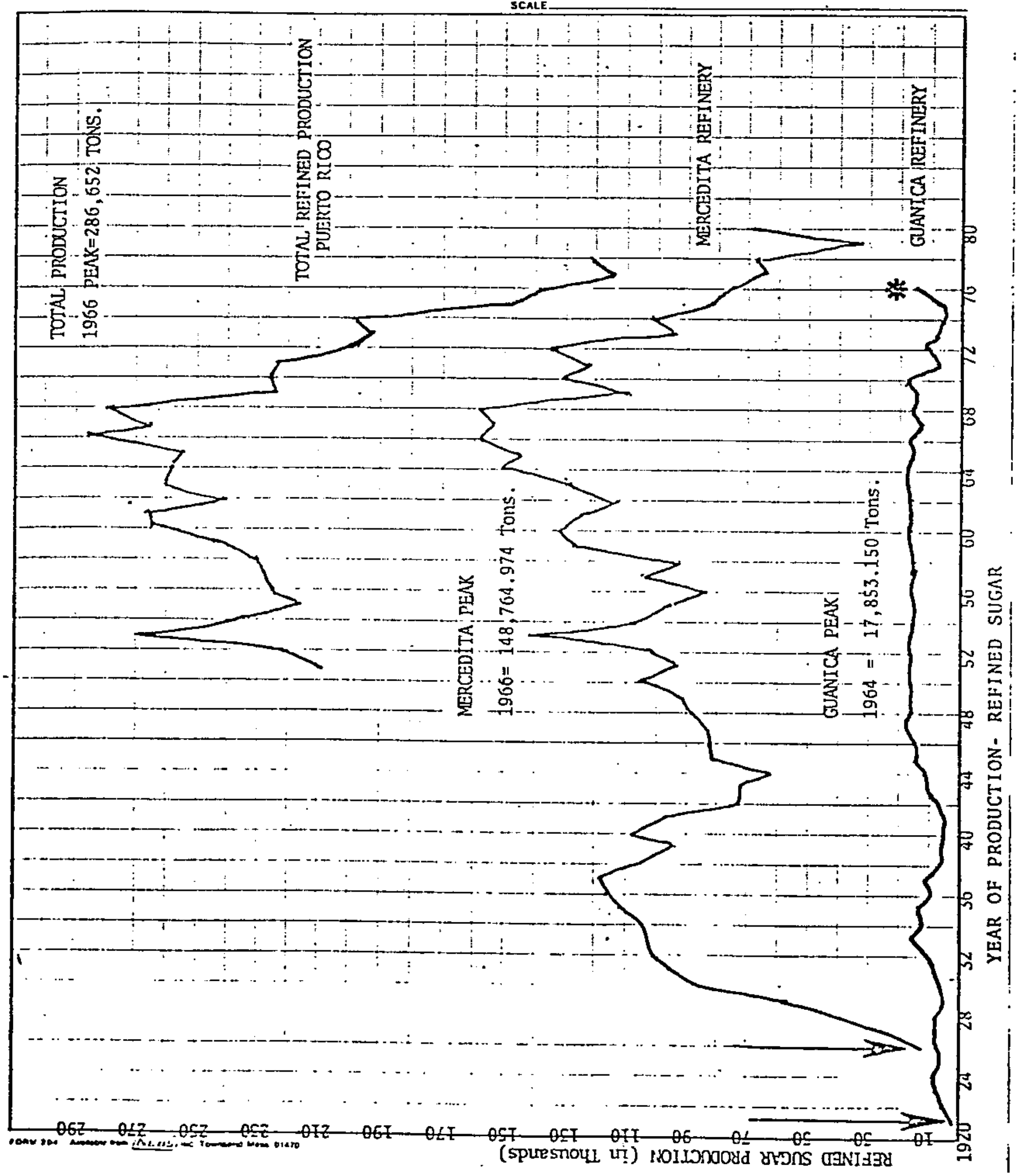

FORM 204

THE ENERGY CANE CONCEPT FOR MOLASSES AND BOILER FUEL

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE UPR CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
Biomass Division, Río Piedras, Puerto Rico

THE ENERGY CANE CONCEPT FOR MOLASSES AND BOILER FUEL

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THE ENERGY CANE CONCEPT FOR MOLASSES AND BOILER FUEL

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ABSTRACT

SINCE 1977 the U.S. Department of Energy has sponsored research in Puerto Rico on sugarcane and other tropical grasses managed specifically as renewable energy sources. The term "energy cane" refers to sugarcane that is managed for its total growth potential rather than sugar. The energy cane concept is basically a concept of management rather than of varieties, species, or taxonomy. Averaged yields from three crop years indicate that more than 80 tons of millable cane can be produced per acre year. Production costs are in the order of $10.12/ton of millable cane, or about $840.00/acre year. Juice quality was low but sugar yields averaged about 5.5 tons sugar/acre (TSA). Yields for both biomass and sugar were appreciably higher for energy cane than for conventional sugarcane in Puerto Rico. Production costs were higher on a per acre basis but lower per ton of cane.

While the energy cane studies are far from complete, the implication of present data trends is quite clear: Whether the PR sugar industry intends to produce sugar, molasses, or biomass, its goals can best be met by managing sugarcane as a biomass energy crop rather than a sugar crop.

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THE ENERGY CANE CONCEPT FOR MOLASSES AND BOILER FUEL

INTRODUCTION

THE TERM "energy cane" was coined in 1979 by Dr. Amador Cobas[1] while preparing a symposium paper on alternative uses of sugarcane (1). He had observed, correctly, that sugarcane studies by CEER-UPR were emphasizing total biomass for energy rather than raw sugar, refined sugar, or molasses.

It seems ironical that sugarcane is a better producer of biomass than sugar. As an **agricultural** entity we have long associated this plant with the commercial sweetener sucrose. However, as a **botanical** entity, sugarcane is first and foremost an effective collector of solar energy. It is a solar collector that operates day and night, 52 weeks per year, to convert sunlight to storage carbohydrates. Its botanical "preference" is to store this energy in the structure of new plant tissues (fiber) rather than to accumulate it as soluble sugars (fermentable solids). Rarely, however, do growth-regulating factors such as climate, water, and nutrients allow sugarcane to sustain growth at maximum rates.

In the upshot, sugarcane produces both fiber and fermentable solids in considerable abundance. The conventional sugar planter (with an eye for sucrose and blackstrap molasses) will tend to constrain new tissue growth beyond that amount which is needed as a storage vehicle for sugar. For the energy planter the tissues themselves are a prime objective and a salable commodity of potentially great importance. Hence, the energy cane concept is basically a concept of **management**. It is a concept of revised management for an existing plant resource, but one that focuses clearly on the energy-converting capabilities of sugarcane.

ENERGY CANE IN PERSPECTIVE

Sugarcane planting for energy will differ from conventional sugar planting in several ways: (a) yields will be higher and production costs lower; (b) juice quality will be lower and sugar yields higher; (c) the harvest season will be longer (approximately 8 months in Puerto Rico); and (d)

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energy cane will be one of several tropical grasses contributing to year-round biomass utilization operations.

1. Yield And Cost Considerations

As a worldwide average, sugarcane planted for sugar yields about 22.6 tons of millable cane/acre year (Table 1). Puerto Rico's average yield is moderately higher at around 28.0 tons/acre year. This is a deceptive figure, however, since it reflects some adverse conditions prevailing in the industry today rather than the yield potential of the plant itself. For example, Puerto Rico's cane yields in the years immediately preceding 1936 averaged 45 tons of cane/acre year (2). These yields were obtained with varieties much inferior to those available today.

Many reasons can be given for the modest cane yields shown by our sugar industry in recent years. It can be argued, for example, that it simply costs too much to plant sugarcane in Puerto Rico today. The average hourly wage has risen from 16 cents in 1939 to over $3.00 in 1981 (Table 2). Depending upon one's source of information, it cost between 22 and 35 cents to produce a pound of sucrose in Puerto Rico during 1979. During the same period sucrose was priced between 12 and 15 cents/pound on the world market.

Today's sugarcane production operations in Puerto Rico cost approximately $600.00 per acre year for "primavera" cane. The position taken by energy cane advocates is that yields can be more than doubled with production inputs costing only about 50% more than present operations, ie, approximately $900.000/acre year. The decisive factor would be the management of production operations for maximum biomass rather than sugar. The higher tonnages realized from energy cane would also yield an appreciable quantity of sugar even though rendement values would be relatively low.

Since 1977, under sponsorship of the U.S. Department of Energy, CEER-UPR has conducted research on sugarcane and other tropical grasses managed specifically as energy crops (3, 4, 5). Total dry matter is the decisive yield parameter rather than sugar or cattle feed. Controlled variables have included varieties, row spacing, harvest frequency, fertilization, and water supply. Averaged yields for three crops (the plant crop plus two ratoon crops) indicate that more than 80 tons of millable cane can be produced per acre year (Table 3). Production costs are in the order of $10.12/ton of millable cane, or about $840.00/acre year (Table 4).

The energy cane studies in Puerto Rico are far from complete; however, results to date very strongly suggest that the yield and cost data from Puerto Rico's commercial cane industry are not a true indicator of sugarcane's potential as a local energy resource. Rather, they appear to be an artifact of Government policy and other circumstances unfavorable for the continued planting of cane as a sugar crop in Puerto Rico.

2. Juice Quality And Sugar Yield

An important feature of energy cane management is the continuous forcing of growth processes and crown expansion. There is no clear-cut period of growth decline, maturation, and natural ripening such as that which characterizes the final months of a well-managed sugar crop. A primary need of the cane plant at this time is to hydrolyze sucrose to invert sugars; these in turn serve as sources of carbon and energy for the structuring of new plant tissues. Relatively little sucrose accumulation is expected in the plant's storage tissues.

Juice analyses for three crops of energy cane verified the relatively low quality of these plants as a sugar crop (6). There were variations among crops, varieties, and row spacing, but sucrose content rarely exceeded 8.0 percent for any treatment[1]. Average Brix and fiber values were in the order of 12° to 14°, and 16 to 18%, respectively.

In computing sucrose yields on a per acre basis (tons sugar/acre, or TSA), the poor quality of cane was effectively compensated by the high tonnage of millable stems. The three-crop averages for standard and narrow row spacing were 6.04 and 5.13 tons sugar/acre, respectively (Table 5). Narrow row spacing is already eliminated as a practical consideration for Puerto Rico, so a sugar-yielding capability of about 6.0 TSA is assumed for energy cane.

It should be noted that a sucrose value of 6.0 tons/acre year is more than double the yield attained by the PR Sugar Corporation in recent years. A yield of 4.0 TSA would be considered good by present standards. It should also be noted that the 6.0 TSA value for energy cane refers to sugar in the field, not sugar that has been recovered in the mill. Low yields by the PR Sugar Corporation

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[1] Variety NCo 310, at standard row spacing in the first ratoon crop, yielded the highest sucrose content to date at 10.2%.

are less a reflection of sugar in the field than of inadequate harvest equipment and procedures used in recovering this sugar (15). For energy cane, it is believed that by combining a continuous whole-cane harvester (the Klass Model 1400, or a suitable modification of this machine) with revised management of harvest operations, a sucrose recovery of at least 70% will be obtained. If so, a final sugar value in excess of 4.0 TSA could be realized for energy cane. This would exceed by a significant margin the sucrose yields presently obtained by Puerto Rico's sugar industry.

MAXIMIZING ENERGY CANE BIOMASS

1. The Worst Case Scenario

The cost estimates presented in Table 4 represent a "worst case" scenario in which indicated costs are higher than an energy planter would reasonably expect to pay. There are several reasons for this: (a) The assumed production operation is that of a private farm family having only 200 acres planted in energy cane. This family would need to hire major equipment items (cane planter, cane harvester, delivery trucks) together with licensed equipment operators. (b) A private farmer will not ordinarily charge himself for "land rental" and "management" (items 1 and 14, Table 4). These two entries make up about 15% of the total production cost. (c) No Federal credits or subsidies are considered for this operation. As a future alternative fuel enterprise in which one or more products are fossil fuel substitutes the energy planter could be eligible for some level of government support.

A fourth reason relates to the use of yield averages rather than practical yield trends. The energy cane yield shown in Table 4 is an average figure derived from several varieties, row spacings, and cropping years. An energy planter is a practical man, not a statistician; he will employ the superior variety, row spacing, and cropping interval for his region. In this instance the superior variety is NCo 310, at standard row spacing, yielding 92 tons/acre of millable cane as opposed to the average figure of 83 tons/acre actually used in making the cost estimates.

A fifth reason was the omission of energy cane trash as a biomass yield component. In the cane sugar industry the term "trash" refers to leaf and leaf-sheath tissues that have desiccated and detached from the sugarcane stem. During the course of a year an appreciable quantity of trash will accumulate. This material is normally left in the field or eliminated entirely in a pre-harvest burning operation. Energy cane studies by CEER-UPR (6) indicate that significant tonnages of trash are produced both by sugarcane and napier grass (Table 6). For variety PR 980 the trash component made up more than 23% of the total dry matter yield (Table 7). In a future energy cane enterprise in which cellulosic materials are a valued product the trash will be harvested and credited to the total biomass yield. Moreover, because trash can be solar-dried and baled independently of cane-milling and bagasse-drying operations, "production" costs for the trash fraction could be significantly lower than the costs for millable cane.

2. The Best Case Scenario

As noted above, a revision of field management objectives is vitally important in attaining the maximum biomass yields from sugarcane. It is equally important to recognize that the experimental energy cane yields obtained to date are only a fraction of the ultimate yield potential for energy cane. From 1977 to 1980 we were obliged to use the best conventional cane varieties then available in the sugar industry (3, 4, 5). Each of these varieties had been bred for sugar planting rather than energy planting. Even if one uses the most productive variety and row spacing, forces growth with increased water and nutrient inputs, and credits trash to the total yield, the maximum output would be around 90 millable tons/acre year, or about 33 dry tons/acre year. It is very probable that the upper yield potential for energy cane lies in the order of 150 tons of millable cane and 50 tons of dry matter per acre year.

The potential for yield improvement through hybridization of *Saccharum* is indeed enormous. The interspecific cross, which is known in a limited number of crop plants, is common among the extant species of *Saccharum*. The inter-generic cross, extremely rare among agricultural plants, is relatively common between *Saccharum* and other genera of tropical grasses. Hence, controlled crosses for increased yield proficiency can be made between *Saccharum* and such diverse genera as *Sorghum, Erianthus, Miscanthus, Zea, Sclerostachya, Pennisetum,* and *Bambusa* (7-11, 14).

Within the genus *Saccharum* the potential for yield improvement is similarly much greater than is generally recognized. Ironically, the genetic make up of most commercial sugarcanes derives from only five or six gametes from among thousands within the genus *Saccharum*; other genera that will cross with *Saccharum* contribute nothing at all (12, 13). Cane breeding programs still utilize germplasm from the ancient Indonesian variety "Kassoer," and *S. sinense* germplasm from "Chunnee" and "Co 281." Some breeding programs have no *S. robustum* germplasm from any source in their parental lines. Arceneaux (11) notes that we have "barely scratched the surface" of the known *S. spontaneum* pool, while many authorities have complained of the sparseness of *S. robustum* and *S. sinense* germplasm in modern interspecific hybrids. As aptly stated by Price (13), "— the great diversity of wild plants that hybridize with sugarcane has been sparsely used."

In terms of production input costs the yield gains expected via cane breeding should be largely free. For example, the production inputs already expended in attaining 83 tons of energy cane (Table 4) represent a kind of input plateau, beyond which additional expenditures would not be needed irrespective of the variety or species being grown. Critical inputs such as 400 pounds of elemental nitrogen/acre year, or 4.5 acre feet of irrigation water/acre year, are optimized factors to be utilized more effectively by future hybrid canes. Basic charges for seedbed preparation, labor, harvest and delivery operations, and a range of capital investments will change proportionately little as productivity increases from 80 to 150 tons/acre year.

Absolute yield increases are not the only improvements to be gained through *Saccharum* hybridization. Additional benefits could include: (a) Increased disease resistance; (b) increased tolerance to insect pests; (c) improved suitability for mechanical harvest; (d) improved suitability to extended harvest season; and (e) improved composition (higher sucrose and *a*-cellulose, lower ash and sulfur). There are potential benefits of even greater importance. Examples of these include an increased adaptability to marginal land and rainfall regimes, and an increased tolerance to cool climates.

YEAR-ROUND PRODUCTION

1. Multiple Species Management

Under tropical conditions the year-round production of tropical grasses is both botanically and agronomically feasible. In temperate and subtropical countries, climatic factors dictate that biomass must be produced on a seasonal basis. For a tropical nation to do so would be a gross mismanagement of its finest natural resource.

In Puerto Rico and most other sugar-planting countries sugarcane is grown on a year-round basis, but it is harvested and milled on a seasonal basis. Puerto Rico's present milling season covers a 6-month period from January through June. Individual mills operate only three to five months since there is insufficient cane to maintain a longer grinding season. Hence, the long "down time" for PR sugar mills constitutes an uneconomical use of some very expensive capital investments. Similarly, a conventional sugar mill is a less than optimal source of feedstocks for biomass processing and utilization operations requiring year-round inputs.

An important feature of energy cane management would be the lengthening of milling operations to about eight months. For Puerto Rico this period would extend from early December to early August. The increased yields of millable cane would enable the energy cane industry to do so; in fact, cane could be ground almost continuously through the year if sufficient tonnages were available. In Puerto Rico this would not be practical owing to the heavy rains which occur from August through November. Nonetheless, the sugar mill itself could be used continuously as a center for biomass drying, processing, storage, and electrical power production.

(a) *Integration Of Maturity Profiles:* As indicated elsewhere (16), sugarcane, like other herbaceous plants, must be harvested after a period of tissue maturation in order to maximize its dry matter yields. Energy cane will require at least 12 months between harvests to complete its tissue expansion and maturation processes. A whole range of planting and harvest dates must therefore be planned and coordinated by field managers in order to assure an 8-month input of millable cane.

To assure a year-round input of mature biomass, energy cane production would be integrated with several other categories of tropical grasses. The energy planter would produce a series of short-, intermediate-, and long-rotation species having chronologically-distinct profiles of maturation. The profiles of three such species (Sordan, napier grass, sugarcane) are graphically illustrated in Figure 1. By this means, botanically mature biomass could be harvested at 2- to 3-month intervals for Sordan, at 4- to 6-month intervals for napier grass, and at 12- to 18-month intervals for energy cane (Table 8).

(b) *Solar Drying vs Mechanical Dewatering:* As diagrammed schematically in Figure 2, energy cane would supply about 2/3 of the annual feedstock input for a proposed processing and utilization center for tropical biomass (17). This cane would be partially dewatered in a conventional mill tandem, and then further dehydrated by use of waste stack heat. The remaining 1/3 of the incoming feedstock would consist of thin-stemmed, fibrous, non-sugar bearing tropical grasses. These would not be sent to the sugar mill for dewatering; rather, they would be solar-dried and baled in the field as part of the harvest operation. The baled material would have a moisture content of approximately 15 percent. It would be sent to the processing plant for storage and subsequent utilization during the 4-month period when no energy cane is being milled. This biomass can be supplenental with a range of miscellaneous materials, ie, weeds, roadside clippings, tree branches, crop residues, etc. (Figure 2).

There are many advantages of multiple species usage as biomass feedstocks: (a) The year-round growing season is utilized to the maximum possible degree; (b) an energy planter can capitalize on the divergent growth habits of discrete tropical species; (c) solar drying can contribute as an economical means of water removal; (d) dry biomass is made available as an alternative fuel each day of the year; (e) sugar mill facilities are maintained in operation for a longer period of time; (f) employment is increased in field and factory operations; and (g) new jobs are created for rural suppliers of supplemental biomass (for off-season processing).

2. Alternative Products From Energy Cane

The energy cane concept was first proposed to the Commonwealth Government in 1979 (17), essentially as a sugar mill modification project as diagrammed in Figure 2. At that time Puerto Rico was in growing need of two products from energy cane: (a) Fiber, as a boiler fuel substitute for oil, and (b) fermentable solids as a feedstock for the local rum industry (18). Both products are more urgently needed today than they were in 1979.

(a) *Fiber Alternatives:* Several new options emerged during the past year for energy cane utilization. It is improbable now that the fiber components would be burned directly in sugar mill furnaces for electrical power production. CEER-UPR has received repeated inquiries on the availability of tropical grasses for pelletized fuel manufacture. The same materials may have a role as back-up fuels for Puerto Rico's future coal-fired power plants. Because of new developments in cellulose conversion technology (19), bagasse or solar-dried tropical grasses might eventually serve as fermentation substrates.

Of considerable interest to CEER-UPR are recent advances by Combustion Equipment Associates, Inc., in the development of powdered biomass fuels that can be burned as an oil substitute in existing oil furnaces. One CEA product, AGRI-FUEL, apparently can be manufactured from sugarcane bagasse and other tropical grasses. CEER-UPR has joined with CEA and the Battelle-Columbus Division in seeking Federal support for feasibility studies on the production of AGRI-FUEL from tropical grasses in Puerto Rico and Florida.

(b) *Sucrose And Fermentable Solids:* The total diversion of energy cane sugars to high-test molasses, as indicated in Figure 2, would be reconsidered in the light of recent price increases for sucrose on the world market. Less than a year ago sucrose was valued at only 14 cents/pound while local production costs exceeded 20 cents/pound. Under these circumstances it was advisable to send the entire sucrose component of energy cane to the rum industry as a constituent of high-test molasses.

At this writing (October, 1980) the value of sucrose has risen to 41 cents/pound. Under present circumstances it could be profitable to recover part of the sucrose for local consumption or for sales abroad. This might be accomplished at minimum cost by retaining the "first strike" at the sugar factory, representing perhaps 60 percent of the sucrose contained in the raw juice. The remainder would go to the rum industry as a component of a moderately lower quality high-test molasses.

SUMMARY

It is in the production of dry matter rather than sugars or nutritive components that the tropical grasses most naturally excel. An appropriate example of this is seen in the genus *Saccharum.* Of the six extant species of this genus, only one (*S. officinarum*) has any appreciable aptitude for storing sugar, but the entire group of species is proficient in producing dry matter. Even the high-sugar yielding members of *S. officinarum*, given a warm climate, an adequate soil, and high inputs of water and nutrients, will opt to produce biomass rather than sugar.

Energy cane is sugarcane managed to maximize its growth potential rather than sugar. The U.S. Department of Energy has sponsored energy cane studies in Puerto Rico since 1977. Although this work is not complete, data trends for three crop years indicate that yields of both biomass and sugar can be increased appreciably over those obtained in recent years by the PR Sugar Corporation. Production costs were higher on a per acre basis but lower per ton of cane, owing to nearly three-fold increases in yield. Similarly, juice quality values for energy cane were lower than conventional sugarcane, but sugar yields/acre (TSA) were higher by virtue of the increased cane tonnages.

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Table 1

MILLABLE CANE PRODUCTION POTENTIALS

Parameter	Tons/Acre Year 1/
World Average	22.6
Puerto Rico Ave. (1979)	28.0
PR Energy Cane (1980)	83.0
Estimated Theoretical 2/	112.5

1/ Without trash. 2/ N. I. James (20), 1980.

Table 2

HOURLY WAGES IN PR CANE INDUSTRY

Year	Average ($/Hour) 1/
1939	0.16
1957	0.35
1968	0.69
1977	2.10
1981	3.19

1/ US Dept. of Labor, 1980.
2/ Estimated.

Table 3

AVERAGE MILLABLE CANE YIELDS AT STANDARD & NARROW SPACING

Crop [1]	Tons/Acre At Row Spacing	
	150 cm	50 cm
Plant	75.8	71.5
First Ratoon	92.0	90.2
Second Ratoon	84.0	84.3
Mean	83.9	82.0

[1] 12-month harvests. Average of three varieties.

Table 4

PRODUCTION COSTS FOR MILLABLE SUGARCANE MANAGED AS AN ENERGY CROP 1/

Land Area: 200 Acres
Production Interval: 12 Months
Millable Cane Yield: 83 Short Tons/Acre; Total 16,600 Tons

Cost Analysis

Item	Cost ($/Year)
1. Land Rental, at 50.00/Acre	10,000
2. Seedbed Preparation, at 15.00/Acre	3,000
3. Water (800 Acre Feet at 15.00/ft)	12,000
4. Water Application, at 48.00/Acre Year	9,600
5. Seed (For Plant Crop Plus Two Ratoon Crops), 1 Ton/Acre Year at 15.00/Ton	3,000
6. Fertilizer, at 180.00/Acre	36,000
7. Pesticides, at 26.50/Acre	5,300
8. Harvest, Including Equipment Charges, Equipment Depreciation, And Labor	20,000
9. Day Labor, 1 Man Year (2016 hrs at 3.00/hr) 2/	6,048
10. Cultivation, at 5.00/Acre	1,000
11. Land Preparation & Maintenance (Pre-& Post-Harvest)	600
12. Delivery, at 2.78/Ton/3 Miles of Haul	46,200
13. Subtotal:	152,746
14. Management: 10% of Subtotal	15,275
15. Total Cost:	168,023
16. Cost/Ton (168,023 ÷ 16,600)	10.12
17. Cost/Acre (168,023 ÷ 200)	840.15

1/ DOE contract no. DE-AS05-78ET20071.

2/ Labor which is not included in other costs

Table 5

AVERAGE TONS SUCROSE/ACRE (TSA) AT STANDARD & NARROW SPACING

Crop	TSA, At Row Spacing [1/] 150 cm	 50 cm
Plant	5.38	4.29
First Ratoon	6.53	5.41
Second Ratoon	6.20	5.69
Mean	6.04	5.13

[1/] Average of three varieties.

Table 6

TRASH YIELDS BY CANE AND NAPIER GRASS [1/]

Species	Variety	Dry Tons/Acre Year
Cane	PR 980	6.81
	NCo 310	4.71
	PR 64-1791	4.76
Napier Grass	Merker	3.20

[1/] Average of three 12-month crops and two row spacings.

Table 7

TRASH YIELD AS % OF TOTAL CROP

Variety	Trash 1/ (% Of Total DM)
PR 980	23.5
NCo 310	15.5
PR 64-1791	16.7
Napier Grass	14.8

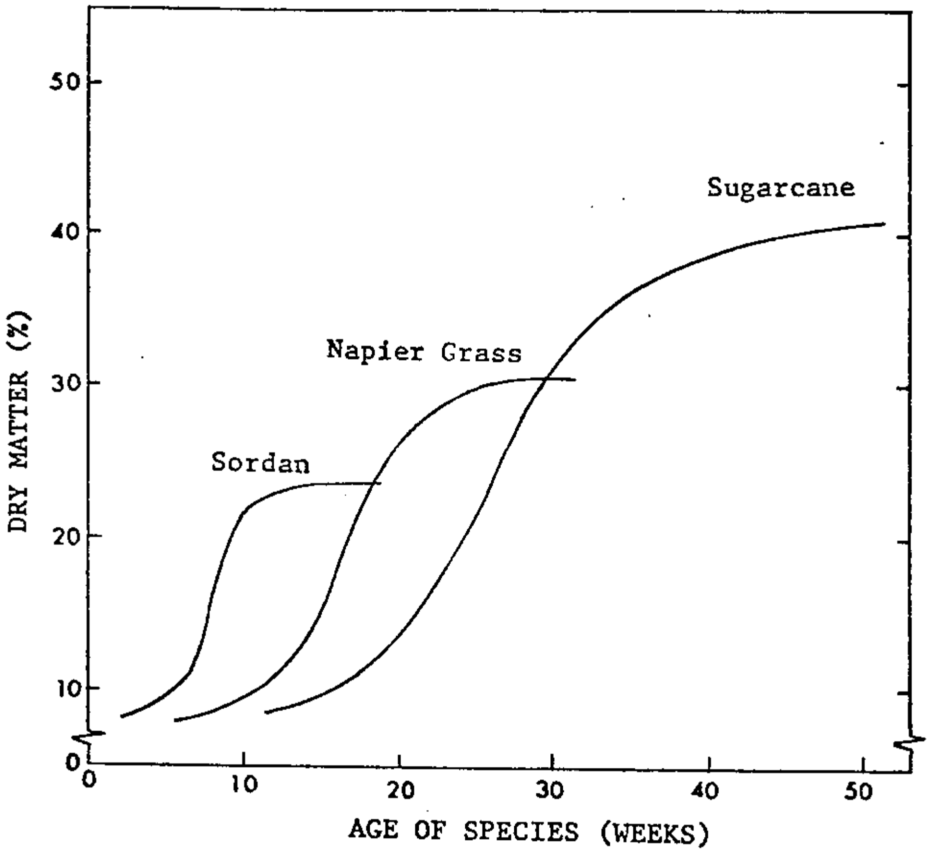
1/ Average of three 12-month crops and two row spacings.

Table 8

CATEGORIES OF TROPICAL GRASSES FOR BIOMASS

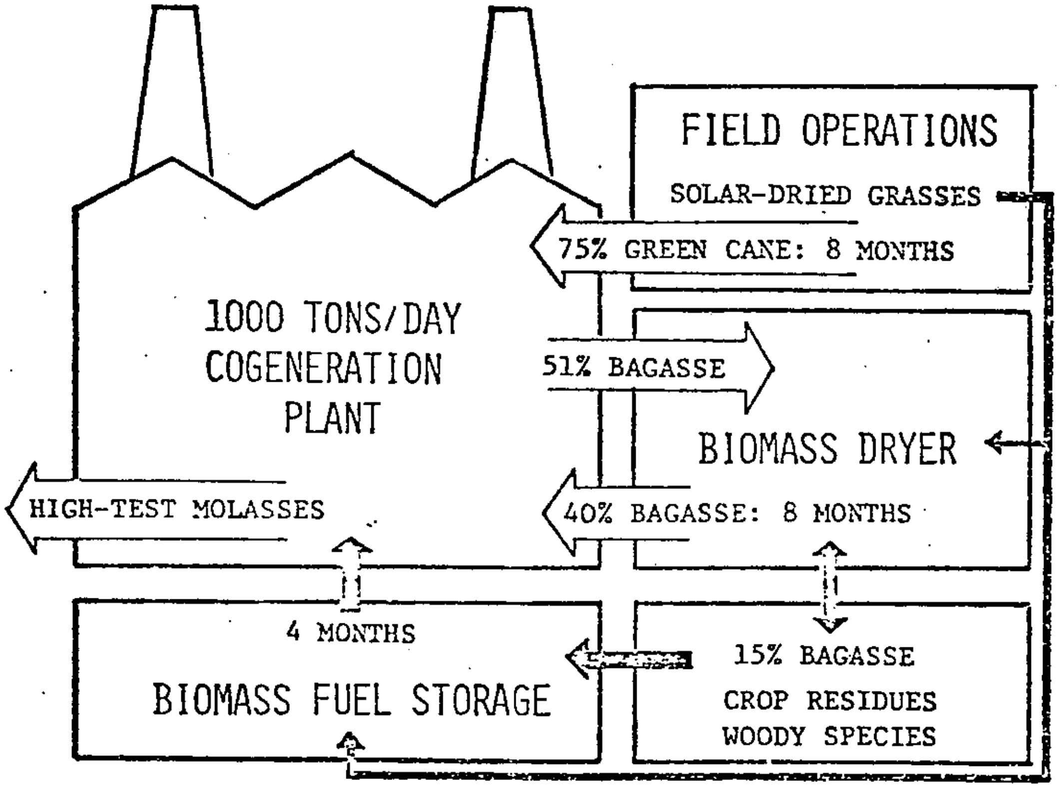
Category	Type Species	Maturation Time (Months)
Short Rotation	Sordan 77	2-3
Intermediate Rotation	Napier Grass	4-6
Long Rotation	Sugarcane	12-18

Figure 1



Relative maturation profiles for Sordan 70A, napier grass, and sugarcane over a time-course of one year. These plants are representative of the short-, intermediate-, and long-rotation cropping categories, respectively.

Figure 2



Integration of energy cane and other biomass sources to produce a year-round fuel supply for an industrial-scale cogeneration plant, plus high-test molasses for the production of rum. Basically a modified sugar mill, major innovations found in Field Operations and the Biomass Dryer make possible the continuous operation.

SOIL AND WATER MANAGEMENT CONCEPTS FOR ENERGY CANE PLANTATIONS

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE UPR DEPARTMENT OF AGRICULTURAL ENGINEERING
UPR Mayaguez Campus, Mayaguez, Puerto Rico

SOIL AND WATER MANAGEMENT CONCEPTS FOR ENERGY CANE PLANTATIONS

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Soil And Water Management Concepts For Energy Cane Plantations

William F. Allison[1]
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ABSTRACT

WATER inputs approaching that of pan evaporation are essential to the growing of sugarcane for biomass production, as the crop growth responds directly with water inputs to this level. Excessive water retards growth, requiring surface and subsurface drainage along with good irrigation management. A soil-water management system must be compatible with the mechanical harvesting system which generally requires a smooth flat soil surface that can be accomplished by land forming and grading followed by precise planting and cultivating.

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INTRODUCTION

SUGARCANE has for centuries been recognized for its large growth potential as well as for its high content of fermentable solids, including sucrose. Therefore, when the need arose to develop alternative fuels and chemical feed-stocks that will substitute for fossil fuels, sugarcane became one of the prime candidates and has proven to be one of the superior candidates in climatic zones in which it is suited. However, water, along with the warm climate, is a basic need of the crop. The growth rate and production of sugarcane are directly related with water availability and management.

SUGARCANE RESPONSE TO WATER INPUTS

Within limits, the growth of sugarcane responds directly with soil water availability, requiring approximately 137 kg of water to produce one kg of dry matter (5), as presented in Figure 1. Generally, the plant is unable to survive in nature and produces its minimal crop when annual rainfall is less than 1000 mm (40 inches). As water inputs increase above minimal to equal pan evaporation, sugarcane growth increases in a direct relationship. As water availability begins to exceed pan evaporation, growth tends to decrease (4), as illustrated by Figure 2.

From Figure 2, one can conclude that water inputs equalling pan evaporation result in the highest levels of production, with higher rates of water inputs reducing production just as lower rates do. Therefore, when water is abundant and cheap, a water input equalling pan evaporation is ideal. However, when water supplies are in short supply or expensive, the proper input is about 86 percent of pan evaporation, since a reduction in water input of 14 percent only causes about 5 percent reduction in growth.

Research has clearly shown that excess soil water reduces production from 30 to 60 percent (3,6), depending on the degree of water excess. Normally, sugarcane responds to the lowering of the water table to depths of 75 to 100 cm, with the greatest response occurring from lowering of the water table from the soil surface to 75 cm.

Thus, to obtain high production of sugarcane, inputs of water should be in the order of 85 to 100 percent of pan evaporation during the growing period when the plant has a full leaf surface. There should be lesser inputs at crop initiation and toward maturity, as shown in Figure 3. Also, in lands having subsurface drainage problems, water tables should be held below 75 cm, and when irrigation is the major source of water, then water tables should be maintained below 100 cm and preferably below 180 cm. This is because of soil salinity problems that are invariably associated with irrigated agriculture.

Sugarcane with its extensive root system is able to fully utilize the water storage capacity of the soil and thus does not respond to light frequent applications of water as well as to larger quantities applied less frequently. This was very capably demonstrated by Ewart in Hawaii (2). This ability to utilize the soil water storage capacity generally lowers the cost of irrigation because irrigation cost is normally associated with frequency.

THE NEED FOR IRRIGATION TO OPTIMIZE GROWTH

As previously discussed, sugarcane needs water constantly; however, few climates provide this constant input of water even in humid areas. This is because rainfall is generally seasonal, with dry periods exceeding 120 days being quite common. Usable water storage in the soil seldom exceeds 15 to 20 cm, with monthly demands of the crop being on the order of 8 to 17 cm, depending on the stage of growth and season of the year. As can be observed from Figure 3, the crop demand exceeds the probable rainfall of the south coastal plains of Puerto Rico every month of the 45 month crop cycle, except for the first four-month period when the crop is initiated. Even this slight precipitation excess can be stored in the soil for future use or preferably utilized to leach the excess salts from the root zone that have accumulated from irrigation. Figure 3 clearly illustrates the need for irrigation to give suitable levels of production and to provide for the survival of the plant. The 3400 mm of rainfall over the 45 month crop cycle, if totally effective, would only produce about 126 tons/ha of dry matter (56 tons/acre, or about 15 tons/acre year), and more likely only about 100 tons/ha. With adequate irrigation the production should be on the order of 277 tons dry matter/ha. This represents an increase of 177 percent with an input of approximately 4070 mm (160 inches) of effective irrigation.

Similar comparisons can be made of the other climatic zones of Puerto Rico, but the greatest need for irrigation is along the southern coastal plains from Guayama to Boquerón. However, during certain periods of the year, water deficiencies exist throughout the island.

THE NEED FOR DRAINAGE TO OPTIMIZE GROWTH

As has already been discussed, water is a necessary input to make sugarcane grow. However, too much water in the system has a depressing effect on production. Thus, both surface and subsurface drainage is required to adequately manage the water resource to optimize production. In an area severely affected by both surface and subsurface drainage near the mouth of the Añasco River, on the Island's west coast, this author supervised research and field trials in 1968-70. The production history of this area was in the order of 16 tons of dry matter/ha/year.

With adequate surface drainage, the production was increased to 33 tons/ha/year, and with both surface and subsurface drainage the production rose to 56 tons dry matter/ha/year, an increase of some 40 tons/ha, with 23 tons attributed to subsurface drainage. Similar results were obtained on the north coast near Vega Baja.

A SOIL AND WATER MANAGEMENT SYSTEM FOR SUGARCANE AS A BIOMASS CROP

In the past, sugarcane has been managed for the production of sucrose. The factory largely controlled the quality of the feedstock delivered for processing. The miller demands raw material high in sucrose, clean, and containing only sufficient fiber to provide process energy. Namely, the miller wants only the mature portion of the stalk, free of soil, leaves, tops, and trash. As a biomass crop the objectives become the production of fiber as well as fermentable solids, of which sucrose is only a part and not the controlling portion.

Soil fertility, tilth, and structure, along with varieties and management, are just as important as water in the growing process; however, the harvesting of the crop is also highly important. A soil-water management system for biomass production must be compatible with mechanical harvesting.

The mechanical harvesting of sugarcane for its sucrose is a formidable task, especially with the traditional mores associated with past culture. As a biomass crop, to mechanically harvest the total above ground portion of the crop becomes even more challenging, especially at first glance. However, in looking back, one can easily see that the greatest problems encountered in mechanically harvesting are caused by field practices, such as furrowing and ditching, along with the separation of the tops, leaves, and other undesirable material from the stalk that contains the sucrose. Furrows are especially undesirable in the mechanical harvest for biomass production since they trap and tend to hold plant material that may fall into the furrow, making harvest more difficult and dirty. Separation of the so-called extraneous material may not be required for biomass harvest as this material has an energy value that is greatly reduced when dropped on the ground and soil is picked up when harvesting this residue. The soil contributes to the ash content in the processing and utilization of this material.

Therefore, for biomass production, field surfaces need to be uniform and flat. This requires land forming and grading for irrigation and drainage. With land forming, irrigation can be easily accomplished with border irrigation, which just happens to be the most economical method of applying irrigation water (8). On land unsuitable for land forming the center pivot or wheel line system of sprinkler irrigation may be used.

Harvest is best accomplished when the top 45 cm of the soil is dry, because harvest equipment can severely compact the soil and materially reduce production of succeeding crops. Subsoiling can give temporary relief for soil compacted by the harvest equipment, provided the compacted soil is relatively dry. The subsoiling of wet soil may be of no benefit and can even create a more severe problem.

Harvesting systems have been developed that can harvest the biomass energy cane provided they have been made as part of the planning and management process. Bringing the whole plant to the mill greatly simplifies field harvesting and in Puerto Rico would probably have little effect on mill performance. In many cases, harvesting the whole plant would probably enhance milling, as soil content could be almost eliminated by having flat field surfaces and never dropping the crop on the ground.

SUMMARY

Sugarcane growth responds to water and soil management. A fertile soil in good physical condition in Puerto Rico can produce approximately 2.7 tons of dry sugarcane biomass per month when provided with adequate water management. Irrigation is required throughout the Island to maximize production, but the south coastal plains having the least rainfall give the highest returns to irrigation. The north, east, and west coastal plains require both surface and subsurface drainage to remove excess water. Biomass plantings need to facilitate mechanical harvesting which can be greatly enhanced by preparing flat uniform field surfaces.

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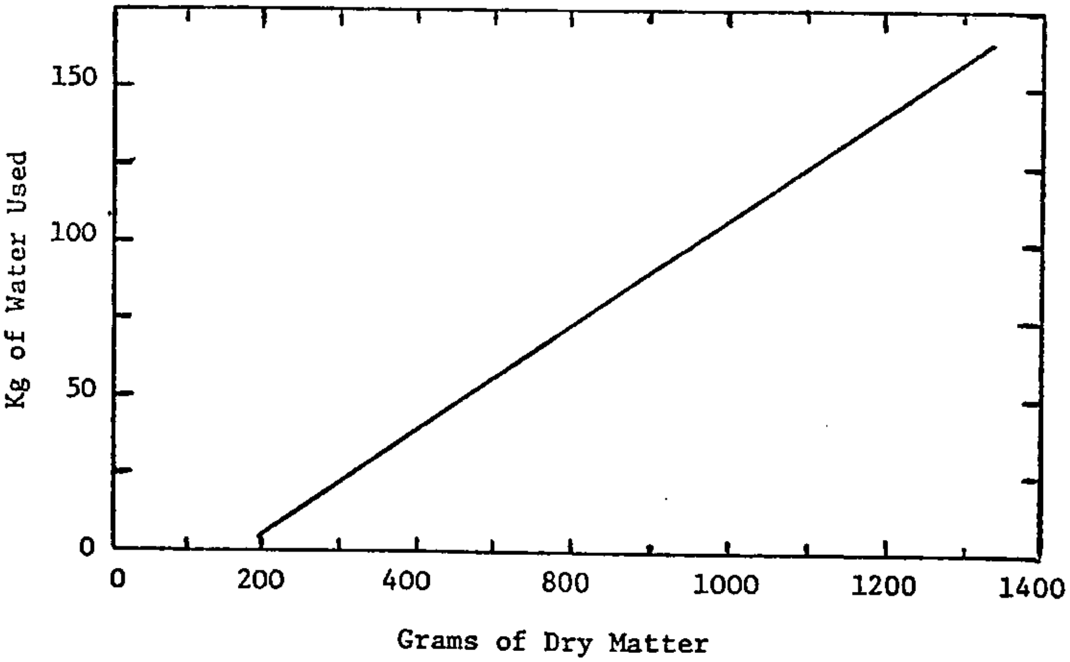

Fig. 1. Dry matter produced in a controlled environment compared to water used. (Redrawn from Jen-Hu Chang et al.).

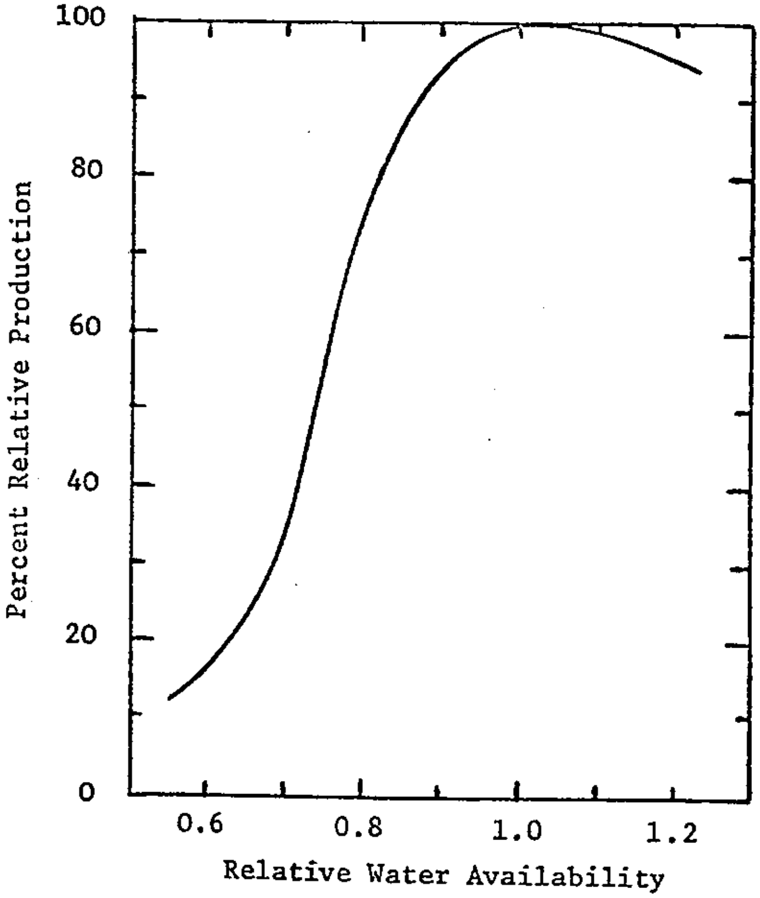

Fig. 2. The effect of water availability on cane production

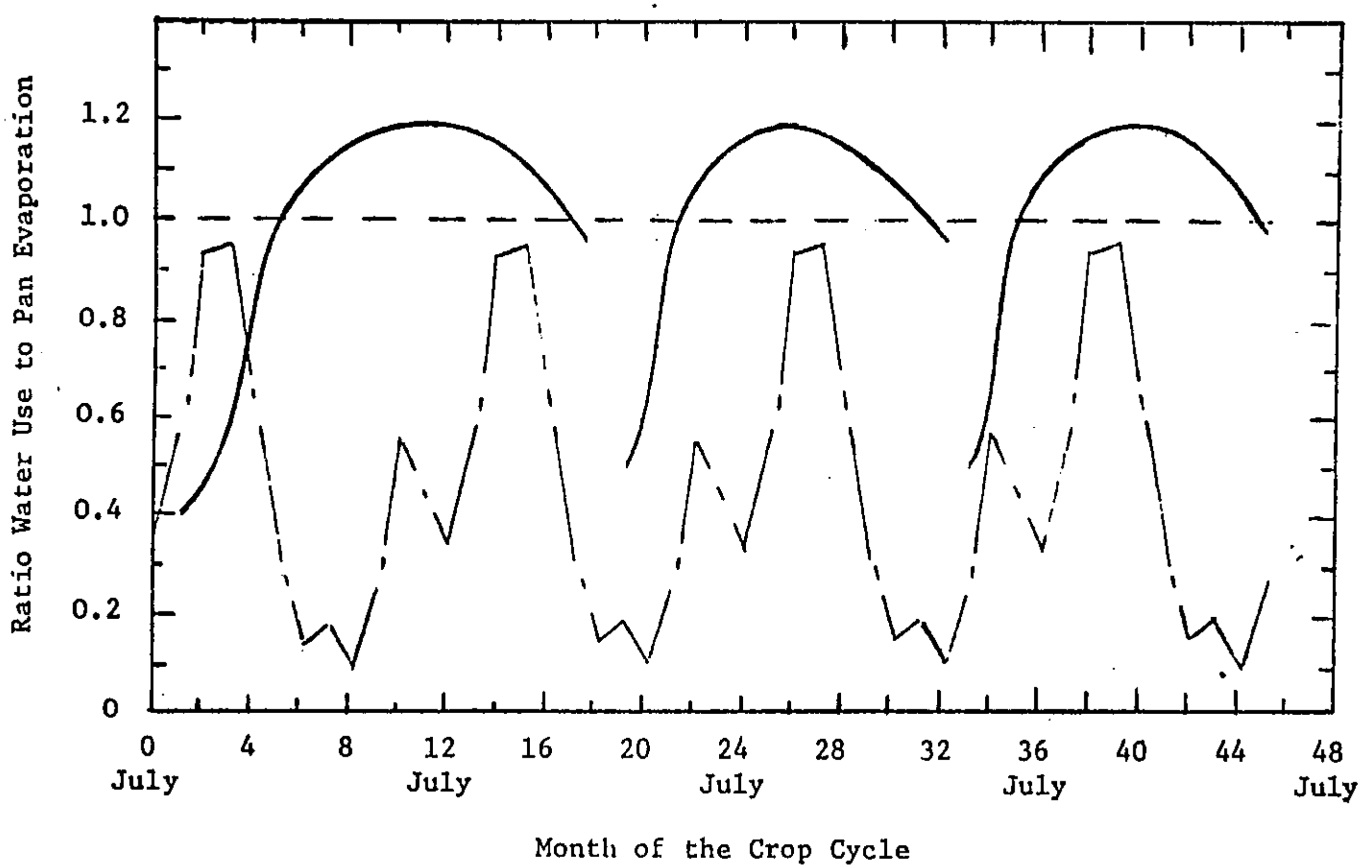

Fig. 3. Water use of sugarcane compared to probable rainfall along the south coastal plains of Puerto Rico for a 4-year crop cycle initiated in July.

X

HYBRIDIZATION OF TROPICAL GRASSES FOR FUEL AND ALCOHOL

Presented To The Symposium

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HYBRIDIZATION OF TROPICAL GRASSES FOR FUEL AND ALCOHOL

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HYBRIDIZATION OF TROPICAL GRASSES FOR FUEL AND ALCOHOL

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ABSTRACT

IN VIEW of the increasing interest being directed toward the tropical grasses as a renewable energy source for Puerto Rico, a review is presented of our initial exploration of the genetic potential for biomass in the tropical grasses, with special reference to the genus *Saccharum*. The potential parental material, combinations, and the preliminary evaluation of performance for F_1 progenies for biomass production rather than sugar are discussed. On the basis of available information it is believed that there are extensive opportunities for the plant breeder to develop new biomass resources within *Saccharum* and the allied tropical grasses. These can be developed through breeding and selection specifically for the attributes of high yield for total dry matter and fermentable solids.

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TROPICAL GRASSES AS AN ENERGY CROP

PUERTO RICO'S dependence on imported fossil energy has spurred local interest in energy resources that are both renewable and domestic. Among energy alternatives for Puerto Rico, the U.S. National Academy of Sciences has identified biomass as the most important renewable energy source for the Island's intermediate future (17). If managed as a major agricultural activity, NAS estimates that up to 10 percent of Puerto Rico's electricity could derive from biomass fuels. CEER-UPR estimates are considerably higher (20).

1. Biomass Potentials

Species such as sugarbeet, cassava, maize, sweet sorghum, and tropical grasses have been studied recently as candidate crops for the production of boiler fuels and alcohol (2,6,10,11,12,15). However, considering the Island's needs, climate, and historical background, the tropical grasses have probably the largest potential as an energy crop for Puerto Rico. Within this group of species sugarcane is widely reputed to be a relatively efficient collector of solar energy. It can perform as a solar energy collector on a year-round basis in the tropics and seasonally in subtropical regions (2,10,11).

The tropical grasses are well qualified to produce biomass. The maximum growth rate (dry matter production) for C_3 plants has been placed at 34 to 39 $g/m^2/day$, while C_4 species such as sugarcane, corn, and sorghum can produce up to 54 $g/m^2/day$ (13). Thompson (16) estimates that irrigated sugarcane should have a photosynthetic efficiency of 1.7 percent; rainfed cane in South Africa has an efficiency of about 1.1 percent. These figures correspond roughly to 11.0 and 7.5 g dry matter/m^2/day, respectively. DOE-sponsored studies in Puerto Rico (3) revealed an average DM yield of 21.5 $g/m^2/day$ on a year-round basis, and 27.1 $g/m^2/day$ on a "seasonal" basis (180 days).

The theoretical maximum yield for sugarcane has been estimated in the order of 280 millable tons/ha/year, or about 113 tons/acre/year (5,11). Workers in Puerto Rico (3) attained 92 green tons cane/acre/year, with the first-ratoon crop of conventional sugarcane varieties managed for total growth. It is believed that yields in the order of 150 green tons/acre/year could be commonplace if certain breakthroughs are achieved in the breeding technology for *Saccharum* species (18). The Puerto Rico sugar industry is currently producing about 28 green tons/acre/year as an Island-wide average (2).

The hybrid tropical grasses Sordan 70A and Sordan 77 are leading candidates for short-rotation energy crops in Puerto Rico (1,18). Each was produced from sorghum-Sudan grass parents. *Pennisetum* sp. (napier grass and napier hybrids) are superior intermediate-rotation species. Such grasses under management as solar-dried forages could fill the time-frame when sugarcane bagasse is not available as a fuel or cellulosic feedstock in Puerto Rico (2). Sorghum x Sudan grass hybrids have also been produced by the Dekalb Company, and several appear to be more tolerant of arid conditions than Sordan 70A and Sordan 77 (4). Breeding studies in Puerto Rico have utilized a male-sterile Rhodesian Sudan-grass to develop superior F_1 hybrids. Certain of these have produced more than 20,000 kg/ha of dry matter in 140 days (14). These local hybrids should be screened locally as candidates for short-rotation energy cropping.

2. Alcohol Potentials

As an alcohol source, sweet sorghum has been evaluated by DOE contractors on the U.S. mainland (12). Total U.S. production from this plant has been estimated in the order of 25 to 30 billion liters of ethanol/year, at a cost of $0.32/liter, by the year 2000.

For ethanol production from sugarcane, yield estimates amounting to 3,700 to 15,000 liters/ha have been published (4,11). A net energy ratio (energy output/energy input) ranging from 1.9 to 2.7 has been reported for rainfed and irrigated regions, respectively, in South Africa (15).

As discussed by Samuels (19), alcohol from sugarcane in Puerto Rico is generally depicted in terms of rum production rather than total ethanol/acre or ethanol/ton of cane. Rum distillers ordinarily utilize "blackstrap" molasses (from which part of the sucrose has been removed) for this purpose, but they also use "high-test" molasses (molasses from which sucrose has not been removed). The composition of molasses varies considerably with the variety of cane planted and the management it has received from the time of planting until delivery at the sugar mill. One gallon of blackstrap molasses contains approximately 6.8 pounds of sucrose and will yield about 0.75 proof gallons of rum. As an Island-wide average, PR sugarcane today yields about 6.0 gallons of blackstrap molasses and 17.6 gallons of high-test molasses per ton of cane (19). One gallon of high-test molasses will yield around 1.13 proof gallons of rum.

GENETIC POTENTIAL FOR BIOMASS IN *SACCHARUM*

The genetic potential of the genus *Saccharum* at an energy crop is indeed large, but for the most part this potential remains unexplored (2,6,10). In Puerto Rico, as elsewhere, the breeding of *Saccharum* with fuel and fermentable solids as the key objectives has not been attempted until very recently.

1. Initial Evaluation of *Saccharum spontaneum*

Our first attempt to identify candidate clones for biomass production rather than sugar was made with original *S. spontaneum* clones and *S. spontaneum* hybrids. These candidates derived from F_1, BC_1, and BC_2 generations imported into Puerto Rico from USDA collections during the mid-1970s. The importations were made by the AES-UPR Sugarcane Breeding Program in an effort to broaden the genetic base of our local germplasm pool (6). As a result, the *S. spontaneum* hybrids US 67-22-2 (BC_1), B 70701 (F_1), SES 231 (*S. spont.*), and an unknown (wild) *S. spontaneum* hybrid were identified as having exceptional promise as biomass producers (3).

2. Second Generation Candidates

Both US 67-22-2 and B 70701 are regarded as leading "second generation" biomass canes in Puerto Rico today (4). Yet, for each clone there are both advantages and disadvantages. US 67-22-2, for example, has excellent germination, rapid early growth with abundant tillering, excellent ratooning ability, resistance to mosaic and rust diseases, and an erect growth habit. It also has a higher than average sugar content, which, for an energy candidate in a sugar-planting world is a positive attribute of decisive importance. There are two disadvantages of US 67-22-2: It has a relatively low fiber content and it flowers profusely. The clone B 70701 also has rapid early growth, a good ratooning ability, and resistance to mosaic and rust. Its germination, erectness, and tillering features are less pronounced than in US 67-22-2. Similarly, its internodes are perceptively longer and the overall plant height is considerably greater. Like US 67-22-2, it has the disadvantage of an early flowering habit.

In view of the characteristics noted above, US 67-22-2 is regarded as a major candidate for energy cropping where both cellulosic feedstocks and fermentable solids for alcohol are required products. B 70701, on the other hand, seems to be a fiber (biomass) producer with limited prospects for fermentable solids. It should be noted that, when sufficiently high tonnages of millable cane are harvested, the per acre yield of sugars can be very appreciable even from cane having otherwise a low juice quality (18).

Other promising clones include US 76-7 and US 76-82, each a second back cross progeny of the *S. spontaneum* parent US 56-15-8 (Table 1). The latter clone, a Thailand *S. spontaneum*, has already demonstrated exceptional growth potential and a source of genetic material for breeding high-tonnage cane (9). US 56-15-8 was imported into Puerto Rico during September of 1980, together with other canes viewed as potential breeding stock for developing high-biomass yielding hybrids.

Out of nine intergeneric hybrids imported into Puerto Rico during October of 1978 (6), only US 61-66-6 (*Saccharum* x *Sorgo rex*) and US 64-37 (*Saccharum* x *Sclerostachya fusca*) have demonstrated good biomass potential in small field observation plots. These are continuing under survey as biomass resources in 20' x 20' plots at the AES-UPR Gurabo Substation.

HYBRIDIZATION PROGRAM FOR *SACCHARUM*

1. 1978 Breeding Season

In view of an enormous, untapped genetic potential in the genus *Saccharum* (2,6,10), a limited hybridization program for biomass was initiated by the author during the 1978 breeding season. This work is being performed in conjunction with the AES-UPR Sugarcane Breeding Program. Three crosses were performed in which biomass rather than sugar was the primary objective. In the first cross (US 67-22-2 x B 70701) both parents are regarded as superior biomass producers in their own right. Two additional crosses were designed to incorporate germplasm of an extremely vigorous *S. spontaneum* hybrid into high-yield and high-juice quality canes previously developed by the AES breeding program (7). The *S. spontaneum* hybrid is an early-flowering cane found in the wild near Río Piedras and Bayamón. It served as the male parent in these crosses. The two female parents are mid- to late-season flowering, but some synchronization of tasseling was attained by using the "cut back" method on select stands of the early-flowering male parent (3). The highest selection rate (16.3%) was obtained from the cross PR 67-245 x *S. spontaneum* hybrid (Table 2).

The Brix, fiber, and sucrose values were determined for each of fourteen F_1 hybrid progenies and their parents using the pol-ratio method (Table 3). Samples consisted of five whole canes from each hybrid. Within this progeny group, °Brix values ranged from 8.32 to 12.63, and fiber ranged from 17.7 to 25%. By contrast, the parental clones (PR 67-245 and the *S. spont.* hybrid) indicated °Brix values of 16.25 and 4.68, respectively, and fiber contents of 13.1% and 40.1%, respectively.

The highest sucrose content (rendement) for the same 14 progeny was 9.16%, for the selection PR 79-4-2. The lowest sucrose content was 4.87%, recorded for PR 79-4-1 (Table 3). These initial results seemed to indicate that fairly good juice quality could accompany the high fiber and vigorous growth expected of first generation (F_1) hybrids of *S. spontaneum*.

F_1 progenies of the cross US 67-22-2 x B 70701 indicated a remarkably vigorous growth performance plus a high number of stems/seedling. A majority were characterized by long internodes, a trait apparently inherited from the male parent B 70701.

In order to accelerate the evaluation process leading to better selections, twenty four of some 47 selected hybrids, together with their parents, were planted in a field-plot trial at the Gurabo Substation during May of 1980. A partially balanced incomplete block design with three replications was employed. Experimental plots consisted of single rows, 20 feet in length and spaced five feet apart. A 15-5-10 fertilizer ration was applied at the rate of 600 lbs/acre to each plot at the time of planting. Samples consisted of 10 stems harvested from each plot at approximately five months after planting. Stem length and diameter measurements were recorded together with total green weights. Plant number, on a per hectare basis, was computed from total stem counts for the three plots of each progeny. Stem volumes/hectare were then computed from available data (Table 4).

In terms of stalk volume/hectare, the selection PR 79-1-10 exceeded that of the female parent (US 67-22-2) by some 90 percent (Table 4). This value derives from both high stem counts and an exceptional length of stems. An additional five F_1 hybrids exceeded the female parent in stem volume by more than 40 percent. This appears to suggest that the cross US 67-22-2 x B 70701 has a high probability of producing offspring with outstanding growth potential.

2. The 1979 Breeding Season

Additional crosses were performed during the 1979 breeding season in which biomass was the primary objective (Table 5). All crosses but one were designed to maximize fiber and fermentable solids. Three clones served as male parents: US 67-22-2, 57 NG 54 (*S. robustum*), and the wild *S. spontaneum* hybrid. They were crossed with a series of high-yielding, good to high juice quality canes developed in Puerto Rico or introduced here by the AES-UPR sugarcane breeding program. Unfortunately, certain crosses of considerable interest (NCo 310 x US 67-22-2, NCo 310 x B 70701, and B 70701 x 57 NG 4) failed to produce sufficient viable seed. These crosses will be attempted again during the 1980 breeding season. Judging from initial growth and tillering performances of F_1 progeny, the crosses PR 980 x *S. spontaneum* hybrid, PR 67-1070 x *S. spontaneum* hybrid, and PR 68-355 x 57 NG 54 all appear to be potentially good sources of new genotypes favoring the biomass attribute (Table 5).

The clone US 67-22-2, serving as a male parent, was hybridized with a series of high quality canes developed locally or abroad as conventional sugar varieties. Since US 67-22-2 is an early-flowering cane, its crossing with intermediate- and late-flowering canes was accomplished by a leaf-trimming technique developed to synchronize the period of tassel emergence (8). The apparent effect of this method is to delay tasseling by restricting the production or translocation of an unknown flowering hormone produced in the sugarcane canopy. A large number of selections from these crosses are presently under evaluation in field-plot trials at four AES-UPR Substations.

CONCLUSION

Only a very limited hybridization program for high biomass has been attempted to date in Puerto Rico. Nonetheless, in view of certain highly promising selections that have already emerged, and from seedling performance trends with very limited amounts of seed, it is safe to state that a whole range of new opportunities await the plant breeder seeking superior biomass-yielding hybrids in the genus *Saccharum*. It is very probable that these opportunities extend to the "Allied" tropical grasses, and to other genera of tropical grasses that will cross with *Saccharum* but have never been examined as energy crops *per se.*

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Table 1

PERFORMANCE OF CLONES TESTED FOR BIOMASS IN A NON-REPLICATED FIELD TRIAL; AES-UPR GURABO SUBSTATION 1/

Clone	Parentage	Breeding Line	Quality Features			Biomass (Tons Cane/A) 2/	Biomass Index 3/
			°Brix	% Fiber	% Sucrose		
US 76-7 5/	CP 65-357 x US 74-14	BC_2 *S.* sp. US 56-15-18	15.2	21.2	11.8	123	141
US 76-82	CP 61-37 x US 74-18	BC_2 *S.* sp. US 56-15-8	12.9	21.6	8.7	95	109
US 76-87	CP 61-37 x US 74-18	BC_2 *S.* sp. US 56-15-8	15.3	18.0	11.5	58	66
US 76-165	US 74-15 x CP 70-300	BC_2 *S.* sp. US 56-15-8	13.3	20.5	10.6	53	60
HL 11	Unknown	BC_1 Or BC_2 S. sp.	15.1	21.6	12.9	87	100
B 70701	(28 NG 288 x ?) x SES 197 A	F_1 (*S.* *off*. x *S.* sp.)	4/	4/	4/	87	100

1/ Plot size = 1/200 acre.

2/ Harvested at 16 months of age.

3/ Reference clone, B 70701, = 100.

4/ Data not available.

5/ Susceptible to rust.

Table 2

CROSSES FOR BIOMASS IN *SACCHARUM* DURING THE 1978 BREEDING SEASON; AES-UPR GURABO SUBSTATION

Cross Number	Parentage	Seedlings Planted	First Selections	Selection Rate (%)	Objectives
PR 79-1	US 67-22-2 x B 70701	815	47	5.8	Biomass And Fermentable Solids
PR 79-2	PR 69-2 x *S*. sp. Hybrid	40	0	0	Biomass And Fermentable Solids
PR 79-4	PR 67-245 x *S*. sp. Hybrid	312	51	16.3	Biomass And Fermentable Solids

Table 3

QUALITATIVE FEATURES OF FOURTEEN F_1 PROGENY FROM A CROSS BETWEEN A WILD S. SPONTANEUM HYBRID (MALE PARENT) AND THE COMMERCIAL HYBRID PR 67-245

Progeny	°Brix	% Fiber	% Sucrose
PR 67-245	16.25	13.13	11.52
S. sp. Hybrid	4.68	40.09	-2.08
PR 79-4-9	12.62	17.72	7.60
PR 79-4-2	12.18	19.45	9.16
PR 79-4-14	11.45	18.41	6.95
PR 79-4-13	11.39	20.39	5.32
PR 79-4-6	11.32	22.75	6.95
PR 79-4-5	11.26	24.72	6.42
PR 79-4-7	10.26	19.97	6.66
PR 79-4-1	10.26	19.97	4.87
PR 79-4-10	10.24	20.61	6.48
PR 79-4-4	9.80	22.93	5.14
PR 79-4-8	9.09	21.10	4.89
PR 79-4-3	8.99	25.39	6.13
PR 79-4-12	8.98	25.67	5.98
PR 79-4-11	8.32	21.90	5.17

Table 4

GROWTH FEATURES OF TWENTY FOUR F_1 PROGENY FROM BIOMASS-DIRECTED CROSSES OF PR 67-245 AND B 70701.

Progeny	Stem Characteristics [1/]				Stalk Index [2/]
	Height (cm)	Diameter (cm)	No./Ha	Volume (m^3/Ha)	
PR 79-1-10	220.7	2.3	114,417	104.80	190.2
PR 79-1-23	195.0	2.2	107,466	81.11	147.2
PR 79-1-16	214.1	2.2	99,025	80.56	146.2
PR 79-1-18	203.1	2.0	122,382	78.05	141.7
PR 79-1-7	196.1	2.2	104,730	78.04	141.6
PR 79-1-14	190.0	2.1	118,077	77.62	140.9
PR 79-1-22	219.6	2.2	90,091	75.18	136.3
PR 79-1-3	220.4	2.0	105,061	72.71	132.0
PR 79-1-4	212.2	2.1	98,702	72.47	131.5
PR 79-1-1	219.5	2.3	73,731	67.16	121.9
PR 79-1-20	211.4	2.1	89,661	65.58	119.0
PR 79-1-21	180.1	1.9	128,410	65.45	118.8
PR 79-1-6	198.6	1.7	144,556	65.17	118.3
PR 79-1-5	201.7	2.0	101,932	64.56	117.2
PR 79-1-8	197.2	2.2	85,968	64.42	116.9
PR 79-1-13	211.8	2.2	76,422	61.51	111.6
PR 79-1-24	166.1	2.1	105,161	60.44	109.7
PR 79-1-2	191.8	1.9	110,865	60.18	109.2
PR 79-1-9	175.8	2.0	105,806	54.41	106.0
PR 79-1-17	183.4	2.1	88,262	56.01	101.7
PR 79-1-11	174.6	1.9	113,341	56.00	101.6
US 67-22-2	161.4	2.3	82,126	55.10	100.0
PR 79-1-12	197.1	2.0	76,422	47.30	85.8
PR 79-1-15	209.0	2.0	67,486	44.29	80.4
PR 79-1-19	169.4	1.8	102,254	44.00	79.9
B 70-701	163.5	1.9	31,968 [3/]	14.79	26.8

[1/] Harvested 5 months after planting.

[2/] The reference clone, US 67-22-2, = 100.

[3/] Poor germination accounts for the low stalk number.

Table 5

CROSSES PERFORMED FOR BIOMASS DURING THE 1979 BREEDING SEASON; AES-UPR GURABO SUBSTATION

Cross No.	Parentages	No. Seedlings	Objectives	Remarks
PR 80-1	PR 980 x *S*. sp. Hybrid	422	Biomass, Fermentable Solids	Rapid Early Growth, High Stem Number
PR 80-2	PR 64-1618 x *S*. sp. Hybrid	115	Biomass, Fermentable Solids	Rapid Growth, Very Tall Stems
PR 80-3	PR 67-1070 x *S*. sp. Hybrid	519	Biomass, Fermentable Solids	Rapid Growth, High Stem Number
PR 80-4	PR 68-355 x 57 NG 54 1/	910	Biomass, Fermentable Solids	Vigorous Growth, Thick Stems, High Stem Number
PR 80-8	PR 62-195 x 57 NG 54 1/	200	Biomass, Fermentable Solids	Vigorous Growth

1/ Clone 57 NG 54 is *S. robustum*.

ENERGY BALANCES FOR FUEL AND ALCOHOL FROM PUERTO RICO ENERGY CANE

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ENERGY BALANCES FOR FUEL AND ALCOHOL FROM PUERTO RICO ENERGY CANE

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ENERGY BALANCES FOR FUEL AND ALCOHOL FROM PUERTO RICO ENERGY CANE

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ABSTRACT

RECENT Middle East developments underscore the long-term folly of Puerto Rico's dependence on imports for 99 percent of its energy and 88 percent of the molasses used for its rum. Puerto Rico urgently needs alternatives to imported petroleum. One of these alternatives is "energy cane," a concept of sugarcane management developed by the CEER-UPR Biomass Division under sponsorship of the U.S. Department of Energy. Energy cane is sugarcane managed for maximum yield of combustible materials rather than sugar.

One way of evaluating such an alternative is to determine its "energy balance," ie., the energy value of other fuel forms replaced (especially fuel imports) less the energy value of inputs. The inputs may be energy products themselves or products such as machinery which required energy in their manufacture. This paper concludes that, despite some conceptual difficulties with energy balances, they are a useful first-stage screening device for new energy systems. Energy balances are obtained for two alternative uses of energy cane. In Alternative A, cane is milled to produce bagasse and high-test molasses (HTM) for the rum industry. The bagasse plus cane "trash" is dried and burned to supply the mill and other plants with steam. The energy output/input ratio is estimated at 11.4, when bagasse consumed by the mill is excluded from both inputs and outputs. When included, the ratio is 4.0. In Alternative B, the HTM is converted to ethanol for gasohol. The ethanol ratio is 1.8, and the overall ratio is 2.9.

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ENERGY BALANCES FOR FUEL AND ALCOHOL FROM PUERTO RICO ENERGY CANE

INTRODUCTION

THE CURRENT war between Iran and Iraq, the hostages held by Iran, the renewal of fighting in Lebanon and other Middle East developments of the past few years underline Puerto Rico's risk in depending on imports for 99% of its energy and 88% of the molasses used in the manufacture of rum, which supplies about one seventh of the recurring revenues of the Commonwealth Government.

In the last few years, under the leadership of the Center for Energy and Environment Research of the University of Puerto Rico and primarily with funds from the Department of Energy, a great deal of work has been done to develop alternatives to imported petroleum fuels. Some of the most successful efforts are the result of work by CEER's Biomass Division. This division has developed a number of energy crops which appear to be ready for commercial production and definitely competitive with petroleum fuels.

One of these crops is "energy cane," sugarcane chosen and managed, not for nutritive values, but for its yield per acre of combustible solids. As shown by Table 2, page 19, impressive yields have been attained.

Unfortunately the yield record of Puerto Rican agriculture has been fairly miserable for years, so it is hard for those not familiar with the Division's work to believe the results. Also the numerous controversies over the energy balances of corn-based ethanol for gasohol have created a large number of doubting Thomases as to the net energy benefits available from energy crops.

This paper, then, explores the conceptual problems of energy balances, describes a system for producing biomass for direct combustion, and high-test molasses for rum (Alternative A) or for ethanol for gasohol (Alternative B). The energy balances are found to be significantly favorable in all cases, but policy questions about the use of molasses are raised. Energy output/input ratios of 4.0 are estimated for alternative A and 2.9 for alternative B, including bagasse consumed in process as both input and output (see Table 6).

SOME CONCEPTUAL PROBLEMS

Anyone who sets out to estimate an energy balance for all but the simplest processes will find the mathematics fairly straightforward. But the underlying concepts are full of hidden assumptions and other intellectual booby traps.

Indeed, the estimator will be somewhat in the position of an economist who tries to calculate the real economic situation of an internationally funded organization which operates in many countries, with different currencies, different consumption patterns, different price structures and different inflation rates. Like the Special Drawing Rights of the International Monetary Fund, BTU's give only the appearance of comparability. Thus it is well to review some of the methodological difficulties, before we undertake the task at hand.

1. All BTUs Are Not Created Equal

It is well known in industry that different fuels have very different qualities (of combustion, control, convenience, pollution, etc.) and are *not* readily substitutible in a given use, at least not on short notice. Even where substitution is possible, it often requires a time-consuming and expensive conversion or replacement of equipment. Moreover, a particular fuel (e.g. natural gas) may be preferred over a wide range of relative prices, precisely because of characteristics other than its calorific content. It may even take a law, a regulation or severe difficulties with suppliers to persuade a manufacturer to switch. This applies both to fuels of different origins (e.g. biomass fuels versus petroleum fuels) and to fuels of the same origin, where one is a transformation of the other to a higher form (e.g. bagasse to fuel pellets). In brief, BTU's, like price, are only part of the story.

Yet, many researchers blithely compare fuel values, or quote costs per BTU, on the basis of high heating values (HHV), as if the different fuels were so many interchangeable boxes of laundry soap, bought off the shelf of a supermarket.

Reviewing recent literature on biomass energy costs (1), little more than a year ago, Kathryn A. Zeimetz wrote, "None of the estimates include the cost of conversion from chemical energy in (unprocessed) biomass to a more usable source of energy. . . .A serious defect is that, in current research generally, the estimates of the costs of, and the land needed for, biomass production, per energy unit, is calculated on the total energy content (HHV) of the harvested biomass."

Thus, if energy values are to be comparable, different fuels must ultimately be expressed in terms of some common denominator such as steam of a given psig, gasoline equivalents, electricity or the fuel whose imports will be reduced by the proposed alternative energy source. Sometimes, of course, the practical difficulties will be insurmountable, but at least the attempt should be made.

The foregoing applies to energy balances as well, even though they can be expressed in dimensionless terms, i.e. in terms of energy ratios. This is because the production of energy, or its transformation to a higher form, each require energy as an input. And, in many cases, the energy input will consist of several fuels other than the one which constitutes the output. For example, in the case we will study, diesel fuel, among others, will be used to produce energy cane on the farm. In turn, energy cane will be used to produce bagasse in the cane mill and also high-test molasses (HTM). The bagasse serves as fuel for the mill and possibly the distillery, where the HTM is turned into still another fuel, ethanol.

2. Energy Balances Are Neither Eternal Nor Universal

Outside of residential use, energy is normally but one of many inputs to the production of goods and services, albeit an important one. Thus, a given energy balance is a function of such factors as costs and prices, laws and regulations, markets, operating and maintenance practices, past investment decisions and technology, not just immutable physical laws. In the case of biomass energy facilities, we must add agricultural patterns, climate, rainfall and soil conditions. Since most of these factors change from time to time, and some may be highly site specific, a given energy balance may not "travel well" nor be valid for your children.

3. Define Your Processes

Precisely because of the first two difficulties, one should specify the critical aspects of the manufacturing and combustion processes for which a given energy balance is calculated. As an illustration of the complexities involved, see Table 1, page 18, which shows possible relations between bagasse moisture content and boiler efficiency, based on Hawaiian experience. Moreover, in translating increased output of one fuel into savings in the use of another, one must also take account of the different combustion systems which may be involved in each case.

For example, if one ton of bagasse with 3% sugar and 30% moisture has an HHV of

11,540,000 BTU/short ton by Hessey's formula[1], it will *not* substitute for No. 6 fuel oil with an HHV of 6,216,000 BTU per barrel in accordance with the ratio 11,540/6,216 = 1.86 barrels per ton. Assume it is possible to burn the bagasse in a cane mill boiler at 74% efficiency, and the fuel oil, in a utility boiler, at 85% efficiency. Ignoring psig differentials, on a steam equivalent basis, the correct ratio would be 1.62, or about 13% less. On an electricity equivalent basis, due to differences in generating facilities, the ratio would be even lower.

The problem is not solved by resorting to comparisons based on low heat values, instead of high ones. It is true that low heat values assume that the water vapor, formed by the oxidation of free hydrogen in the fuel, goes up the stack, rather than condensing and releasing useful heat. This is often realistic. However, what if stack gasses are used for drying? Moreover, in any case, there are other causes of heat losses in boilers. These include moisture in the atmosphere, moisture in the fuel, how tightly the latter is "bound," incomplete combustion, variations in fuel composition and moisture content and the stack gas-ambient temperature differential. Moreover, if electricity is the common denominator, one must take account of energy losses in the turbine and generator stages.

In addition, scale effects are important. An energy balance carefully estimated for one size of plant may not be valid for one 25% smaller or 25% larger. Also, in dealing with proposed facilities, one must be aware of possible differences between stand alone facilities and those operated in tandem with coproduct processors; between grass roots construction and conversion or upgrading of existing facilities (3).

In summary, the safest procedure would seem to be to define the combustion system, from fuel through common denominator or end product, and, if system efficiency is not easily approximated, estimate all significant sources of energy loss, one by one, starting with the HHV of the boiler charge. (The latter is most frequently used, both as an energy value and as the denominator in calculating efficiency.) Obviously, the entire facility of which the combustion system forms a part must be defined as well. Boiler fuel is seldom the only energy input to an energy producing or transforming system.

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[1] HHV = 8,345 – 22.14S – 83.63W, where S = sucrose % and W = moisture %. (In BTU/lb). See (2), Figure 1, page 25.

4. What Are Energy Inputs?

Should we consider only energy inputs which are consumed *in the form of energy*? What about the energy used to transport inputs to the facility under study, or the energy consumed in the fabrication of buildings, structures and equipment used by the facility, or the energy consumed by the employees of the facility in the course of their work? And how should these inputs be measured? There are no easy answers to this problem (4).

One could trace back product and energy flows indefinitely, in a form of infinite regress. Fortunately, "one remove" (direct energy consumption by inputs) is usually sufficient to capture significant energy inputs of the indirect form. However, this is not a trivial question, for what inputs to include and what not helps to define the boundary between the thermodynamic system and its surroundings. And it is this thermodynamic system which really determines the energy balance, rather than the battery limits of the alternate fuel facility.

5. What Are Energy Outputs?

Typically, energy outputs are considered to be either (a) salable energy products or (b) these plus those other products which substitute for purchased fuels. However, (c) waste heat (such as stack gasses) used in the facility, or even heat losses in the combustion system, could also be considered output which the facility "manufactures" and "sells" to itself. Again there are no rules engraved in stone. However, the energy balance and the energy ratio will obviously be different, depending on the method used.

6. Externalities

It is well known, from cost-benefit analysis and environmental impact studies, that most human activities have effects (both favorable and unfavorable) which are not captured by or reflected in their accounting, costing, pricing or statistical systems. Indeed, many of these effects can only be expressed in energy or monetary terms crudely, if at all. To the extent that an alternative fuel facility has an impact outside the "system," as defined for purposes of the energy balance, or changes the "energy behavior" of other facilities and organizations, we should try to take these effects into account. Such externalities may be particularly critical in calculating the energy balance for gasohol systems.

7. What Are We Trying To Optimize?

An energy balance is a "snapshot" of only one aspect of a human activity. It is not complete, any more than it is eternal or universal. Nevertheless, it is a snapshot of a very import aspect. How then to take it into account? What is an energy balance good for?

If you are a "one issue" person and that issue is energy conservation, the answer is obvious. However, most people and most countries have multiple objectives which, in an imperfect world, can only be partially attained. Thus we are forced to estimate and evaluate tradeoffs–between more of this, and less of that. Given the state of the analytical arts, the best way to do this, as a practical (not an ideological) matter, would seem to be to optimize the economics of a system, subject to energy, environmental and other constraints. However, this does not relegate energy balances to the sidelines. They can provide a useful screening device for determining the classes of facilities to be studied by the optimizing process.

Regardless of what we optimize, we still must define what it is we want to do with energy. What is to be our principal criterion for separating energy sheep from energy goats? Save total energy, decrease energy imports, increase energy efficiency, decentralize society–or some combination thereof? If we are primarily concerned about security of supply, and I think Puerto Rico should be, then we would emphasize the second goal. However, we should recognize that imported BTUs saved have a greater social and economic value than an equal number of domestic BTUs consumed. Also, that businessmen do not necessarily perceive a new fuel made locally by a new firm with a new technology as "more secure" than No. 6 fuel oil made from imported crude oil.

8. The Allocation Problem

Energy production from biomass frequently results in multiple products (some non-energy) from integral processes. Many costs and inputs, including energy, may therefore be both joint and variable with respect to outputs.

standard processes exist for their manufacture. Thus, any errors in estimating the energy value of the inputs to the agricultural sector are of small consequence in the energy balance of the entire system.

SYSTEM DESCRIPTION: CANE MILL PHASE

In this phase, adapting (8), we hypothezise a conventional Puerto Rican cane mill modified so as to burn efficiently 100% bagasse dried by flue gasses to 30% moisture. The mill is assumed to grind 5,000 green tons of millable cane per day, six days a week, eight months a year. Such a facility would require more than 12,000 planted acres of energy cane, or somewhat less than 15,000 acres of farmland, in the supporting agricultural phase.

The materials balance and flows for the biomass energy system through the cane mill are shown in Figure 1, page 25. An inspection of this figure shows two obvious inputs, "loose trash recovery" and "millable cane." There are also three obvious products, the loose trash as a source of energy sales, the bagasse as a source of energy sales and the HTM. But what about the bagasse for process heat? Since we have the alternative of putting this material into energy sales and buying No. 6 fuel oil to supply process heat, we might consider it a product, in which case we should consider it an input also. So right away, three of our difficulties appear: What is an input? What is an output? And how do we allocate the joint inputs of energy?

As before, we evaluate outputs in terms of the energy value of the No. 6 fuel oil displaced, using Hessey's formula and the same assumptions, except that trash is assumed to have zero % sugar and 15% moisture, as boiler feed.

Note here that the common denominator is steam. If the excess steam cannot be sold or used economically, or if it must be converted to electricity, the energy balance, however calculated, would be less favorable. This is an argument for further processing excess biomass before burning.

Let us consider first, Alternative (A), in which all HTM goes for the manufacture of rum. There are a number of ways in which we could allocate the joint energy inputs; but, to keep things simple, let us always allocate them in proportion to the oven dry weight of the outputs, whatever these may be. Still we may consider two allocation methods. According to the *first method, output consumed for process heat is excluded from both inputs and outputs.* Agricultural energy inputs are allocated by oven-dry weight among the three sources of external sales: Loose trash, bagasse for energy sales, and HTM. According to the *second method, the bagasse used for waste heat is both an input and an output.* Agricultural inputs must be allocated among all combustibles. Process heat is allocated between bagasse and HTM. These two methods (and we could devise others) give different energy balances and energy ratios, as shown by Table 4, page 21. If we were to throw in waste heat used in drying the bagasse as an additional input and an additional output the energy balance would undoubtedly increase over method No. 2, while the energy ratio would decrease again.

In the case of Table 4, both the energy ratio and the volume of inputs turn out to be quite sensitive to the definition of inputs and outputs. This suggests that one should be very careful about comparing ratios for different facilities, especially where they have been calculated by different persons. Even where the estimates of inputs and outputs are carefully done, the ratio may be very sensitive to changes in the scale of operations.

More meaningful would seem to be the net energy balance as compared with some resource commitment. For example, Table 4 implies that there will be a reduction in crude oil imports of 30 to 34 barrels per year, for every acre planted to energy cane. (The assumed alternative to biomass energy is No. 6 fuel oil, but we further assume that a reduction in one barrel of this product backs out one barrel of crude. Obviously, because of refinery balances, there are limits to such an assumption in the short run). Alternatively we might compare the net energy balance with the initial dollar outlays required to establish the biomass energy system as a going concern.

As for allocation methods, the author is inclined to those which treat energy produced and consumed in the same facility as both an input and an output, whenever the alternative is to purchase energy. Otherwise an essential input will not be treated consistently over time or over facilities. However, it must be recognized that our own energy use or efforts to use waste heat may lower the energy ratio, even when they increase the balance, as happened in Table 4. If people are mislead by this, it will tend to penalize efforts for energy conservation and efficiency. One may even conceive of cases where use of our own energy or waste heat may lead to a *reduction* in the balance, in exchange for savings in cost and/or an increase in the security of supply, the stability of costs, etc. Once again we are back to tradeoffs.

Regardless of these difficulties, Alternative (A) seems to be a very "profitable" operation from an energy point of view. Moreover, the energy balance and ratio of this alternative do not reflect two important energy benefits from this project. The first is the increased security of supply which comes from substituting a domestic source of energy for a foreign one. The second is the fact that the energy balance *in terms of imported fuels* is even better than shown by Table 4. All of the outputs displace imported petroleum, but a good portion of the agricultural energy inputs probably represent the use of oil produced in the U.S.

With regard to Alternative (B), still another allocation method comes to mind. Since all products are now energy products, we may value them in terms of the barrels of imported crude which they back out of the economy, assuming again that one barrel of product is equivalent to one barrel of crude oil. In the case of the HTM, it is valued on the basis that one gallon of HTM will yield about 0.64 gallon of ethanol [calculated from reference (8)], and one gallon of ethanol will directly replace 0.8 gallon of gasoline (3). In the case of the other products, they are valued in terms of No. 6 fuel oil equivalents, as before, divided by 6.216 million BTUs per barrel. Inputs are then allocated in accordance with the appropriate crude oil equivalents.

The results of allocation method No. 3 are shown in Table 5. For the energy obtained by the direct combustion of biomass, the results are more or less like those obtained from method No. 2. (See Table 4). However, we have balanced the first two phases of Alternative (B) in the same way as we will balance the third, distillery phase. Also, we know how many BTUs of input we must "carry forward" to this latter phase. Finally, the balance for ethanol in Table 5 gives us a preliminary notion of what the final balance will be for that product.*

SYSTEM DESCRIPTION: DISTILLERY PHASE

The design of the fermentation and distillation processes for ethanol, and the choice of a fuel for the distillery, are perhaps the most critical factors in determining the energy balance for a gasohol system, due to the wide variation in energy inputs that is possible. This variation—plus the additional variation induced by differences in feedstocks, byproducts and byproduct "energy accounting"—explains most of the wide differences in energy ratios for gasohol systems. As noted

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* Since all BTU's are not equal, ideally Table 5 (and Table 6) should be expressed entirely in crude oil equivalents. BTU's of No. 6 are retained to facilitate comparison with Table 4.

previously, these differences have generated considerable controversy and confusion. According to the Office of Economic Assessment of the Congress of the U.S., an energy efficient, stand-alone corn ethanol-for-gasohol distillery can consume in operation the energy equivalent of half a gallon of gasoline, in order to produce a gallon of ethanol which directly replaces 0.8 gallon of gasoline [as an additive in gasoline (3)].

For these and other reasons, in some cases it may not be possible to achieve a favorable energy balance for a gasohol energy system. And to achieve a favorable balance in terms of imported energy alone, it may be necessary to approve laws which (a) prohibit the use of imported fuels in ethanol distilleries for gasohol, and (b) require the use of lower octane gasoline for blending into gasohol (3, 9).

Following is a range of estimates as to the BTUs consumed in operating an ethanol distillery, per gallon of ethanol produced (from molasses, except as noted):

Source	BTUs/Gal
Chambers, et al [corn (11)]	141,500
Hopkinson & Day (10)	43,400
Misselhorn (12)	
Conventional Process	36,600—46,600[1/]
Two-Pressure Distillation	25,000[1/]
OTA [corn (3)]	
Natural Gas & Waste Heat	29,250[2/]
Petroleum Fuels	46,800—70,200[2/]
Coal	50,000—70,000
Rodríguez-Torres & Horta (8)	108,000
Ofoli & Stout (13)	68,400
Schroeder Process [corn (14)]	31,900

[1/] Mainly from Table 2. Clarification, fermentation and distillation only.
[2/] In gasoline equivalents. Excludes byproduct waste heat.

Now accountants, who must prepare monthly financial statements, have invented various and ingenious allocation techniques to deal with just such situations. Unfortunately, the only way to optimize such processes economically is to ignore the allocation methods and maximize the total contribution of all products to joint costs, after deducting from revenues those costs associated with one product exclusively. Under the circumstances, any allocation of costs is arbitrary and liable to be suboptimal, no matter how reasonable the particular allocation method (5).

An analogous optimization procedure could be defined in energy terms. However, it would prevent us from calculating a meaningful energy balance for an individual product. Thus we must allocate joint energy inputs among outputs in some one of several rational ways, with the understanding that what we are doing is somewhat arbitrary and should not be used for optimization of the overall system.

SYSTEM DESCRIPTION: AGRICULTURAL PHASE

We shall now describe the agricultural phase of a system to produce biomass energy products in Puerto Rico from energy cane. The primary objective of this system is to reduce our dependence on imported crude oil. A secondary objective is to reduce our dependence on imported molasses for our rum industry. Two alternatives are considered: (A) The direct combustion of biomass energy products, with the HTM being used for rum; and (B) with the HTM used to manufacture ethanol for gasohol. This is not a complete biomass energy system. As indicated elsewhere (6), it should be complemented by intermediate-rotation crops, such as energy Napier grass ("pasto elefante"), and short-rotation crops, such as Sordan 70A. Furthermore it is probably desirable to add a processing step to convert the dry grasses and bagasse into higher forms of energy, such as Combustion Equipment Associate's "Agri-fuel" or "Woodex fuel pellets." However, the energy balance aspects of these other crops and steps are relatively straightforward and quite favorable, so they will be left for another day.

The agricultural facility consists of 60 "energy farms" of 200 acres each, planted in energy cane on a three year planting cycle. Harvests take place at the end of every 12 months, and replanting every three years. Yields are those described in Table 2, page 19. For convenience, these yields are those obtained in experimental work at the Lajas (Puerto Rico) Substation of the

Agricultural Experiment Station of the University of Puerto Rico. This work is funded by the Department of Energy and carried out jointly with the University's Center for Energy and Environment Research (7).

These yields are considered attainable in commercial operations on cane lands throughout Puerto Rico for the following reasons (6):

1. Botanically, cane is a better fiber producer than a sucrose producer. Indeed, despite inferior varieties and emphasis on sucrose, Puerto Rico averaged yields of 45 green tons of millable cane during the early 1930's, compared with 28 tons today. (Some farms obtained 100 tons!)

2. The energy gain is totally managed so as to maximize the yield of combustible solids per acre, not the percentage of sucrose or other nutritive values. In particular, varieties, row spacing, harvest frequency, fertilization, water supply and machinery have all been chosen with the former in mind.

3. The manager of a commercial energy farm would undoubtedly vary practices to meet soil conditions and climate in other locations. Irrigation would be used everywhere, to some degree, to better control water intake. Also the manager could be expected to select the best varieties for his location. In Lajas, the best variety was NCo 310, whose second ratoon crop attained 92 green short tons of millable cane per acre, with standard spacing, versus a three-variety average of 83.9 tons, for the same crop.

4. Table 2 omits cane tops and attached dead matter, which are removed before the cane is sent to the mill. On a commercial farm, most of this material would be collected as a source of biomass energy, in addition to the loose trash shown in the Table. Note that trash can be solar dried, baled and burned or further processed, without milling.

5. Breeding work has barely explored the potential of cane for producing combustible materials. Yields of 150 green tons and 50 oven dry tons per acre are reasonable long-term objectives.

The energy inputs required for such an operation are estimated in Table 3, page 20. Because the primary sources of the data for energy per unit are numerous and the magnitude of the inputs is small relative to outputs, conversion problems not handled in the original are ignored.

Note that, in terms of No. 6 fuel oil equivalent, at 148,000 BTU's per gallon, we are talking, roughly speaking, about 189 gallons per acre per year, or 6.4 gallons per oven-dry short ton of combustible material. By comparison, bagasse dried to 30% moisture could displace 91 gallons of No. 6 fuel, per short ton of oven dry material. (In fact, if the No. 6 is to be burned in a cane mill boiler, the displacement would be even higher.) Moreover, over half the energy inputs to the agricultural phase are represented by the energy value of fertilizers, whose use can be controlled and measured quite closely. The chemical content of these products is also known with exactness, and

From the above we select the Misselhorn estimate of 25,000 BTUs per gallon, for the following reasons:

1. It is the lowest commercial scale figure for ethanol from cane.
2. Starcosa Gmbh, which supplied Brazil's first ethanol plant in 1960 (13,200 gallons per day), designs and supplies distillation systems based on the two-pressure concept.
3. This estimate is derived from an integrated design and is not a hodge podge of pieces of data taken from different sources in the literature.

Now per Figure 1, we obtain 1,643 gallons of HTM per acre per year. This yields (at 64%) almost 1,052 gallons of pure ethanol, so we will require 26.3 million BTUs of energy per acre per year to operate the distillery. Nearly all of this is in steam, which, per Table 4, can readily be supplied by the cane mill. Per (10), we estimate the energy incorporated in the distillery itself at approximately 4% of the energy requirements for operations. Hence our total energy inputs for the distillation phase are 27.3 million BTUs per acre per year.

However, we have not yet disposed of all the energy considerations related to this phase. The fermentation process produces about 5 lbs of CO_2 per gallon of pure alcohol, which can be recovered, scrubbed and purified for sale. The slops from the distillation process may be evaporated for cattle feed, concentrated for foundry core binder or for adhesives, or dried and calcined for the extraction of activated carbon and potash fertilizer. These byproduct processes introduce further energy inputs and raise problems of energy allocation (12, 15). Since the potential markets in Puerto Rico for additional amounts of such products in large quantities are speculative, we will omit them from the energy balance.

Given the need for 12,000 planted acres plus to support the cane mill phase, we must distill around 12.7 million gallons of pure alcohol per year. This is equivalent to 13.4 million gallons of 95% alcohol, or about 41,000 gallons per day at a 90% operating rate.

We have now completed the description of each phase and may proceed to estimating the final energy balance. Hopefully the reader has become aware of the necessity of defining the process.

ENERGY BALANCE

Table 6 shows the energy balance for the entire Alternative (B), in which all products are energy products. The total energy balance is broken down between ethanol and other energy products (the latter in fuel oil equivalents). Since allocation method No. 3 does not substantially change the results for the direct combustion products, the “Biomass” column in Table 6 may be considered to represent Alternative (A), in which all HTM goes for the manufacture of rum.

One important externality is included in Table 6. Since ethanol tends to have a higher octane than the gasoline with which it is blended, the octane of the gasoline can be lowered in a compensatory manner. If this is done, there is an energy saving in the refineries which the Office of Technology Assessment estimates at 0.36 gallons of gasoline equivalent per gallon of ethanol (3). For the purposes of Table 6, we have assumed that this saving would be only half as great in Puerto Rico, due to the lower octanes in use here.

Given the externality, Table 6 is not too different from Table 5, for the saving in refinery operations (which the Commonwealth could probably achieve) coincidently compensates for most of the energy input to the distilling phase.

Again the energy balance is favorable, both overall and for each of the components–ethanol for gasohol and bagasse for steam. Of course, the bagasse is “more profitable” energy wise than the ethanol. The energy ratio for biomass is 4.0, versus 1.8 for ethanol. Overall, depending on refinery feedstocks, design and operating conditions, imports of crude oil will be reduced by approximately 44 barrels of crude oil for every acre of energy cane planted and processed in accordance with Alternative B.

What the energy balance cannot answer is whether the incremental saving in gasoline costs and improvement in gasoline security of supply is worth depriving the rum industry of security of supply of molasses, and possible protection against exhorbitant price increases by would-be ayatollahs. However, we note commonwealth revenues of $21.00 per gallon of pure ethanol ($10.50 per proof gallon) for Puerto Rican rum sold in the states. Also we can solve most of the rum industry’s problem with HTM, but only a small part of the motorist’s problem. Gasohol, after all, is 90% gasoline, made from imported crude in Puerto Rico’s case. In our opinion, the rum industry deserves priority in the use of HTM.

HOW DO WE COMPARE?

Because of the wide variety of methods used for calculating energy balances and ratios, we must recalculate our figures almost every time we compare ourselves with others. However, the comparisons are always favorable. For example, see Table 7 (based on the estimates collected by Zeimetz (1)) and also Hopkinson and Day (10). The latter estimate an energy ratio of only 1.8, obtaining all process heat from bagasse and counting this heat as both input and output. Per Table 6, the corresponding ratio for Puerto Rico is 2.9. For corn-based ethanol, fractional ratios are possible (3)(13).* The most critical factor in these comparisons is the energy cane itself, particularly the high yields per acre obtainable in a subtropical climate with management for energy, not nutrients.

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* i.e., the energy balance is negative.

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Table 1

BOILER LOSSES AND BOILER EFFICIENCY

Bagasse Moisture (Wet Basis) %	Boiler Losses						Boiler Efficiency
	L_{dg} Eq. (2) %	L_a Eq. (9) %	T_F =	L_f Eq. (10) %	L_h Eq. (11) %	L_{other}	η_b Eq. (12) %
0	5.86	0.15	350°F	0	8.07	5.00	80.92
	6.95	0.18	400°F	0	8.23	5.00	79.64
	8.04	0.21	450°F	0	8.39	5.00	78.36
	9.12	0.24	500°F	0	8.55	5.00	77.09
10	5.86	0.15	350°F	1.64	8.19	5.00	79.16
	6.94	0.18	400°F	1.67	8.35	5.00	77.86
	8.03	0.21	450°F	1.70	8.51	5.00	76.55
	9.11	0.24	500°F	1.73	8.67	5.00	75.25
20	5.88	0.15	350°F	3.51	8.30	5.00	77.16
	6.96	0.18	400°F	3.58	8.46	5.00	75.82
	8.05	0.21	450°F	3.65	8.62	5.00	74.47
	9.14	0.24	500°F	3.72	8.78	5.00	73.12
30	5.86	0.15	350°F	6.55	8.42	5.00	74.02
	6.94	0.18	400°F	6.68	8.59	5.00	72.61
	8.03	0.21	450°F	6.81	8.76	5.00	71.19
	9.11	0.24	500°F	6.94	8.92	5.00	69.79
40	5.86	0.15	350°F	9.83	8.52	5.00	70.64
	6.95	0.18	400°F	10.02	8.68	5.00	69.17
	8.04	0.21	450°F	10.21	8.85	5.00	67.69
	9.12	0.24	500°F	10.41	9.02	5.00	66.21
50	5.87	0.15	350°F	13.46	8.70	5.00	66.82
	6.96	0.18	400°F	13.72	8.88	5.00	65.26
	8.05	0.21	450°F	13.98	9.05	5.00	63.71
	9.13	0.24	500°F	14.25	9.22	5.00	62.16
60	5.84	0.15	350°F	23.40	8.99	5.00	56.62
	6.92	0.18	400°F	23.86	9.16	5.00	54.88
	8.00	0.21	450°F	24.32	9.34	5.00	53.13
	9.08	0.24	500°F	24.78	9.52	5.00	51.38

Notes:-

Adapted from Table E-3, reference 15. L_{dg} = losses from dry gases of combustion; L_a = losses due to moisture in air; T_F = flue temperature; L_f = losses due to moisture in bagasse; L_h = losses due to moisture of combustion; L_{other} = other boiler losses.

Table 2

ATTAINABLE ANNUAL YIELDS FROM ENERGY CROPS IN PUERTO RICO
(short tons per acre planted)

	Type of plant, harvest frequency and row spacing	
Type of material and crop	Energy cane1/ 12 months 150 cm	Napier grass2/ 6 months 50 cm
Green matter3/		
Plant crop (1st yr)	77.8	75.0
1st ratoon (2nd yr)	93.6	93.1
2nd ratoon (3rd yr)	83.9	89.0
Ave. for cycle	85.1	85.7
Dry matter		
Contained in green matter		4/
Plant crop	21.5	
1st ratoon	29.5	
2nd ratoon	22.1	
Ave. for cycle	24.4	
Contained in loose trash		4/
Plant crop	3.9	
1st ratoon	6.0	
2nd ratoon	5.7	
Ave. for cycle	5.2	
Total dry matter		
Plant crop	25.4	25.4
1st ratoon	35.5	33.5
2nd ratoon	27.8	24.6
Ave. for cycle	29.6	27.8

1/ Average of three varieties - NCo 310, PR 64-1791 and PR 980.
2/ Variety "common Merker" (pasto elefante)
3/ For energy cane, millable cane only. (Excludes tops and attached dead matter, which are removed in the field.)
4/ With 6 month harvest, loose trash picked up by bailer with cuttings.
Sources: Ref (7), first quarterly reports.

Table 3

ANNUAL ENERGY INPUTS REQUIRED FOR ENERGY CANE IN PUERTO RICO

Input	Unit	Units per acre	Energy per unit BTU	Energy per area (x 10^6)	
				BTU/A	KCal/Ha
Fertilizers					
Nitrogen	lb	400	33,333	13.33	8.30
Phosphorus	lb	100	6,032	0.60	0.38
Potassium	lb	200	4,167	0.83	0.52
Sub-total				14.76	9.20
Fuel (distillate)	gal	64	138,690	8.86	5.52
Herbicides and pesticides	lb	12.85	43,652	0.56	0.35
Labor	hr	25	2,159	0.05	0.03
Machinery				3.37	2.10
Seed	lb	183	2,410	0.44	0.27
Total				28.04	17.47

Note: Area refers to area planted.

Fuel includes transportation to mill'

Sources: Units per acre - reference (7).

Energy per unit (except fuel) - reference (10)

Fuel energy per gallon - reference (16)

Table 4
ENERGY BALANCE FOR ALTERNATIVE A
(High test molasses (HTM) to rum)

	Ave. annual yield ST/acre[1]	Energy balance (x10^6) Method #1 BTU/acre	 Method #2 BTU/acre
Energy output by source[2]			
Loose trash[3]	5.2	72.5	72.5
Bagasse for process heat[4]	6.2	-	83.6
Other bagasse[4]	9.6	129.5	129.5
Total outputs	21.0	202.0	285.6
Energy inputs			
Bagasse for process heat[4]		-	83.6
less BTU's charged[5] to HTM			(29.6)
Agricultural phase (from Table 3)		28.0	28.0
less BTU's charged[5] to HTM		(10.3)	(8.2)
Total inputs		17.7	73.8
Energy balance			
Net energy gain (outputs *less* inputs)		184.3	211.8
Energy ratio			
Outputs/inputs		11.4	3.9

1/ Oven dry short tons, from Figure 1.

2/ Evaluated at high heating value of No. 6 fuel oil displaced, on a steam equivalent basis. Bagasse boiler efficiency 74%; No. 6, 85%.

3/ HHV calculated by Hessey formula (2) for 0% sugar, 15% moisture material, then converted to oven dry basis.

4/ Same as 3/, but with 3% sugar and 30% moisture.

5/ See text for description of allocation methods.

Table 5
ENERGY BALANCE FOR ALTERNATIVE B
(High test molasses to ethanol)
AGRICULTURAL AND CANE MILL PHASES

	Crude oil equivalent bbl/acre	Energy balance $(x10^6)$ Allocation method #3		
		Ethanol BTU/acre	Biomass BTU/acre	Total[1] BTU/acre
<u>Energy output by source</u>				
Loose trash[2]	11.7	-	72.5	72.5
Bagasse for process heat[2]	13.4	-	83.6	83.6
Other bagasse[2]	20.8	-	129.5	129.5
HTM[3]	20.1	98.4	-	98.4
Total outputs	66.0	98.4	285.6	384.0
<u>Energy inputs</u>[4]				
Bagasse for process heat		30.9	52.7	83.6
Agricultural phase		8.5	19.5	28.0
Total inputs		39.4	72.2	111.6
<u>Energy balance</u>				
Net energy gain (outputs <u>less</u> inputs)		59.0	213.4	272.4
<u>Energy ratio</u>				
Outputs/inputs		2.5	4.0	3.4

[1] From Table 4, except for HTM.

[2] Converted to barrels of crude oil at 6.216 million/BTU per barrel of No. 6 fuel oil, and one barrel of No. 6 = one barrel of crude oil.

[3] Assumes, per Table 2 and Figure 4, reference (8), one gallon of HTM = 0.64 gallons of ethanol (pure). Converted at 0.8 gallon of gasoline = one gallon of ethanol, 4.914 million BTU per barrel of gasoline, which = one barrel of crude oil. See also ref. (3). Crude oil equivalence may vary.

[4] Allocated on the basis of appropriate crude oil equivalents of outputs.

Table 6
ENERGY BALANCE FOR ALTERNATIVE B
(High test molasses to ethanol)
ALL PHASES

	Energy balance ($x10^6$) Allocation method #3		
	Ethanol BTU/acre	Biomass BTU/acre	Total BTU/acre
Energy outputs by source			
Loose trash	-	72.5	72.5
Bagasse for process heat	-	83.6	83.6
Other bagasse	-	129.5	129.5
High test molasses	98.4	-	98.4
Octane reduction in refining (externality)[1]	22.1	-	22.1
Total outputs	120.5	285.6	406.1
Energy inputs			
Distillery[2]	27.3	-	27.3
Bagasse for process heat	30.9	52.7	83.6
Agricultural phase	8.5	19.5	28.0
Total inputs	66.7	72.2	138.9
Energy balance			
Net energy gain (outputs *less* inputs)	53.8	213.4	267.2
Energy ratio			
Outputs/inputs [3]	1.8	4.0	2.9

---

[1] Equivalent to 0.18 gallon gasoline per gallon of ethanol. (One half U.S. saving shown in Table 1, reference (3).

[2] See text for source.

Sources: Table 5, except where noted.

[3] In crude oil equivalents 2.3 4.0 3.2

Table 7

COMPARISON OF ESTIMATED YIELDS FROM ENERGY CROPS [1]

(after Zeimetz' Table 5)

Crop and location	"Dry tons" per acre	BTU (x10^6) Output per ton	Output per acre	Input per acre	Energy balance	Energy ratio
Cane						
Puerto Rico [2]						
(B)	29.6	14.9	441.3	24.2	417.1	18.2
(A)	21.0	15.5	326.4	15.3	311.1	21.3
Texas	13.2	13.1	172.3	N/A	N/A	N/A
Florida	12.3	13.0	159.6	18.1	141.5	8.8
Louisiana	8.9	13.1	116.4	19.7	96.7	5.9
Alfalfa						
California [2]	6.3	13.0	82.0	9.1	72.9	9.0
Corn						
Indiana	4.6	13.2	60.6	12.4	48.2	4.9
Nebraska [2]	4.6	13.0	60.0	11.8	48.2	5.1
Michigan	3.8	12.8	48.7	13.9	34.8	3.5
Alfalfa						
Iowa	3.3	13.0	42.9	5.5	37.4	7.8
Oklahoma	3.2	13.0	41.7	5.7	36.0	7.3
Corn						
Missouri	3.0	13.0	39.1	11.8	27.3	3.3

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[1] Output value is heating value of dry harvested material with no allowance for losses in converting biomass to higher forms of energy, nor for energy inputs to conversion process. Puerto Rico Alternative (A) exludes high test molasses (HTM) used for rum and also excludes HTM's share of energy inputs. Input energy represents value of fertilizers, fuel and pesticides only.

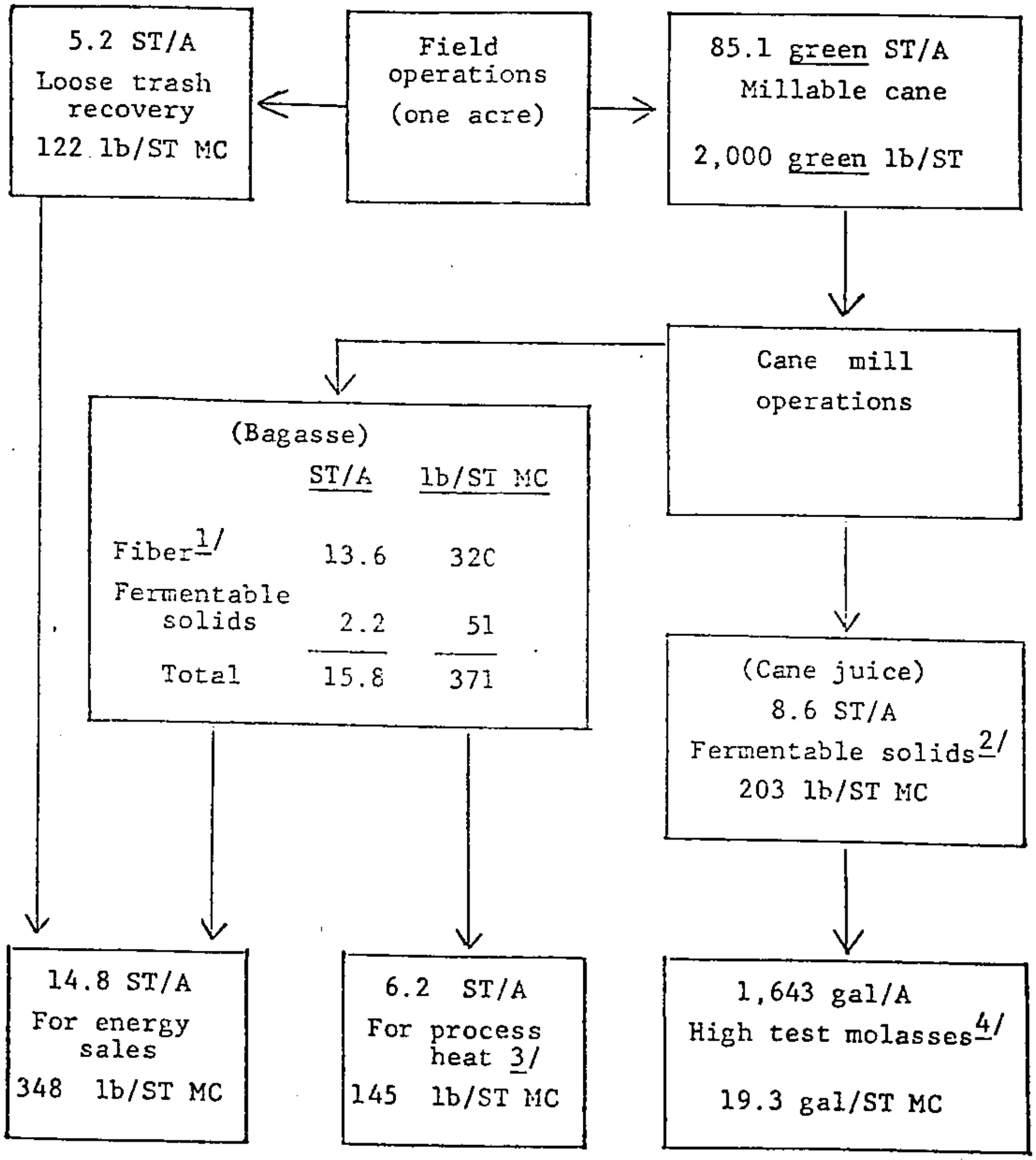
[2] With irrigation.

Sources: Puerto Rico - Tables 3, 4 and 6 preceeding. All other locations - calculated from Table 5, page 11, reference (1). With regard to Table 5, see also pages 12 and 13 of (1).

Figure 1

MATERIALS BALANCE AND FLOW FOR ENERGY CANE IN PUERTO RICO

(oven dry weight, except where noted)



Key: ST/A = oven dry short tons per acre (6% moisture)
lb/ST = pounds per short ton
lb/ST MC = oven dry pounds per short ton of (green) millable cane.

1/ 16% of (green) millable cane.

2/ With 80% extraction (conservative)

3/ Assumes stack-gas drying of bagasse to 30% moisture and 74% boiler efficiency. Calculated from Figure 5, reference (8).

4/ Assumes 10.5 pounds of fermentable solids per gallon.

BIOMASS FROM THE ENGINEERING PERSPECTIVE

Presented To The Symposium

FUELS AND FOODSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE UPR CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
Biomass Division, Río Piedras, Puerto Rico

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

November 24, 1980 – 4:00 P.M.

PANEL: BIOMASS FROM THE ENGINEERING PERSPECTIVE

Ing. Julio Negroni, Chairman

1. Engineer Héctor Rodríguez

Upgrading Sugar Factory Operations for Improved Energy Utilization

Sugar mills in Puerto Rico operate their steam boilers at low pressures resulting in inefficient thermodynamic conditions. Advantages of high pressure steam generation are presently being assessed. Two cases are compared. In one case a 600 psi pressure boiler is considered with enough steam generating capacity to fully use the energy potential of the bagasse. This case requires disposing of excess steam in an associated industrial operation. The second case uses a smaller capacity boiler to satisfy the sugar mill steam requirements but excess bagasse will be available for sale.

2. Engineer Modesto Iriarte

Biomass for Utility Boilers

CEER has shown that biomass fuel can compete very favorably with coal in stoker fired boilers. Cost comparisons included desulfurization systems for coal fired boilers.

Very recent studies by CEER show that biomass derived fuels can still compete favorably with coal, in the planned PREPA suspension type pulverized coal fired boilers. Flow process, energy and mass balances, costs and biomass derived fuel specifications for a fuel fabrication facility will be discussed.

3. Engineer Rafael Sardina

Biomass fueled boilers as the lowest energy alternative, excluding nuclear

Studies performed indicate that, excluding nuclear power which is shown to be the lowest cost energy alternative, biomass represents the lowest cost energy alternative when compared to OTEC, wind, photovoltaics, coal and oil.

MEMORANDUM

Miguel Angel Garcia Mendez

Presented To The Symposium

FUELS AND FOODSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE UPR CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
Biomass Division, Río Piedras, Puerto Rico

MEMORANDUM

Miguel Angel García Méndez[1]

I appreciate having this opportunity to offer some observations in this important meeting of experts discussing the potential of fuels and feedstocks from tropical biomass as alternate energy sources for petroleum.

Since the beginning of 1977 I have been emphasizing to the Commonwealth government authorities, and specifically to the Governor of Puerto Rico, the need for a pragmatic approach to transform the sugar industry to one focussing on the production of ethanol or molasses and biomass using juice and bagasse respectively. And I have recently learned of the successful achievements of distinguished scientists, such as Dr. Alexander, Dr. Bonnet, Dr. Smith, Dr. Werner, Dr. Gary Martin, Marcos Lugo Ramírez and Michael Senyi and others in Puerto Rico; J. Irvine and G.T.A. Benda in Louisiana and Al Mavis in Illinois; engineer Fernando Caldas in Costa Rica; Dahiya, Bardiega and Dhamija in the Agricultural University of Hissar in India; and a large number of chemists from Puerto Rico, Brazil and other parts of the world–among them distinguished participants in this Seminar– who have been working to develop alternative sources of energy so as to free us from an economic tyranny set up by OPEC.

An encouraging movement–growing at an extraordinary pace–in Brazil has promoted the production of gasohol in huge quantity and also many plants which change over to that fuel engines that previously used gasoline. And I have read that in the United States more than thirty plants devoted in great part to the processing of corn are getting ready to produce gasohol after the investment of many millions of dollars.

I believe that in Puerto Rico we are now ready to initiate on our farm lands a new chapter in our agricultural/industrial history: the Energy Chapter.

The auguries for the success of this meritorious endeavor are as follows:

a) Puerto Rico has produced in the past up to 1,320,000 tons of sugar from 13,200,000 tons

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[1] Present address: Western Federal Building, Mayaguez, P.R. 00708

of sugarcane (one ton of sugar from each 10 tons of cane) harvested from 450,000 acres planted to cane.

In order to produce sufficient sugar for local consumption—less than 200,000 tons—but at a prohibitively high cost using traditional approaches, only about one-seventh of the land previously used for sugar is needed. That is to say, six-sevenths of the 450,000 acres previously cultivated are, in effect, surplus.

In addition we have thousands of uncultivated acres which would be a fine base for tropical grass which would serve to increase the production of biomass and use to capacity the machinery and equipment that will give us molasses and/or gasohol from sugarcane.

b) Instead of using technicians and laborers only 100 days a year (which used to be the normal grinding period in the times of high sugar production) there could be work almost year-round, with the resulting high employment average and money influx into the Island's economy.

c) The U.S. Department of Energy programs, covered by Public Law 95-238, authorize up to $2 billion to stimulate the production of alcohol fuel. Also, under Law 932, the Synthetic Fuels Corporation provides, with the purpose of attaining a volume of 10% of the estimated total gasoline consumption in the U.S., loan guarantees and price guarantees and agreements of up to $1.2 billion. The U.S. Department of Agriculture, through Farmers Home Administration is implementing a program of guaranteed loans up to $100 million and direct loans up to $10 million to facilitate the production of alcohol to fulfill the presidential goal of achieving the production of 500 million gallons in 1981.

d) If the expense incurred in purchasing gasoline and other carburetants from abroad in 1979 was in excess of one thousand million dollars ($1,000,000,000) and if the goal of eliminating as much as 10% of such expense could be achieved, the result would be a big increase in the employment of workers—not only in the field but also in the industrial sector—along with a further multiplier effect in the transportation of agricultural supplies and finished product, raw material, etc.; internal income for small farmers would increase with corollary benefits; and we would reduce the balance of payments deficit between imports and exports from foreign countries for the first time in many years (our trade balance with the United States has recently been favorable).

e) If gasoline is substituted up to 20% by alcohol (gasohol) no change in engines is required in cars and trucks and such engines would run at lower temperatures.

In summary, if this idea to devote the production of sugarcane and tropical grass to substitute for part of our consumption of gasoline and fuel oil is successful, we would have the satisfaction of *producing energy and jobs in the Island and possibly exporting proteins abroad.*

I trust that the noble efforts of so many devoted scientists in this interesting symposium will have great benefit to the industrial and economic progress of Puerto Rico, our Nation, and the Western hemisphere of which we are a part.

We surely hope that, with God's help, it will be so.

FOSSIL FUELS OUTLOOK FOR PUERTO RICO'S PRIVATE INDUSTRIAL SECTOR

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

Eng. Carlos Yepes
PUERTO RICAN CEMENT COMPANY, INC.
Ponce, Puerto Rico

FOSSIL FUELS OUTLOOK FOR PUERTO RICO'S PRIVATE INDUSTRIAL SECTOR

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FOSSIL FUELS OUTLOOK FOR PUERTO RICO'S PRIVATE INDUSTRIAL SECTOR

Mr. Carlos Yepes[1]
P. M. Manager, Puerto Rican Cement Company, Inc.
Ponce, Puerto Rico

ABSTRACT

A SHORT history of fossil fuels is presented, from their origin to present times as energy producing natural resources in America and the world. The present and future energy situation resulting from the indiscriminate use of our energy resources is briefly analyzed. A presentation is also made of the distribution of the world's energy resources.

The price escalation of fossil fuels is discussed in the context of its effect on Puerto Rico's industrial development and economy, both for the present and future. Energy conservation, together with the use of other conventional and non-conventional energy sources, is evaluated as a Puerto Rican option. Also presented is a brief analysis of Puerto Rico's energy policy today, and the eventual discovery of oil in Puerto Rico.

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[1] Present address: Puerto Rico Cement Co., Inc., P.O. Box 1349, Ponce, Puerto Rico

DEFINITION OF TERMS

1. Fuel

   Any material, solid, liquid or gas which burns in the presence of air or decomposes liberating considerable heat energy.

2. Fossils

   Applied to substances of organic origin, more or less petrified, found in earth strata. (F. O., coal, natural gas, oil shales).

3. BTU

   Unit of heat energy used to measure the heat capacity of fuels. It is equivalent to the heat necessary to raise the temperature of one pound of water by one degree Fahrenheit.

4. Kilowatt-hour

   Unit of electric energy equivalent to 3,412 BTU's.

5. Hydraulic energy

   Kinetic and potential energy contained in the flowing river waters.

6. Biomass[1]

   Conversion to energy of anything biological either thru burning or decomposition.

7. MBDOE

   Millions of barrels per day of oil equivalent.

8. OPEC

   Organization of Petroleum Exporting Countries.
   Algeria, Ecuador, Gabon, Indonesia, Iran, Irak, Kuwait, Lybia, Nigeria, Qatar, Saudi Arabia, United Arab Emirates (Abu Dhabi-Bubai-Sharjah), Venezuela.

9. WOCA

   World Outside Communist Area

10. North America

    U.S. and Canada

11. Western Europe

    Denmark, Finland, France, Netherlands, Norway, Sweden, U.K., Austria, Belgium, Greece, Iceland, Ireland, Luxembourg, Portugal, Spain, Switzerland.

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[1] Editor's note: Author definitions are given as received in the original manuscript.

INTRODUCTION

WHILE peering into the future to see where man is going relative to energy sources, it would also be well to look back in time. Modern man, especially in the industrialized world with all of its energy consuming conveniences, tends to loose sight of his much more humble beginnings. It is hard for us with cars, and electric lights, and central heating, and air conditioning, and radio, and television and other conveniences we enjoy, to imagine man in his more primitive state. In 1700 the world population was about 600 million. By 1900 it had shot up to 1,500 million, and it is predicted to reach 7,000 million by the year 2000.

In the United States we use more energy per capita than any other nation. In 1972 we used approximately 346 million BTU per person, equivalent to 2,306 Bbls. of oil per year. To maintain an improving standard of living, we will require roughly 380 million BTU's per person in 1985. This is equivalent to 2,530 gallons of oil per year. By the year 2000 this figure could increase to a per capita rate of 450 million BTU's per year, equivalent to 3,000 gallons of oil per year.

The problem, of course, is that the fossil fuels, which are the current primary source of energy, are finite. We cannot deny that the amount of fossil fuel on earth is limited. If we keep relying on it to the extent we do now, someday we will run out. The only question open for debate is when that may be.

The problem of limited supply is compounded by three other factors: One is pollution, another is the type of fossil fuel now being used, and the third is where these fuels are coming from. In the U.S., oil and natural gas make up 75% of our consumption and 7% of our reserves. Coal, on the other hand, constitutes about 90% of our country's reserves.

While the demand for oil has been rising at more than 5% per year, domestic production has been dropping at a rate of 6% a year since 1970 when production peaked. The picture is similar for natural gas. What we have done to close this gap is to buy additional needed fuel overseas. We experienced the disastrous results of this trend during the 1973 embargo and the subsequent price hikes. So we are faced with increasing demand, a diminishing supply, and an increased dependency on foreign sources.

What are we going to do about this problem?

The newly-created U.S. Department of Energy (DOE) outlined the effect it sees each of these measures having. In general, increasing the efficiency of energy use (conservation) can have the greatest immediate impact on the nation's energy system between now and 2000. The expansion in the production and use of existing fuels, such as oil and natural gas, coal, and uranium, can also provide a substantial contribution to solving the nation's energy problem between now and 2000.

DOE, the main conduit for Federal funds into energy research and development, is planning to spend billions of dollars in the next few years. About $700 million will be devoted to the Fossil Fuel Development Program. DOE has noted, however, that some new technologies, such as solar heating and cooling, geothermal, biomass, and oil shale utilization are likely to make "significant" contributions to the pre-2000 energy picture. Other potential energy sources currently under investigation include a means for harvesting the potential energy in oil shale, tar sands, and the geothermal heat below the surface of the earth. Work is also being done to recover presently unreachable oil and gas deposits.

Although much of the future is in question, there are a few things of which we can be sure. Oil, gas, and coal will run out. But the sun, the sea, the winds, the rivers and the plants will be here forever. Let us best learn to live with and make the best possible use of these forces of nature.

Don't expect miracles in the short term. We had better face the fact that for the next 25 years we are going to rely on coal, nuclear power, gas and oil.

ORIGIN, COMPOSITION, AND CLASSIFICATION OF FOSSIL FUELS

Fossil fuels are combustible materials of organic origin, produced by nature through long decaying, heating and pressure of accumulated decomposed vegetation in previous geological ages. They are, chemically, composed chiefly of carbon, hydrogen and oxygen, with lesser amounts of nitrogen, sulfur, and varying amounts of moisture and mineral impurities. Fossil fuels may exist in the solid state (coal), the liquid state (petroleum), or in the gaseous state (natural gas), depending on how much heat and pressure they were subjected to and for how long.

ENERGY: THE PROBLEM OF THE CENTURY

There can be no longer any doubt that the world has reached the end of an era in its energy history. Increasing oil imports, the basis for three decades of unparalleled economic growth, will not be available anymore.

Complex factors ranging from increasing consumption to rising fuel oil prices and environmental considerations are the most important contributing elements to the very serious situation we will be facing during the next decade or so. Fortunately, the world is not running out of potential sources of energy. It will, of course, take a major effort and considerable lead time to develop new resources to meet future needs.

The United States will remain the largest oil consuming country and will become increasingly dependent on imported oil at least for the next ten to fifteen years. The world will be dependent on the Middle East for an increasing share of oil supplies for some years to come. Efforts to find new oil will not be as easy as in the past. Our industry has to search in increasingly difficult environments such as the Arctic and North Sea. The very large fields in the Middle East represent discoveries whose size is unmatched in the history of oil.

Even if demand growth were moderated, as we believe it must be, we need to face the fact that the world's conventional oil resources will not indefinitely support increases in production. To prepare for such a situation and for an orderly transition into a new energy era, consuming nations must create the political and economic environments that will encourage energy conservation and speed the development of other conventional and non-conventional energy sources. The United States has wider choices than any other nation because of the scale of our basic energy resources. The current crisis is a warning of the energy problems the world will be facing if supply and demand trends continue the way they are headed. Failure to recognize the importance of this problem and to take appropriate and timely action will almost certainly result in a world of confrontation and conflict. Higher energy prices, as the supply/demand imbalance becomes more apparent, will have depressant effects on the economies of the world and will frustrate the aspirations of the less developed countries. The longer the world delays in facing this issue, the more serious the danger will be. Even with prompt action the margin between success and failure in the 1985-2000 period is slim. Time has become one of the most precious of our resources. Recognizing the importance of time and the need to respond can help us through the period of transition that lies ahead. The years up to 1985 are critical ones. Events and policy decisions in the decade before 1985 will determine the success in demand reduction, fuel substitution, or additions to supply in the 1985-2000 period.

The transition away from primary reliance on oil will be well under way by the year 2000. For this to be a smooth transition, greater international cooperation among increasingly interdependent nations is essential. Vigorous research, development, and demonstration of new supply sources, plus conservation and fuel-switching programs, must move forward on an international scale.

The period to the end of the century will be one of energy transition away from oil as the world's dominant fuel. It will be a challenging and critical period. Our energy world then, and in the 21st century, depends on it.

FOSSIL FUELS INVENTORY

Fossil fuels (oil, coal, natural gas) are found in the earth in sufficiently large quantities to take care of all of the world's energy needs for 100 to 150 years at today's rate of consumption. At the present time, 66% of present oil reserves are in the Middle East and North Africa. About 50% of total reserves are in the countries bordering the Persian or Arabian Gulf. Total oil reserves are distributed in approximately the following pattern:

Middle East	53%
Africa	16%
Russia & Communist Countries	15%
Europe	2%
North America	7%
South America	5%
Indonesia	2%

In relation to natural gas, proven reserves are distributed as follows:

OPEC	38%
North America	13%
Western Europe	9%
Rest WOCA	8%
Communist areas	32%

The estimated world natural gas reserves are equivalent to 386 billion barrels of oil.

Coal will again be the world's dominant commercial fuel. Today's leading coal producers are the major industrialized countries of the western world and the communist area. Three countries, the United States, Russia, and China, account for nearly 60% of world output, with Poland, West Germany, and the United Kingdom producing over 15%. The single largest producer and consumer of coal is the United States, with nearly half the production and over half of the known reserves.

The world possesses vast reserves of coal, far in excess of those of any other fossil fuel. The total estimated recoverable reserves of 737 billion tons are enough for over 200 years of consumption at the current rate of coal usage. Expressed in terms of oil equivalents, this is equal to around 3,000 billion barrels, from 4 to 5 times the current level of proven reserves of crude oil.

The world's recoverable coal reserves are distributed approximately as follows:

United States	34%
Western Europe	6%
Rest of WOCA	7%
USSR and Eastern Europe	39%
China	14%
United Kingdom & Canada	1%

Energy sources other than oil, natural gas, and coal could make a growing contribution to energy supply before the year 2000. These supply sources include other fossil fuels such as oil shale, oil sands, and heavy oil.

Known deposits of oil sands, heavy oil, and oil shale, are much larger than the world's proven reserves of conventional oil. Such deposits represent a potential means for supply of petroleum long after conventional oil and gas fields are exhausted.

In Canada, oil or tar sands lie in beds 50 to 100 feet thick under an area of 12,000 square miles near the Mackenzie River in Northern Alberta. It is estimated that 300 billion barrels of oil are recoverable if fully exploited. Such oil sand reserves would produce 3 MBD for 25 years.

Significant deposits of heavy oil have been found in Canada and Venezuela. In Canada, estimates of recoverable oil are in the order of 2 to 4.5 billion barrels. In Venezuela, in the Orinoco oil belt, the thickness of the oil sands is greater than the originally estimated oil equivalent of 700 billion barrels.

Oil shale is another significant energy resource. The largest known reserves are in the USA, with significant amounts found also in Brazil, Canada, Burma, USSR and China. U.S. oil shale deposits are estimated to contain 2,000 billion barrels of oil. However, only about 6% of the deposits are sufficiently accessible and commercially exploitable.

PUERTO RICO AND THE WORLD'S ENERGY SITUATION

The effects of the world's energy situation are particularly serious for Puerto Rico. We, in Puerto Rico, depend on oil for about 99% of our energy needs. Puerto Rico not only consumes a relatively large amount of energy, but we do so in a very inefficient way. Oil is the only source of energy for our petrochemical industry, for the production of electric power, and to run our system of transportation. These are the most energy consuming activities in our daily life. Most other activities such as industry, agriculture, and others are also greatly dependent on oil.

To solve this problem of inefficiency and high energy consumption, the only available alternative is the wise and prudent use of energy in the different sectors of our activities.

Puerto Rico currently imports 120 million barrels of crude oil and naphtha. Venezuela supplies about 40 to 50% of this amount. It is estimated that nearly 40% of all imported crude oil and naphtha are exported as refined products or petrochemicals, mostly to the eastern U.S. Approximately 60% of imported petroleum is consumed in processing (10%) and supply of local energy needs (50%). This means that 60 to 70 million barrels of imported petroleum are required to meet our internal energy demands.

We must stress the concept of energy conservation as our only way to reduce our consumption of oil and to reduce our dependency on imported petroleum, at least for the present and near future, and until we are fortunate enough to discover our own oil deposits, or to develop other sources of energy, including the use of other fossil fuels (coal), solar, hydraulic, nuclear, biomass, etc.

You may not believe this, but the Puerto Rican spends a higher percentage (8%) of his income on energy than a mainland resident does (5%).

The PR Government has already prepared a document that presents a public energy policy for Puerto Rico. It is a plan for the careful administration and control of our energy consumption, based primarily on the saving of energy combined with the eventual substitution of present conventional fuel (oil). The immediate goal is to save 5 to 6% of our actual consumption in 1980. This saving will represent approximately 3 to 3.5 million barrels of petroleum every year, or an equivalent of 50 to 60 million dollars. The two most critical areas for control of energy are transportation (gasoline) and residential-commercial (air conditioning and illumination). This program requires the joint effort of government, industry, business in general, and all citizens as well.

All of the above measures should help save energy and some money but will not free us from our oil dependency at all. There are only two ways in which we can get away from our need of importing petroleum: To discover oil in Puerto Rico, or to change over from oil to coal.

The discovery of oil in Puerto Rico would, of course, be the most welcome event. If, unfortunately, it does not occur, we will definitely have to base our energy future on the use of coal which is quite abundant in America and much cheaper than petroleum. If oil is present in Puerto Rico, natural gas should also be available. Then we may count on two very important sources of energy which will completely change our energy picture. Let us hope and pray that this is true. There are, fortunately, a few renewable natural sources of energy quite abundant in nature. These are the sun, the ocean, the winds, and biomass. There is also solid waste.

These are potential future alternatives for development before we run short of the three primary energy sources ie, oil, coal, and natural gas. Which of these renewable resources will help us better face our energy situation is hard to predict. This may ultimately depend on what kind of a decision we make and how we develop a successful alternative energy program.

ENERGY AND PUERTO RICO INDUSTRY

The three most intensive energy consumers in the industrial sector of our economy are: Petro-chemicals, electric energy utilities (PREPA) and the cement industry. I will present to you, gentlemen, a short review of the cement industry in relation to the energy problem, which I suppose will be relatively alike in effect, if not in dimension, to other large industries.

As you very well know, the cement industry is a high energy consumer. Fuel oil and electric power represent almost 60% of all current operating costs. The industry consumes 1.5 million barrels of fuel oil each year, now costing approximately 35 million dollars. It consumes 200,000,000 KWH of electric power costing 14 million dollars annually. These costs may very well rise to $50 million and $20 million, respectively, in the next five years or so.

There are a few alternatives we have been considering as possible solutions to our energy problem. These are:

1. Change from wet process to dry process.
2. Change over from oil burning to coal burning.
3. Use biomass energy.

Alternative No. 1 is the most attractive one in terms of heat energy saving and increase in production obtained, but the investment involved in the change is very high. The dry process is indeed a revolutionary approach to the saving of energy in the cement industry. While in the wet process the average energy is approximately 1,000,000 BTU/barrel, in the dry process it is reduced to 550,000 BTU/barrel. In a 6,000,000 barrel plant such as ours, this could represent a saving of approximately 500,000 barrels of fuel oil every year amounting to 13 million dollars. Besides this saving in fuel oil, conversion from the wet to dry process could mean an increase in production by the converted unit of approximately 40%.

This indeed would be a very attractive proposal if it were not for the large investment involved of about 125 to 150 dollars per ton of capacity. In our case the investment could amount to 150 million dollars. Very few industries in Puerto Rico can afford to spend that much money. We are among the very many who cannot.

Alternative No. 2 is actually the most viable in terms of time, availability of coal, and also in terms of investment involved and savings through the use of a cheaper fuel. It is also a less complicated conversion. We have already gone through most of the preliminary studies and we hope to be able to move along with this project in a short time. This change means the complete substitution of oil with coal.

At present prices the conversion from fuel oil to coal may represent in our case a good saving of approximately \$1.50/million BTU, or about 10 to 12 million dollars per year. The approximate investment required for the conversion could be around 10 to 15 million dollars. This could be a more realistic approach to our energy problem in terms of economy, availability of fuel, and time required for conversion.

The third alternative is biomass energy. We have been in contact with a few individuals interested in this matter, but as of now it looks as a possible alternative by the end of the century.

There are quite a few problems involved in the conversion to coal burning in almost every case, but nothing could be worse than our running short of oil before we are able to use coal and other energy sources. Therefore we had better get started to make whatever adjustments we have to in order to keep our utilities, industries, and transportation operating without any serious difficulties.

We are very much involved in this energy situation and we must make our particular decision in this respect in the very near future. We agree with the general opinion that coal is the best immediate practical alternative to solve our energy situation.

We know what the problem is all about. Fortunately, we have the solution. It is time to make a decision and start moving in the right direction.

CONCLUSIONS

The future of oil supply is uncertain. However, one conclusion is very clear: Potential oil demand in the year 2000 is unlikely to be satisfied by crude oil production from conventional sources. The supply of oil will fail to meet increasing demand, most probably between 1985 and 1995.

The world is near the end of an era in its energy history. Increasing supplies of oil will not be available any more. The end of the era of growth in oil production is probably, at the most, only 10 to 12 years away. Increasing our consumption of oil, in the hope that more optimistic estimates might prove to be correct, is to run the real risk that the peak in oil production could be brought forward, making the necessary adjustments in energy consumption much more severe.

Large investments and long lead times are required to produce alternative fuels on a scale large enough to compensate for the prospective shortage of oil. The task will be to manage a transition from dependence on oil to a greater reliance on other fossil fuels, nuclear energy, and later renewable energy systems.

Demand for energy will continue to grow even if governments adopt vigorous policies to conserve energy. The continued growth of energy demand requires that energy resources be vigorously developed. Electricity from nuclear power is capable of making an important contribution to the world's energy supply. Coal has the potential to contribute substantially to our future energy supply. Coal can bridge the transition from the fading petroleum era to the next century's renewable sources of energy. It is the only fuel capable of doing this in large enough quantities within the time available. Because prices of coal are likely to be based on costs, over the long term, the present price advantage of coal over oil and gas is likely to increase. The major coal use in the year 2000, as today, is projected to be in electric utilities, which now consume 60% of total coal.

Although the resource base of other fossil fuels such as oil sands, heavy oil, and oil shale is very large, they are likely to supply only small amounts of energy before the year 2000.

Other than hydroelectric power, renewable resources of energy like solar, wind power, and wave power are unlikely to contribute significant quantities of additional energy during this century. They are likely to become increasingly important in the 21st century.

Conservation will become, over the next 20 years, one of world's largest energy "sources." A 25% projected energy input per unit of activity would reduce the amount of increased energy needed by almost as much as the projected three-fold expansion of coal. Policies for achieving energy conservation should continue to be key elements of all future energy strategies.

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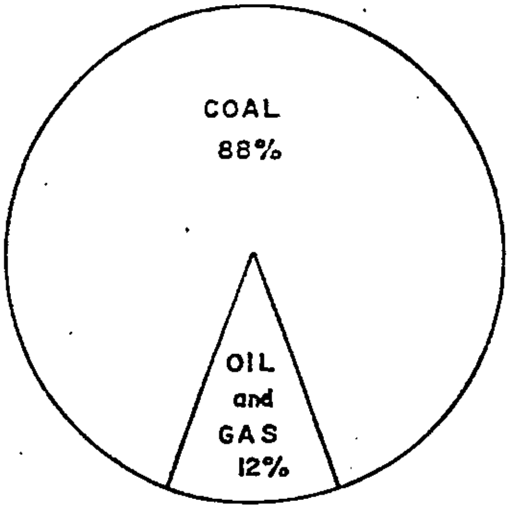
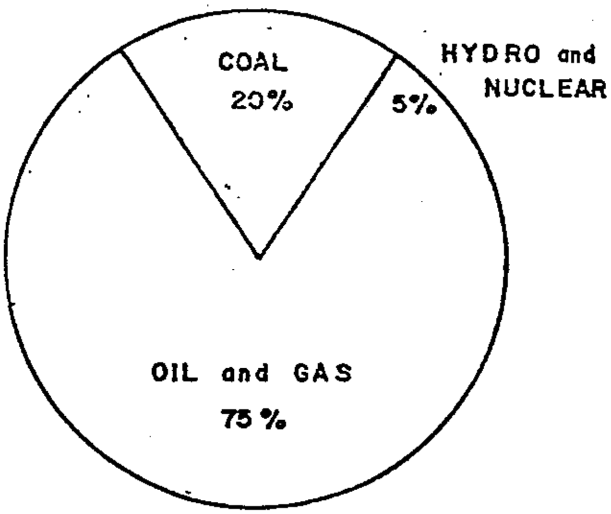
OIL AND COAL IN UNITED STATES



HOW MUCH COAL
WE HAVE

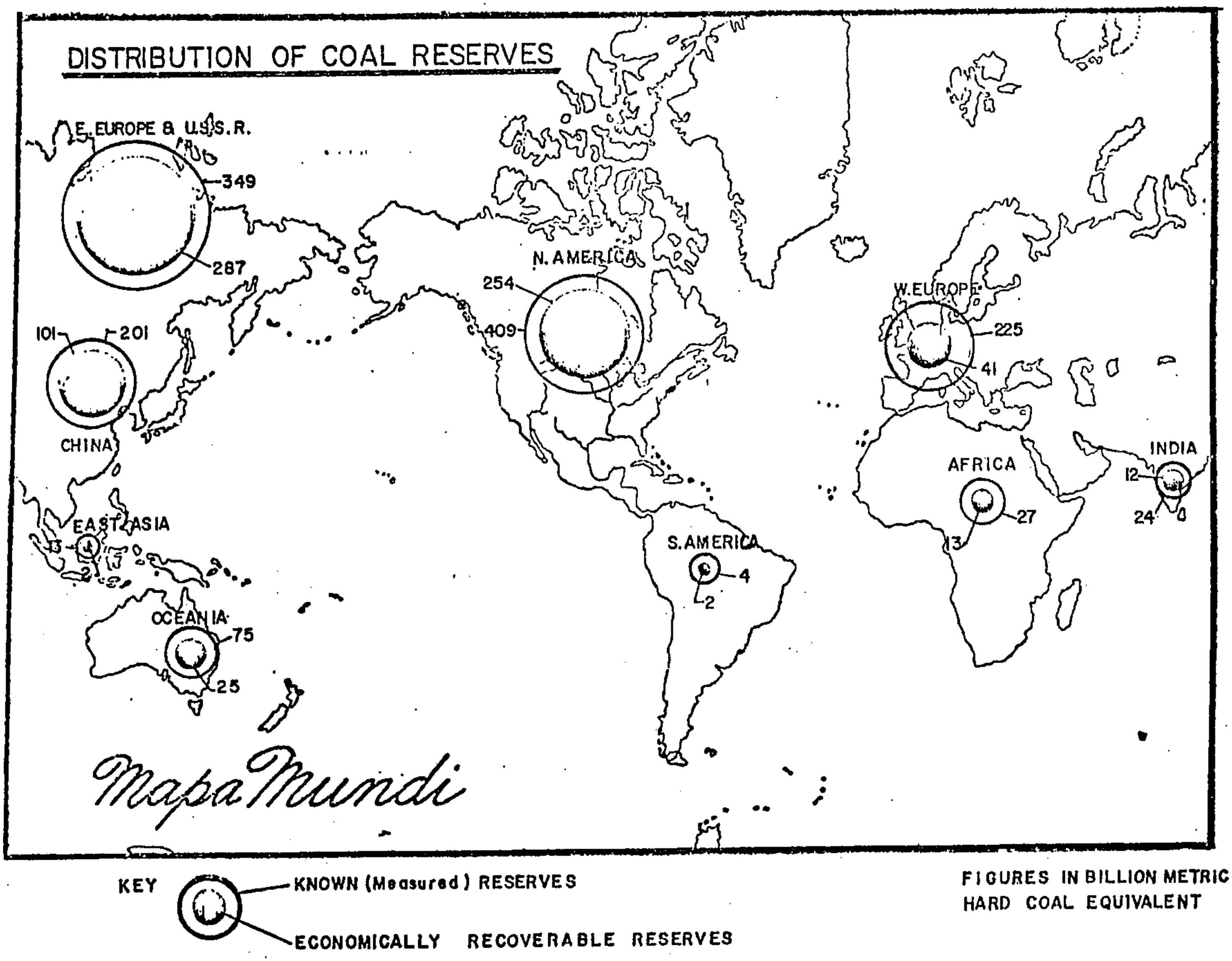
Known Reserves of
Energy Fuels



HOW MUCH COAL
WE NOW USE

Current Energy Sources
in the U.S.

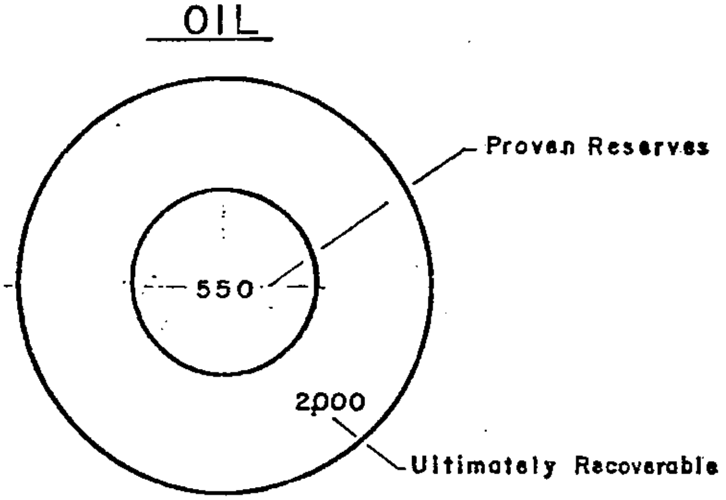
DISTRIBUTION OF COAL RESERVES

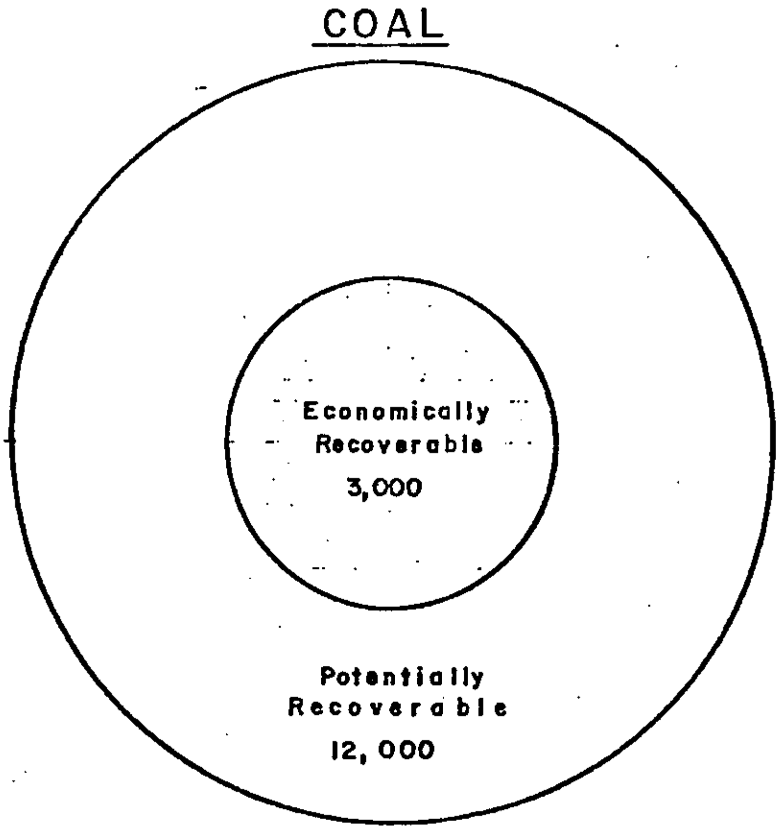


FIGURES IN BILLION METRIC Tons
HARD COAL EQUIVALENT

A COMPARISON OF OIL AND COAL RESERVES

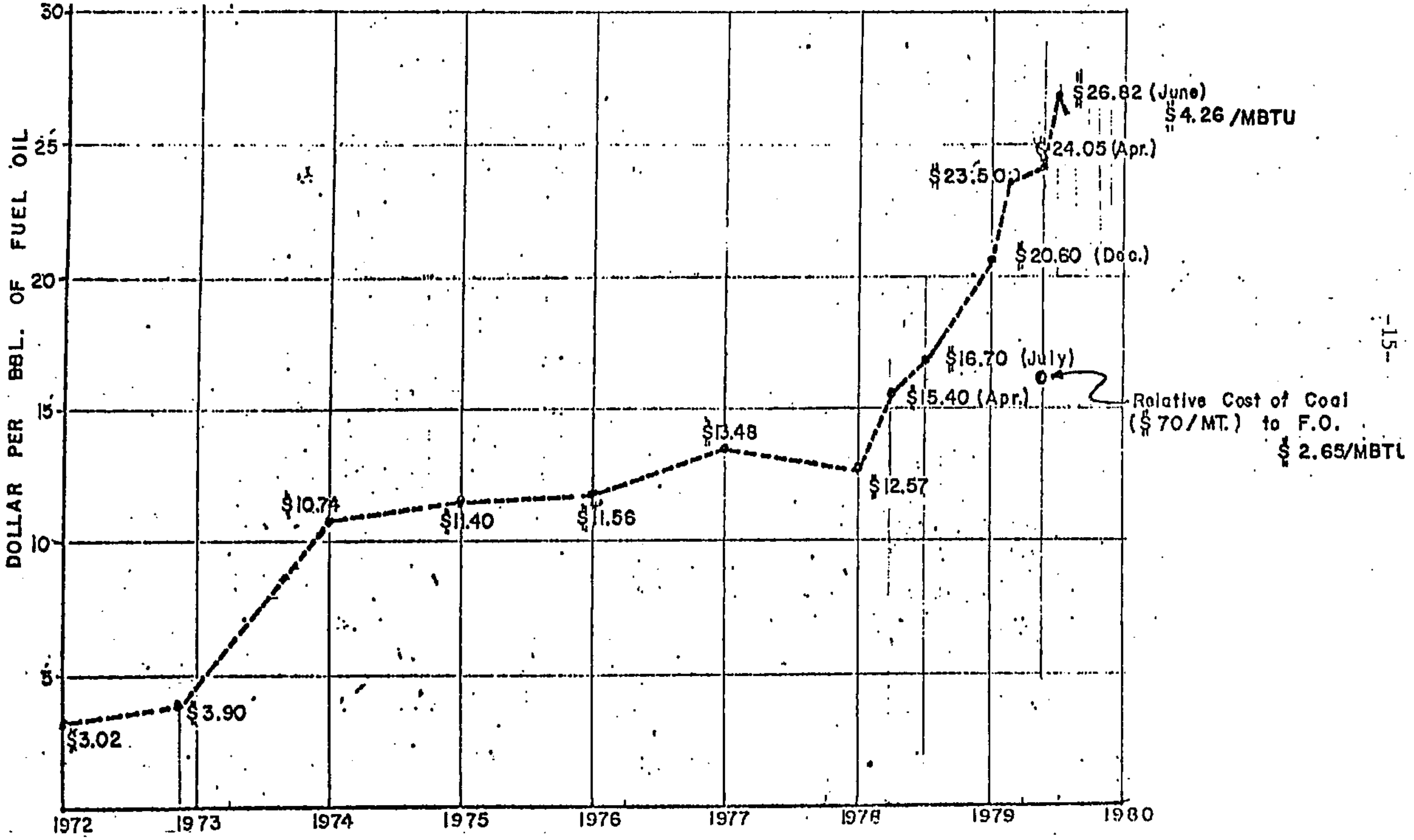
(UNITS: Billion Barrels Oil Equivalent)





FUEL OIL PRICE FLUCTUATIONS

1972 to 1980



COMBUSTION SYSTEMS FOR BAGASSE AND FOSSIL/BAGASSE FUEL BLENDS

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

Eugene S. Yankura, P.E.
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COMBUSTION SYSTEM FOR BAGASSE AND FOSSIL/BAGASSE FUEL BLENDS

THIS PAPER reviews the critical components of combustion systems that are dedicated to the firing of bagasse and fossil/bagasse fuel blends.

OIL

The use of oil poses no special problems. Add on systems would be installed as completely separate systems with their own storage and conveying equipment. There would be no common elements with bagasse or coal systems. On the other hand, coal or bagasse systems cannot be retrofitted to most boilers designed primarily for oil without a severe reduction in capacity. The firing chambers are too small and they have no provision for ash handling facilities. Coal/oil mixtures and pulverized coal burners of the Blaw-Knox type help to overcome some of the limitations.

BAGASSE AND COAL

Except perhaps for the conveying and delivery systems, bagasse and coal are compatible for firing in the same combustion chamber. The vibrating grate stoker and the underfeed single retort stoker with dump grates can be designed to handle equally well bagasse or coal. The designer must have information about the amount of ash, ash fusion temperatures, coal size and moisture.

Both bagasse and coal require spacious firing chambers that allow long flame plaths to give the time needed for complete combustion and to minimize deposition of slag on the boiler tubes.

Both bagasse and coal require similar levels of excess air. The placement of air tuyeres for both underfire and overfire air would be similar for each.

Conveying and delivery equipment should be kept separate. That is, one system could not be equally capable of handling coal as well as bagasse or vice versa. There are widely different design criteria for each material.

DRYERS

More and more attention is being given to using flue gas to reduce the moisture of fuels such as bagasse and wood. They have an inherently low BTU value and a high water content. The successful exploitation of these biomass fuels will be moved forward considerably by the application of this technique. By reducing the moisture, a greater portion of the fuel BTU value is available for useful work.

Such a system was operated by A.C.I. at Central Coloso in 1978. It was found that by reducing the bagasse moisture level, the excess air rate could be reduced. For instance, when the bagasse was fired at a 43% moisture content, the excess air could be reduced to 10% without the formation of detectable carbon monoxide. That is, less than 0.1%. In consequence, a second significant increase is realized in the energy available for useful work.

The drying of bagasse can be employed toward a second equally valuable end, the storage of bagasse for future energy requirements. The moisture content must be reduced to prevent decomposition and degradation.

Figures 1 through 6 show the evolution of a boiler dryer system. The stepwise progression demonstrates the flexibility of design to satisfy various ends. The system is designed around two boilers, although all the elements can be practiced in a single boiler. Drying the bagasse in two steps reduces the fire hazard. In this system, low moisture bagasse is exposed only to dryer gas with a very low oxygen content. In addition, a two-boiler system would permit easier control in load swing situations. The system parameters and design, in particular for the dryer, are based on the results obtained in the Central Coloso tests.

Figure 1 shows the first step in the dryer system. The boiler conditions are patterned after the typical bagasse boiler found in the sugar industry. Combustion takes place with an excess air rate of 50%. This is necessary with a moisture level of 52%. Below 50% excess air, combustion efficiency would degrade rapidly. The factory load requirement is assumed to be 200,000# steam/hr. and boiler one is being fired to carry half the load.

In Figure 2, the 32.5% moist bagasse from the first dryer is fed to the dryer of the second boiler before going to the combustion chamber. In the second dryer, the bagasse is further dried from 32.5% moisture to 20% moisture in an oxygen depleted atmosphere. Since Boiler #2 needs to produce 100,000# steam/hr. to meet demand, all of the 20% moist bagasse is not fired. The remainder may be stored. Note that if the remaining bagasse were fired at the conditions of Boiler

2, it would produce an additional 60,500# steam/hr. Therefore, where present typical firing conditions would produce 200,000# steam/hr. (2x Boiler 1), drying the bagasse before combustion as in Figure 2 would produce 260,500# steam/hr. for an increase of 30.25% in the useful heat value of the bagasse.

Note in Figure 2 that the boiler temperature profile is different in the two boilers. The two boilers are the same and the steam from each is used at the same pressure of 180 PSI. The temperature profile is affected by mass flow rate, gas specific heat, flame temperature and change in ratio of radiant to convection heat transfer. For these designs, the ratio of radiant to convection heat transfer is assumed constant. The radiant heat transfer is proportional to the 4th power of the temperature but there are other variables affecting emissivity, in particular gas composition. It is true, that to a high degree, the various interrelated factors cancel out overall. Therefore, the new temperature profile is found by:

$$U S \Delta t_m = wg\ cg\ \Delta tg$$

where = combined conductance X surface area
= constant for boiler
tm = log mean temp. difference, gas and saturated water
ti = gas temp. entering tube bank
t2 = gas temp. leaving tube bank
t's = saturated temp. of boiler water
wg = weight flow of gas
cg = mean specific heat of gas

The length of time that 20% moist bagasse can be stored without serious degradation is still an unknown. So, let's see what can be done to obtain a still drier bagasse for storage.

In Figure 3, we see that it is necessary to fire more of the bagasse from the Boiler 2 dryer in order to reduce slightly more the bagasse for storage. We have also reduced the quantity remaining for storage. We can pursue this direction further as in Figure 4 and get down to 17% moist bagasse for storage, but have even smaller amount, in fact, a very small amount. This approach has serious constraints. To get drier bagasse, we have to consume more and, in consequence, generate more steam which will have to be wasted if the factory can't use it. Also, to get drier bagasse, we get less of it. It seems as though 17% moist bagasse is the limit. If we try to go drier, there will be virtually none to store.

The dryer, like any mass transfer device, is subject to rate constrained mechanisms. If time were not a factor; that is, infinite, the materials would come to true equilibrium. For instance, if the example in Figure 1 were given infinite time to equilibrate, the final conditions would be those shown in Figure 5 where the bagasse moisture is reduced to 27.6% compared to 32.5%. At greatly increased capital expense and/or operating expense, the dryer efficiency can be increased.

However, let's take another approach. Figure 6 shows this other approach where Boiler 1 is operated at 100% excess air. Some boiler output is sacrificed, but the bagasse is dried to 20% moisture. Continuing, Boiler 2 is fired at a rate to compensate for the reduced output of Boiler 1 so the total steaming rate is the required 200,000# steam/hr. Now the bagasse remaining from Dryer 2 is down to 3% moisture and in such quantity that were it fired in Boiler 2, it would produce another 64,500# steam/hr. The increase in bagasse useful heat value is 32-1/2% over the present typical firing method (see Figure 1). I am letting the 3% moisture stand only to demonstrate the theoretical potential of the technique. It is presumed otherwise that the hygroscopic nature of bagasse below about 15% will result in equilibrium at some higher moisture level.

What we accomplished here is to establish a heat pump. The energy deficit from Boiler 1 raises the BTU's of the extra excess air to a higher energy level to increase the driving force that produces drying—the drying effect being greater than the "deficit" could produce in the former fashion.

Again, I would like to note that these effects can be combined in a single boiler/dryer system with similar end results. I do not show that here, since it is important to preserve the condition where low moisture bagasse is treated with oxygen depleted gases.

Referring to Figures 2, 3 and 4, and the available energy yield from the remaining bagasse; the available # steam/hr. figures were based on firing the remaining bagasse under the existing conditions of Boiler 2. If the firing were done in another boiler/dryer, the ultimate yield in each case would equal that in Figure 6. We have not in any case affected the true ultimate yield under maximized conditions with the equipment available. What we have done is to create a highly flexible system whose operation can be tailored to meet almost any end objective.

To complete the picture, refer to Figure 7. This would be the case where there is a temporary increase in the need for steam. One boiler is shown, but the same applies to both. All the bagasse from the dryer is fed to the boiler with the boiler operating at 10% excess air. Conditions will equilibrate such that the boiler produces 132,750# steam/hr. and the bagasse is dried to 41% moisture. For the two boilers the output would be 265,500# steam/hr. bagasse for an increased useful heat value of 32.7%.

PREHEATER

A preheater is a heat saving device that reduces the heat loss going out the stack. The result is an increased yield in the useful heat value of the fuel. The examples worked out above in the figures do not use a preheater. It would appear that the preheater, by reducing the temperature of the stack gas would reduce the "drying capacity" of the flue gas. But other parameters are changed by the preheater, such as flame temperature, and therefore boiler temperature profile. It is not intuitively obvious what would happen, and the cases have to be worked out. For now, it is an open question, but my educated guess is that it will not detract from the increase in fuel useful heat value afforded by the dryer.

CORROSION

When firing coal in a low pressure boiler, attention must be given to the flue gas temperature. It must be maintained above the dew point of SO_3 or else the rate of corrosion will be serious. This applies in particular to the superheater and preheater. This temperature is usually considered to be about 350°F., but with high levels of coal sulphur, it will be higher.

ACKNOWLEDGMENTS

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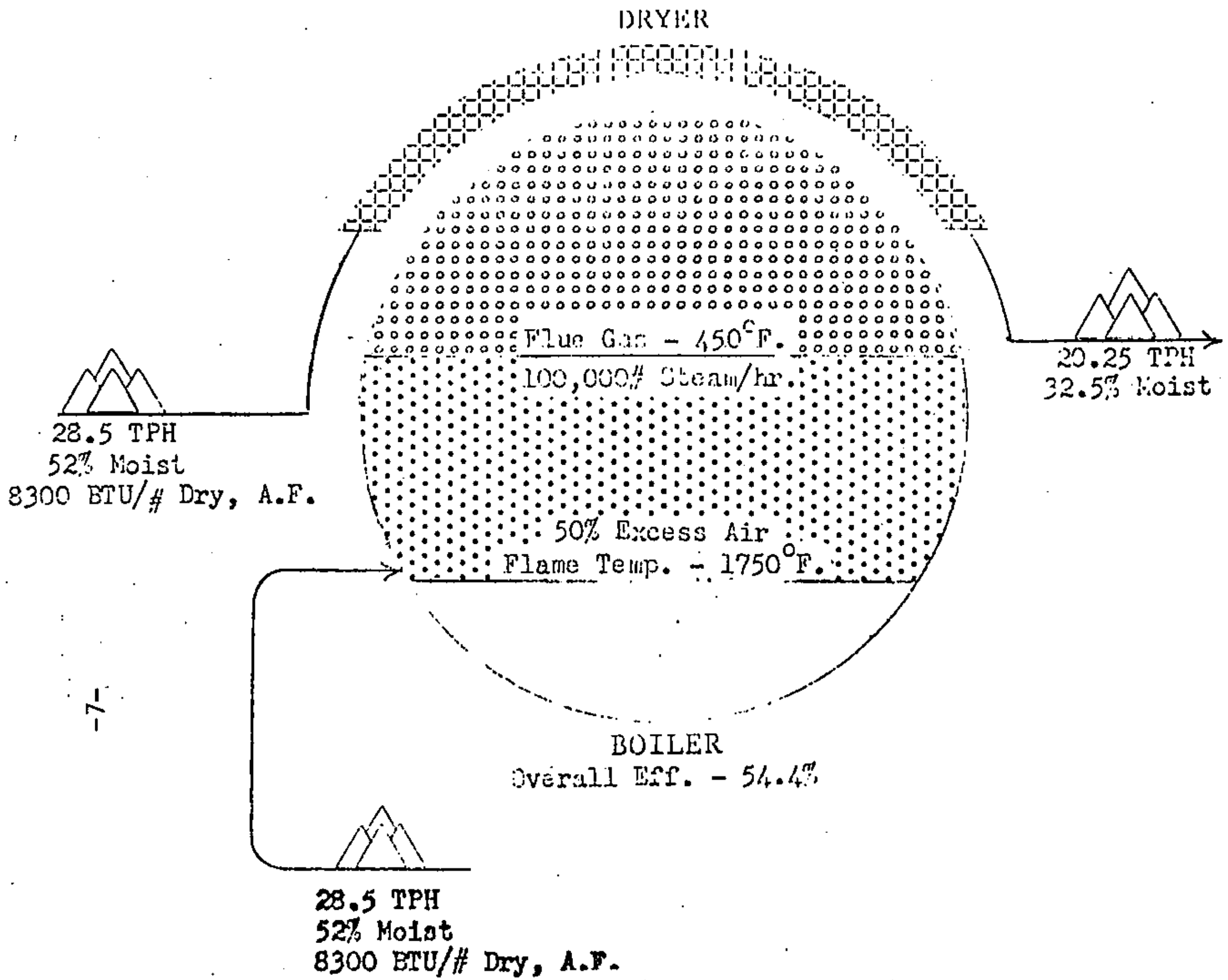
DRYER
Flue Gas - 450°F.
100,000# Steam/hr.
50% Excess Air
Flame Temp. - 1750°F.
BOILER
Overall Eff. - 54.4%
28.5 TPH
52% Moist
8300 BTU/# Dry, A.F.
20.25 TPH
32.5% Moist
28.5 TPH
52% Moist
8300 BTU/# Dry, A.F.

FIGURE 1

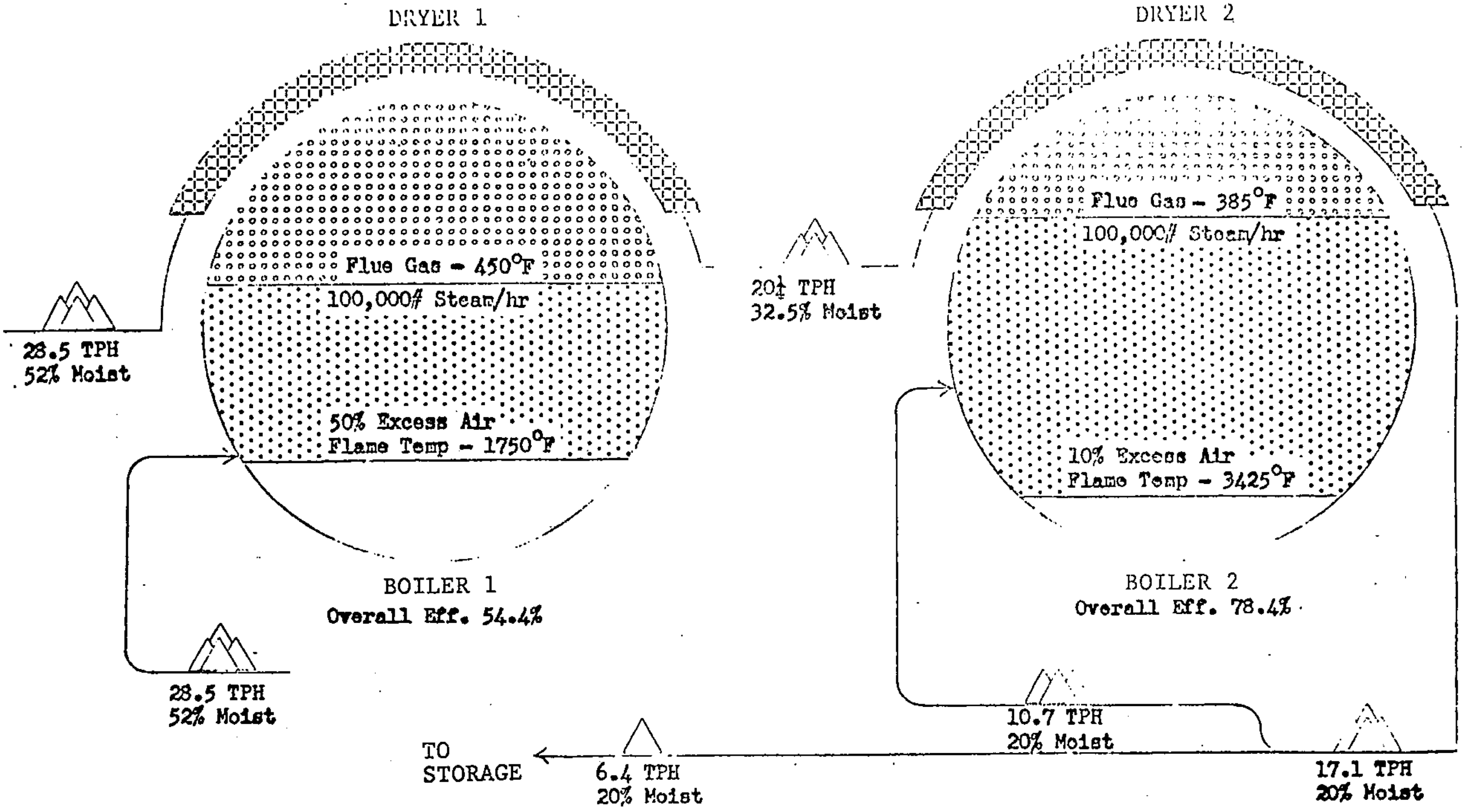
DRYER 1
DRYER 2
28.5 TPH
52% Moist
Flue Gas - 450°F
100,000# Steam/hr
50% Excess Air
Flame Temp - 1750°F
BOILER 1
Overall Eff. 54.4%
28.5 TPH
52% Moist
20¼ TPH
32.5% Moist
Flue Gas - 385°F
100,000# Steam/hr
10% Excess Air
Flame Temp - 3425°F
BOILER 2
Overall Eff. 78.4%
10.7 TPH
20% Moist
17.1 TPH
20% Moist
6.4 TPH
20% Moist
TO
STORAGE

FIGURE 2

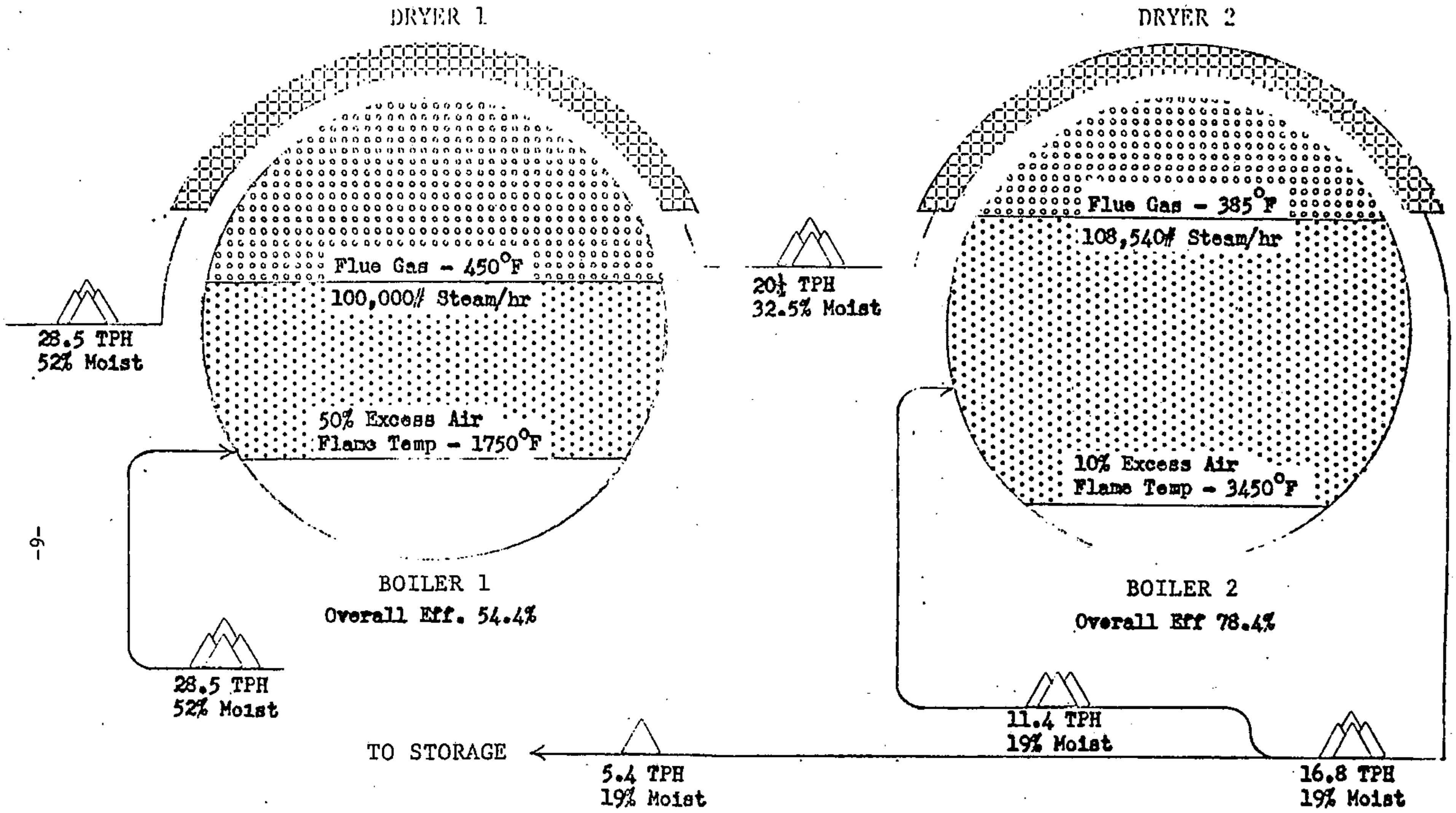
DRYER 1
DRYER 2
Flue Gas - 450°F
100,000# Steam/hr
50% Excess Air
Flame Temp - 1750°F
28.5 TPH
52% Moist
28.5 TPH
52% Moist
BOILER 1
Overall Eff. 54.4%
20½ TPH
32.5% Moist
Flue Gas - 385°F
108,540# Steam/hr
10% Excess Air
Flame Temp - 3450°F
BOILER 2
Overall Eff 78.4%
11.4 TPH
19% Moist
16.8 TPH
19% Moist
TO STORAGE
5.4 TPH
19% Moist

FIGURE 3

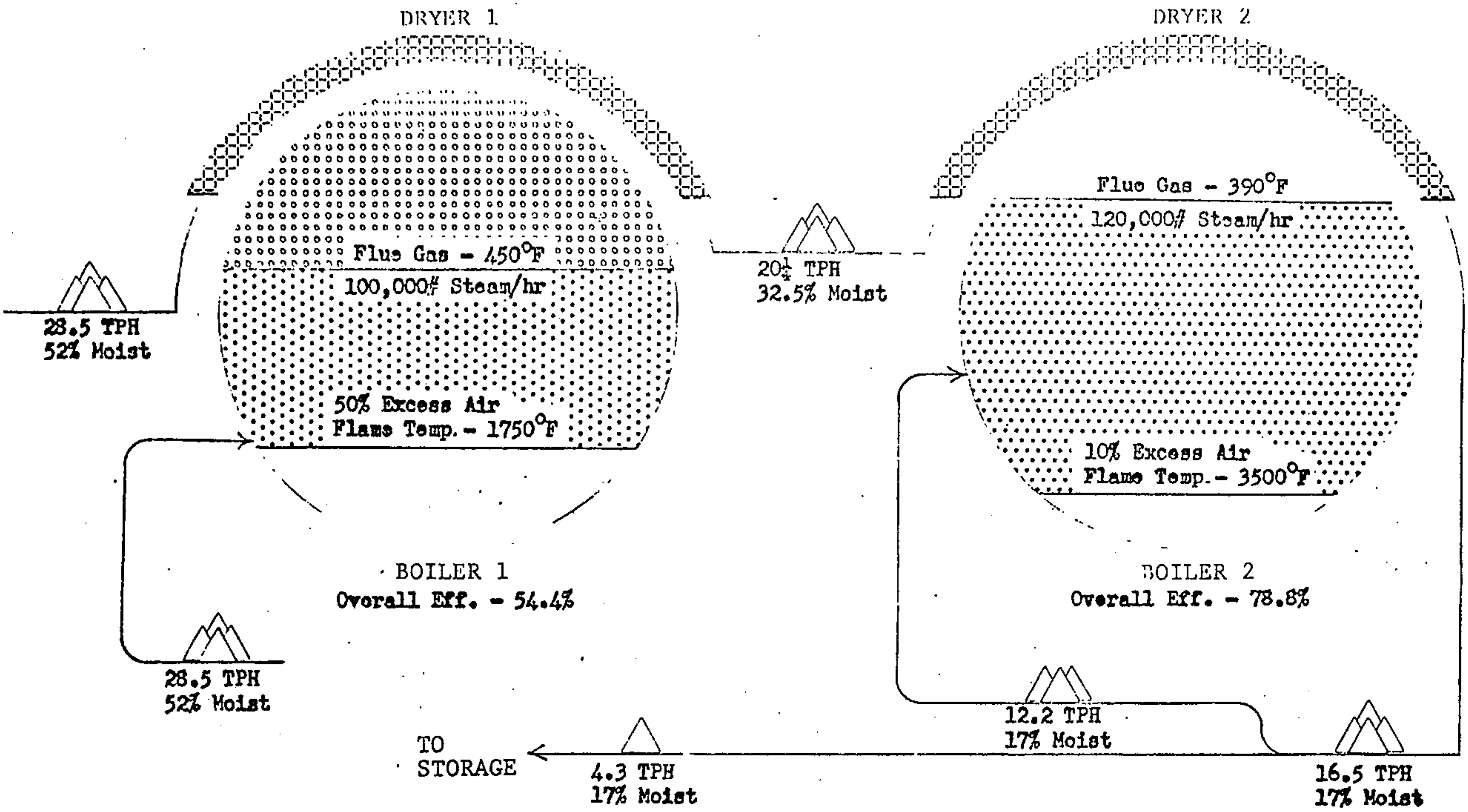
DRYER 1
DRYER 2
Flue Gas - 450°F
100,000# Steam/hr
50% Excess Air
Flame Temp. - 1750°F
BOILER 1
Overall Eff. - 54.4%
Flue Gas - 390°F
120,000# Steam/hr
10% Excess Air
Flame Temp. - 3500°F
BOILER 2
Overall Eff. - 78.8%
28.5 TPH
52% Moist
28.5 TPH
52% Moist
20¼ TPH
32.5% Moist
12.2 TPH
17% Moist
16.5 TPH
17% Moist
4.3 TPH
17% Moist
TO
STORAGE

FIGURE 4

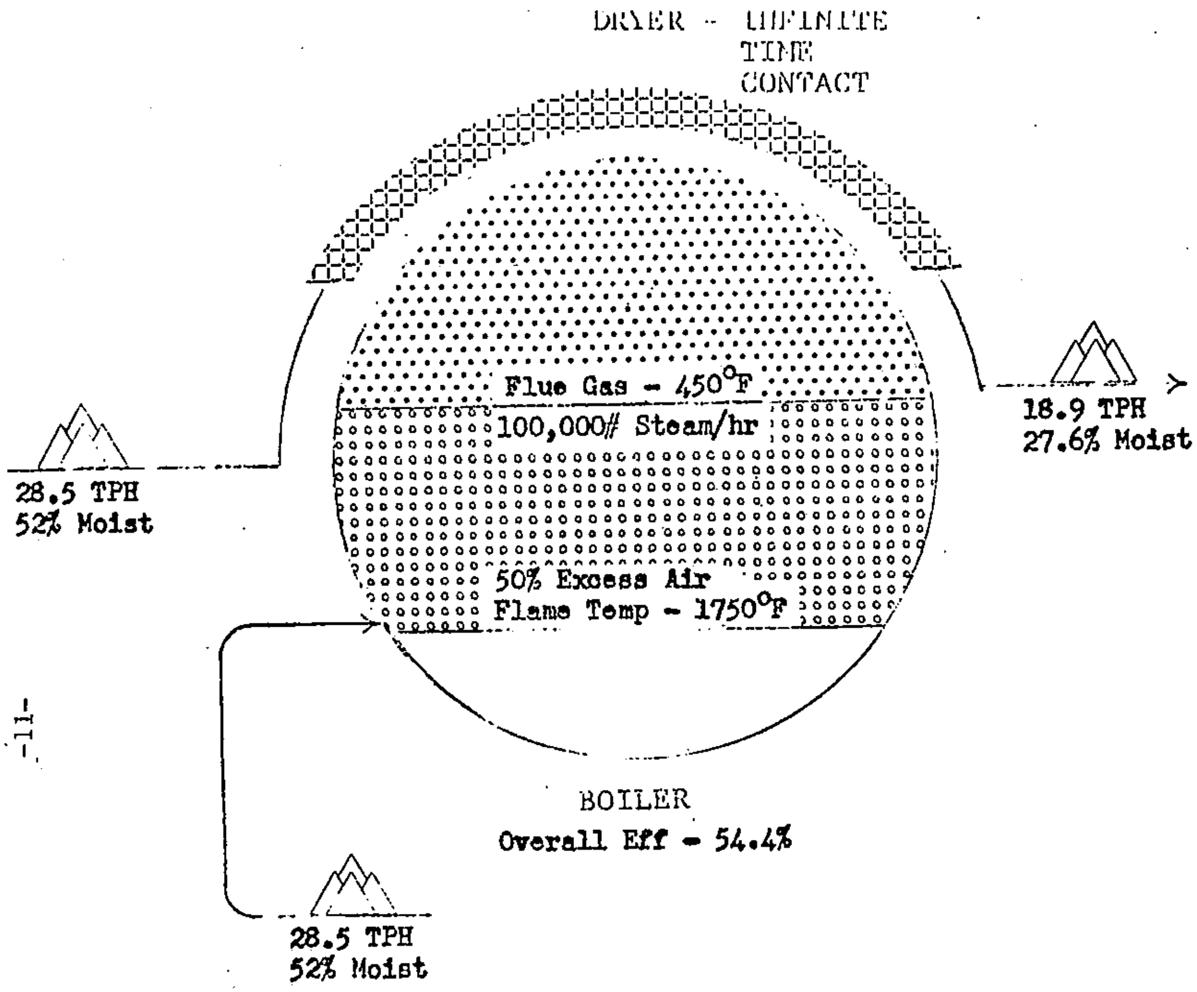
DRYER - INFINITE
TIME
CONTACT
28.5 TPH
52% Moist
Flue Gas - 450°F
100,000# Steam/hr
50% Excess Air
Flame Temp - 1750°F
18.9 TPH
27.6% Moist
BOILER
Overall Eff - 54.4%
28.5 TPH
52% Moist

FIGURE 5

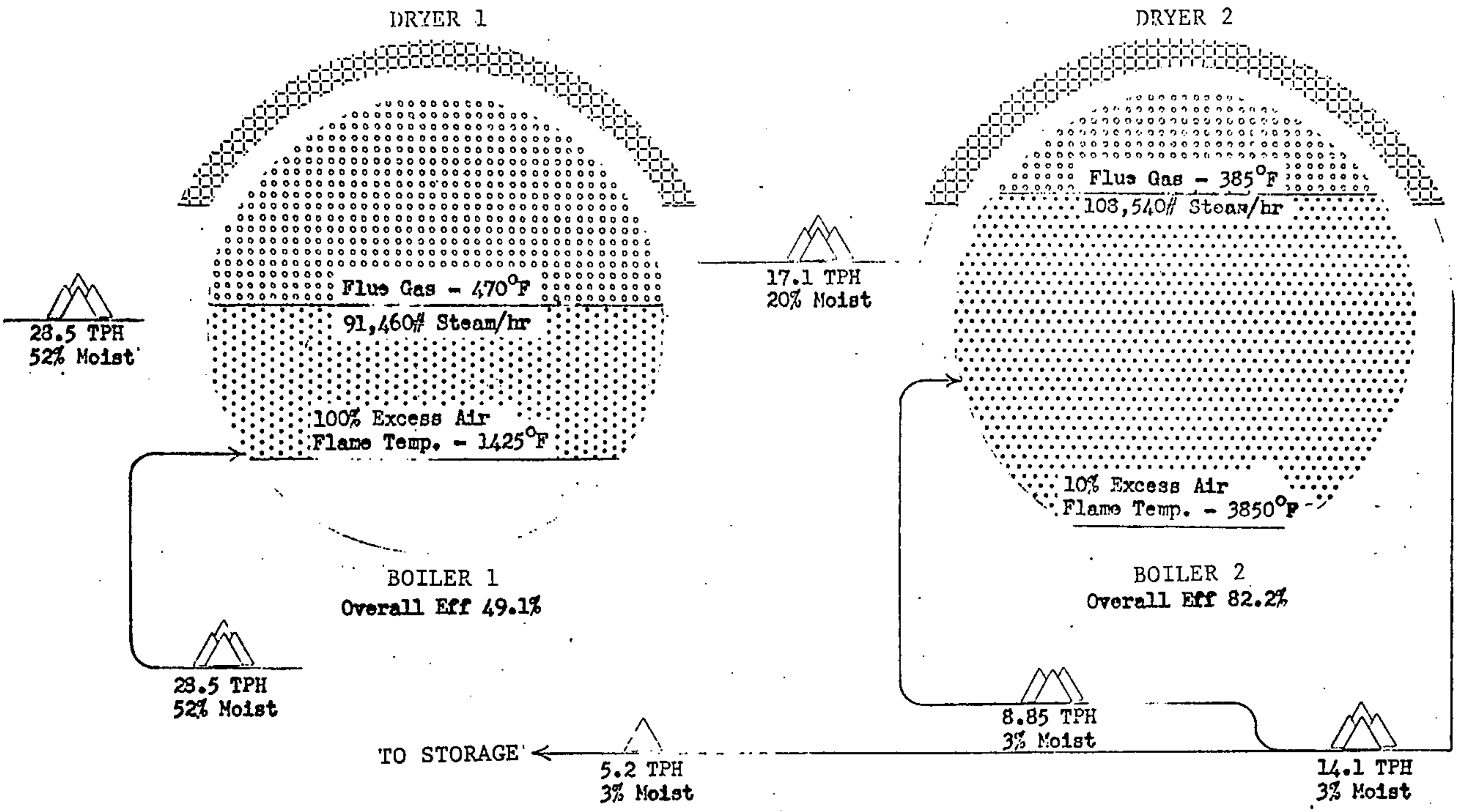
DRYER 1
DRYER 2
28.5 TPH
52% Moist
Flue Gas - 470°F
91,460# Steam/hr
100% Excess Air
Flame Temp. - 1425°F
BOILER 1
Overall Eff 49.1%
28.5 TPH
52% Moist
17.1 TPH
20% Moist
Flue Gas - 385°F
103,540# Steam/hr
10% Excess Air
Flame Temp. - 3850°F
BOILER 2
Overall Eff 82.2%
8.85 TPH
3% Moist
14.1 TPH
3% Moist
TO STORAGE
5.2 TPH
3% Moist

FIGURE 6

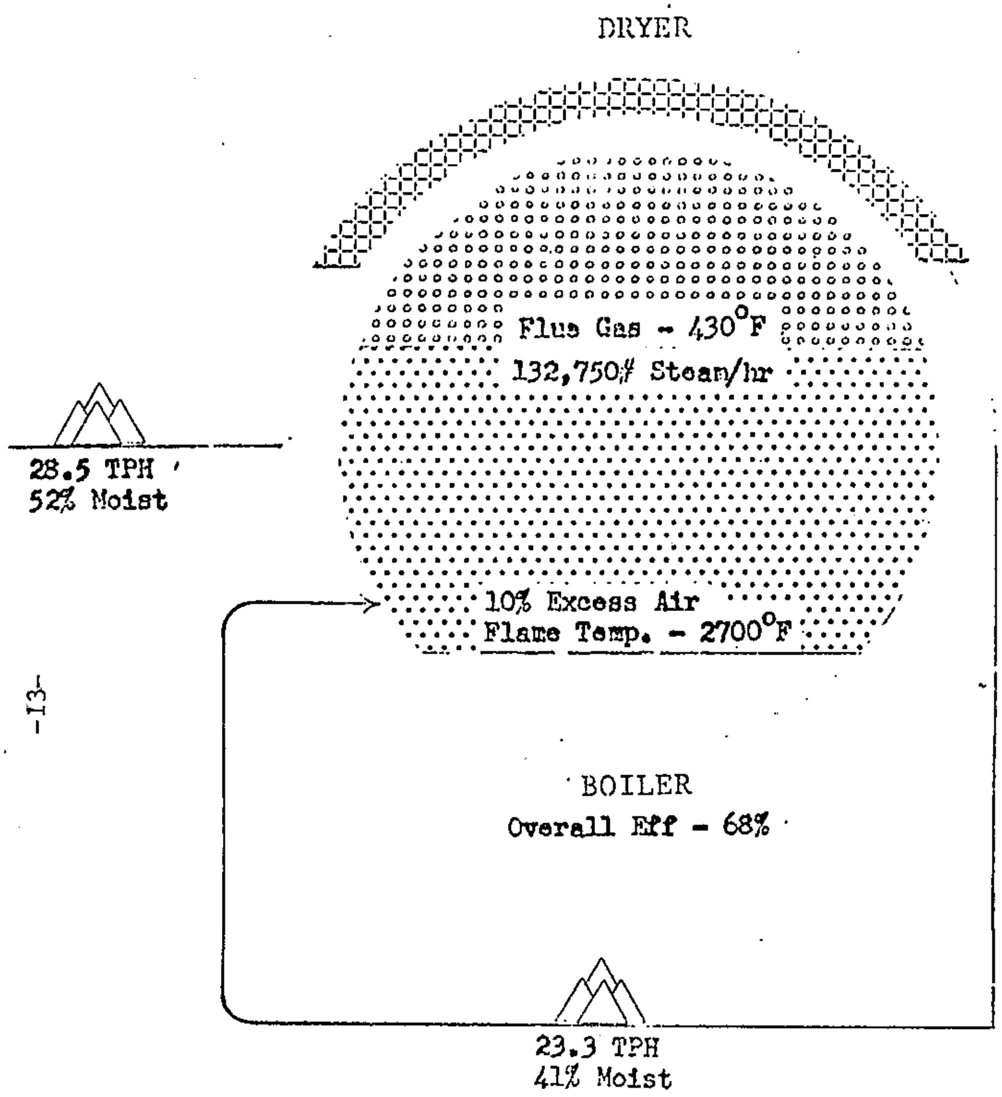
DRYER
Flue Gas - 430°F
132,750# Steam/hr
28.5 TPH
52% Moist
10% Excess Air
Flame Temp. - 2700°F
BOILER
Overall Eff - 68%
23.3 TPH
41% Moist

FIGURE 7

CENTRALS LAFAYETTE AND AGUIRRE AS POTENTIAL SITES FOR ENERGY COGENERATION

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

Mr. Roberto Delucca, Chief Engineer
Central Aguirre, Aguirre, Puerto Rico

CENTRALS LAFAYETTE AND AGUIRRE AS POTENTIAL SITES FOR ENERGY COGENERATION

BAGASSE: A FREE FUEL IN P.R. SUGAR MILLS

BAGASSE is the fiber residue left after grinding sugarcane. Its most important characteristics are its heating value, fiber content, moisture content, and ash. Bagasse has always been used in Puerto Rico's sugar mills as fuel for the generation of steam, which in turn is used for moving the mill engines, for processing (and evaporation), and for the generation of electricity.

The total bagasse produced during the 1980 crop in all the Puerto Rico sugar mills amounted to approximately 827,213 tons (equivalent on an undried basis to 1,109,293 barrels of fuel-oil, which at current prices would amount to $23,572,476). Since not all sugar mills in Puerto Rico have steam-measuring instrumentation, it is not readily known how much steam was actually produced in the sugar mills from bagasse. But using the Aguirre steam production data we can get a rough figure of what the steam production could have been. In this way we have figured a total steam production of 1,216,320 pounds of steam per hour. After using 60% of this steam for cane grinding, we then have left 486,528 pounds of steam per hour. This amount of steam could be used to produce 12,637.1 kwh of energy in the mill power plants (from bagasse fuel only), as surplus energy which could be sold to the P.R. Electric Power Authority. This would have a value of $3,022,890.00 for a 125-day crop.

Bagasse, being a solid fiber, has different burning properties as compared to fuel oil. Whereas fuel oil, being a liquid, is very easy to transport, convey, manipulate, heat and atomize, it constitutes a fuel that is relatively easy to control. With bagasse the picture becomes quite different. Bagasse is a bulky fuel that tends to pack, has a relatively high moisture content, and is not easily dried. It also carries with it variable amounts of soil, which depends on the cane harvesting methods employed and to the extent to which the sugarcane is cleaned prior to grinding. Furthermore, bagasse does not lend itself to easy conveyance through a piped system, and it is relatively difficult to meter. It also presents a problem in its handling due to fugitive dust, and to store because of its potential for spontaneous combustion. Therefore, the process of bagasse burning in a boiler furnace is quite different from the burning of fuel oil, and more like that of burning coal. That is why modern bagasse-burning furnaces and auxiliary equipment are related to those used in coal-burning boilers.

There are two principal types of furnaces for bagasse burning: The horseshoe type furnace in which bagasse is burned in a pile inside a horseshoe (or round refractory lined furnaces, where air is made available from the sides or in some cases from under the pile also), and the most recent method where bagasse is burned in a spreader stoker over a grate, much like those used in coal-burning furnaces. In the first type, bagasse is fed by gravity through a gate whose opening is adjusted manually. In this case the operator feeds the needed amount of bagasse to maintain a constant height in the bagasse pile and in actual practice the amount of air is seldom varied. This is one of the crudest ways of burning bagasse. It is the method most used in the sugar mills of Puerto Rico. In most cases there are no indications of the most basic parameters of combustion, like furnace temperature, air flow, or steam flow (boiler load).

The few spreader-stoker type bagasse boilers that are in use in P.R. mills make use of bagasse-metering devices for feeding bagasse into the furnace, instead of the chute and gate system. Yet these metering devices are also controlled manually by the boiler operator, and there is little or no air flow control. Boilers of this type could be easily improved by means of automatic combustion controls which would adjust automatically the bagasse and air flow in direct relationship to the variations in boiler load, much as is done with coal-burning boilers.

For these reasons, there is still a long way to go in improving Puerto Rico's bagasse-burning boilers for an efficient burning of bagasse. This is certainly one of the main reasons for the large amount of fuel oil that was burned during the past crops, while at the same time throwing away enormous quantities of excess bagasse. For 1980, sugar mills in Puerto Rico burned 3,872,070 gallons of fuel oil, while at the same time all mills in Puerto Rico had to throw away excess bagasse.

LAFAYETTE SUGAR MILL

Central Lafayette, a cane growers' cooperative facility located at Arroyo, has remained closed since milling the 1973 crop. It ground the cane from Arroyo, Patillas, and Maunabo. There are still some 105,700 tons of cane harvested there, mainly colono cane which is now milled at Central Aguirre. The Lafayette mill has since been maintained in good condition by the Lafayette Coop, and the factory is still complete. The interesting fact about Central Lafayette is that it looks suitable for energy co-generation. The cane from this area could be bought from the Colonos, and the factory could be put into a relatively economical operation of cane milling for electric power co-generation and the production of high-test molasses. The operation costs could be kept low by using and repairing only the equipment needed for such purposes. This includes the cane storing and handling equipment, cane milling station, boilers, power plant, clarification equipment, and the evaporation and bagasse-handling equipment.

The proposed operation at Central Lafayette could be accomplished using approximately 30 to 35 men per shift. Some 3,000 tons of cane could be ground daily. By grinding a high fiber cane (20%) which could render 40% bagasse (50% moisture) per ton of cane, some 1,200 tons of bagasse would be produced daily. This is the equivalent of 272.7 tons of fuel-oil.

1. Milling Equipment At Central Lafayette

For the handling of sugarcane, Central Lafayette has two Wellman Hammer Head cranes, one of 10 tons capacity and the other of 15 tons capacity. There is also a truck dumper which unloads trucked cane into the carrier for immediate grinding. There are two sets of cane knives; the first has a 300 hp electric motor and the second a 200 hp motor. One mill has a 2-roll crusher, sized 36" x 87", four other mills have 3-roller crushers with 36" x 84" rolls. The crusher is driven by a 24" x 42" Corliss engine. The first three mills are driven by a 40" x 60" Corliss engine and the last mill is driven by a 26" x 48" Corliss engine.

The steam plant is composed of an Erie City, spreader-stoker type furnace steam boiler having a capacity of 150,000 lbs of steam per hour; a Horseshoe Furnace type Combustion Engineering Boiler, rated at 90,000 lbs of steam per hour; and two smaller horseshoe furnace Stirling Boilers, rated at 40,000 lbs of steam per hour. The electric plant consists of one GE Turbo-Generator of 1,500 kw capacity, and a smaller Turbo-Generator having 200 kw capacity.

There are also two clarifiers, sized 26 ft. diameter and 20 ft. diameter, plus four juice heaters for a total of 5,250 sq. ft. of heating surface. There are also two vacuum filters for handling mud from the clarifiers. The evaporator system has a 15,000 sq. ft. pre-evaporator and a 20,000 sq. ft. quadruple-effect evaporator. There are also five vacuum pans.

2. Operation Of Central Lafayette

The grinding operation would use only the crusher and first two mills. The bagasse production at 20% fiber in cane would be around 50 tons per hour (bagasse with 50% moisture). This would render a steam production of some 206,250 pounds per hour. By deducting 60% of this steam for grinding, there would remain 82,500 pounds of steam per hour for energy cogeneration. This would amount to 2,142.8 kw-hr. Since the actual capacity of the Lafayette power plant is 1,700 kw-hr, of which around 1,500 kw-hr are used for the grinding process, there is no generating capacity for the additional energy to be sold at this moment. This means that, for energy co-generation at Central Lafayette, a 2,000 kw-hr Turbo-Generator would have to be added to its power plant. This is the only drawback found at Central Lafayette in terms of energy cogeneration.

AGUIRRE SUGAR MILL

The Aguirre sugar mill, located some 15 miles west of Lafayette, could possibly be utilized for energy cogeneration. Central Aguirre is still in operation and for this year's crop ground 401,000 tons of cane, although having a capacity to grind over 6,500 tons of cane per day. The Aguirre mill has two tandems for cane grinding. One is an 18-roller Farrel System driven by six individual steam turbines and having a capacity of around 3,800 tons cane per day. The other is a 17-roller Fulton, rated at 3,000 tons cane per day, and driven by three Corliss steam engines. It has a two-roller crusher moved by electric motor.

For the purpose of this study we have considered using only the Fulton-tandem for energy co-generation. The equipment related to this tandem, and which would be utilized for energy-cogeneration, includes: (a) A Railroad car tippler and truck dumper cane table; (b) Three cane conveyors for cane handling; (c) two cane knives, 300 hp each; (d) the 17 roller, 6-1/2 ft roll length Fulton tandem, moved by two 28" x 54" Corliss engines; (e) a 24" x 48" Corliss engine and a 200 hp electric motor for moving the 2-roll crusher; and (f) Five bagasse boilers, four of which have horseshoe type bagasse furnaces, one actually producing 80,000 lbs of steam per hour and three having capacity to produce around 60,000 lbs of steam each.

Also available is one spreader stoker furnace boiler with a capacity of 120,000 pounds of steam per hour. Each boiler is already equipped with an emission control apparatus (scrubber). Also, there are four clarifiers, eight juice heaters, a triple-effect evaporator, and a quadruple-effect evaporator (for a total of 7 bodies). There is a salt water pumping station for jet-type barometric condensers, plus filters, pumps, etc., and a Power Plant, consisting of two, 2,500 kw-hr General Electric Turbo-generators.

By utilizing the Aguirre Fulton tandem for energy co-generation with a capacity of 3,000 tons of cane per day, as in the Lafayette case, only the crusher and the first two mills would be used. The bagasse production (grinding 20% fiber cane) would be 1,200 tons day at 50% moisture, or 50 tons per hour from which 206,250 pounds of steam per hour would be produced. By deducting 60% of the steam production for grinding purposes there would remain 82,500 pounds of steam per hour. This steam would again amount to 2,142 kw-hr of surplus energy. Since at Aguirre the power plant has a total generating capacity of 5,000 kw-hr, and only 1,600 kw-hr would be generated for grinding, there remains enough capacity at the power plant for co-generating the 2,142 kw-hr surplus energy to be sold to PREPA. It should be pointed out that the Aguirre power plant could produce the total electrical energy needed for grinding biomass in the Fulton tandem (1,600 kw-hr), the extra electrical energy needed for the grinding of sugarcane in the Farrel tandem (1,200 kw-hr), and still have capacity for over 2,000 kw-hr of excess electrical energy co-generation.

At present, the Central Aguirre boilers are operating at their maximum capacity (actually some of them are operating above rated capacity). There is no steam production for co-generation with the Fulton tandem while at the same time grinding sugarcane with the Farrel Tandem. The lack of an additional bagasse boiler at Central Aguirre makes it necessary to dispose of some 300 tons of bagasse daily, while at the same time its electrical energy production is down to 3,000 kw-hr due to lack of steam production.

BIOMASS FUELS DEHYDRATION WITH INDUSTRIAL WASTE HEAT

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

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BIOMASS FUELS DEHYDRATION WITH INDUSTRIAL WASTE HEAT

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THANK YOU for the opportunity of discussing with you today "Biomass Fuels Dehydration with Industrial Waste Heat." Recovery of waste heat from industry is certainly in keeping with energy conservation measures of today, as industry is the largest user of fuels. Using waste heat to create additional fuel is doubly important, particularly as applied to materials which are often a disposal problem. Most waste organic materials are combustible if enough moisture can be removed; and this applies to industrial wastes, municipal wastes, and just ordinary agricultural waste such as stalks, leaves, and ordinary weeds. Unfortunately, the energy consumed in handling many wastes exceeds the useful energy that can be produced; therefore, it is necessary to pick and choose among the processes for those most likely to be energy positive.

(Illustration No. 2) Like other forms of energy, heat has the characteristics of both Quality and Quantity. Quality can be defined as "quantity per unit;" quantity can be defined as "quality times number of units." Specifically, in the English system, a material at a higher temperature has a higher heat content or quality, as expressed in Btu/lb, than the same material at lower temperature. The extractable energy is recovered by removing heat from the material and lowering its quality from a higher temperature to a lower temperature. Say that we are removing heat from furnace gases by reducing their combustion temperatures to a constant smoke stack temperature of 500°F. It is obvious that not only do we actually extract more heat per pound of furnace gas produced at 3000°F than we extract from the 2000°F furnace gas, but we also extract a greater percent of the initial heat. Of course, percent figures always depend upon the base used, which in this paper is the usual "steam table" base of 32°F, in place of absolute zero or other.

Historically, dehydration has been used for many purposes including preserving of foods such as raisins, prunes, other dried fruit, grains, and vegetables. Initially, these products were basically sun-dried, which is labor intensive. Obviously, as dehydration demand grew, larger and faster processes were developed. The direct-fired rotary dryer was introduced to the sugar beet industry before the turn of the century. This process produces animal feed from the fiber of the sugar beet.

Also, the rotary direct-fired dryer is producing animal feed from the fibrous portion of corn, as a by-product of the starch and corn sugar industry. Another plant uses a rotary steam tube dryer to dehydrate the germ from the corn before making corn oil.

(Illustration No. 1) Waste heat from other sources is being added today to direct-fired dryers in place of the usual ambient dilution air, which is mixed with the products of combustion in the furnace. This waste heat can come from another source or merely be recycled from the dryer exhaust. These schemes are used in domestic sugar beet pulp dryers as well as a good many in Europe.

Waste heat from other combustion processes is the exclusive drying media in:

A corn processing plant drying corn fiber and steep water concentrate for animal feed. (Note: the boiler on the right and the dryer plant on the left with the connecting flue gas pipe.)

A Canadian saw mill is drying their waste products with boiler flue gas to produce boiler fuel.

An American lumber and particle board plant drys "hog-fuel" with boiler flue gas. (Note: the sophisticated control panel.)

A charcoal producing plant uses the products of combustion of the wood volatiles to dry the raw material entering the process.

A Louisiana raw sugar mill uses boiler flue gas to dry bagasse for boiler fuel.

A Philippine raw sugar mill is also drying bagasse for fuel with boiler flue gas. (Note: the color of smoke from the boiler stack shows the difference between burning wet and dried bagasse. Obviously, the clear stack represents the dried bagasse operation.)

There are many purposes for drying fuels, of which several *just make it burn better.* We have all had some experience with a smoldering camp fire or trash fire. Damp wood and paper have a difficult time in reaching the kindling temperature having expended much of the heat of combustion in evaporating the moisture. The steam generated from this evaporation tends to shield the air from the surface of the material and the flame suffocates from lack of oxygen. To maintain combustion, more excess air is blown into the furnace, with the net result that the combustion temperature is again lowered. Until a bed of coals is established to maintain a kindling temperature, a large part of the carbon remains unburnt in the form of smoke or is discarded with the ashes.

The low temperature combustion produces a low quality heat as described earlier with the bar graph. The cooler gases not only carry less recoverable heat per pound, but a greater heat transfer surface or volume is required to obtain this heat. This is to say that the equipment required to transfer the same amount of heat will have to be much larger in the case of the colder gases, as the rate of transfer varies directly as the amount of temperature difference between the doner and receiver of the heat. The usual engineering expression for this phenomina is—Q = UA Delta, where the amount of heat exchanged equals a constant times the equipment size times the temperature difference.

(Illustration No. 5) The actual heating value of the fuel is increased by removing its moisture. A part of the heat of combustion is used to evaporate the water, as noted before, which lowers the net heat value of the fuel as illustrated on this graph of "moisture versus net Btu/lb of bagasse." Do not make the "optimistic error" of saying that the apparent increase in Btu/lb is proportionate to the same amount of heat increase in a fixed amount of moist fuel to be dried. (Illustration No. 3) One pound of bagasse at 51% moisture and 3300 Btu/lb becomes .78 pounds of bagasse when dried to 37% moisture with a heating value of 4750 Btu/lb. While the ratio of heating value is 4750/3300 = 1.44, the ratio of total heat content is 3705/3300 = 1.12. The 12% increase in total heat of a crop of sugarcane will produce a lot of energy.

Another common argument, against the operation of a boiler in conjunction with a waste heat fuel dryer, is that the energy used to dry the fuel could be used to heat boiler feed water or combustion air and would amount to the same overall boiler efficiency; or to say waste heat recovery in the case of the use of boiler stack gases would be identical. (Illustration No. 2) Please recall from previous discussions that wet fuels will tend to produce lower temperature products of combustion in greater quantities because of steam generated in the furnace along with additional excess air; therefore, a lower percentage of recoverable heat. (Illustration No. 6) Also, the percent heat recoverable from the exhaust gases is higher when a small amount of hotter gases is available. (A better example of the final stack loss would be illustrated by making the bar representing the colder gases wider to show increased quantity and calling everything below the 250°F line the loss.)

Other reasons for drying fuel are to reduce the quantity and weight of these materials for handling and storage purposes. Also, in the case of biodegradable materials, to prevent losses as CO_2 (or spontaneous combustion).

(Illustration No. 1) The usual rotary dryer looks about like this.

1. A heat source which can be a furnace or a duct from some other process.
2. A stationary feed section, which is shown here as a part of the furnace with a feed chute into the drum. This can also be a screw conveyor extended into the drum.
3. The rotating drum with carrying rollers and drive gears (or sprockets). The drum contains some type of lifters to mix the material being dried with the gases.
4. A stationary discharge section, to receive the material and gases from the drum and either separate and discharge them individually or simply blow everything to the cyclone.
5. An induced draft fan to pull the gases through the system along with the material. (It may be before or after the dust collector.)
6. The cyclone, which separates the material from the gases or merely removes the remaining dust from the exhaust.
7. An optional recycle duct which can be used to return some exhaust gas to the furnace.

The control of the rotary dryer operation can vary to some extent depending upon the heat source and the desired product quality. In the case of beet pulp where a 9% to 11% moisture product is desired, a furnace is required to turn the heat on and off as the feed load fluctuates. The final moisture is held within these limits by controlling a set discharge gas temperature, which in turn controls the furnace firing rate. The other usual control on the rotary dryer is the rate of gas flow through the drum, which if too high will blow the material through the dryer without sufficient retention time to accomplish the drying; or if too low will cause the dryer to plug. This gas flow rate is measured by one of the following indications: the furnace negative pressure, the pressure drop across the drum, or the fan motor load (all of which vary with the quantity of material in the drum). The controller, sensing one of the above indications, operates a damper on the I.D. fan to maintain the gas flow rate.

In the case of using waste heat from another source, the gas flow rate needs some control as above but the product moisture is allowed to float to some extent with the load to the dryer. Actually, the feed rate can be varied to maintain the desired final product moisture.

The size of a dryer obviously varies with the quantity of materials to be dried; but more especially with the quantity of water to be evaporated. Since the gas flow rate is fairly constant, as previously described, the only reasonable way to increase the quantity of gas flow for additional evaporation is to increase the dryer drum cross section. This is to say that the capacity of a dryer will vary as the square of the diameter, within the range of gas temperature restrictions (controlling the gas temperature will vary the evaporation rate within the operating range as previously explained).

The retention time of the material being dried determines the efficiency of the dryer (where "efficient" is the lowest discharge gas temperature that will accomplish the desired result). Retention time can be increased by increasing the dryer length. (Illustration No. 4) A two or three pass dryer is actually one long drum with a capacity proportional to its smallest cross section. Retention can be increased by increasing the percent of the drum filled with material. One method of doing this is to use internal baffling which holds material throughout its cross section, as opposed to dropping the material from peripheral lifters alone.

Various styles of internal baffling are used for various purposes, all of which have developed from the original beet pulp dryer design. In addition to increasing the percent of the drum filled with material, these internal baffles distribute the material across the drum, thus preventing the gases by-passing to dryer exhaust. The additional metal also acts as a heat transfer media between the gases and the moisture in the material (like a frying pan). All of these features increase the rate of heat transfer and thereby the dryer efficiency.

There are practical limitations on the size of a waste heat dryer as dictated by capital cost versus annual total heat recovery. As previously explained, cooler waste heat sources require larger equipment at higher costs, but at lower percent heat recovery. Year 'round operations are preferable to seasonal operations and drying at high moisture levels (say 40% to 80%) are more economical than drying at lower moisture levels. The use of cooler waste heat gases requires a larger dryer for two reasons:

1. A larger quantity of gases is needed to carry the required quantity of heat.
2. A larger volume of contact between the gases and the material is required to offset the smaller temperature differential, (Delta T).

The above factors are not additive, but since they are not proportional to temperature change to the same degree, they both have to be considered in dryer sizing.

(Illustration No. 10) Waste heat fuel dryers are well suited for operation with steam boilers, as not only does the boiler use the fuel, but it also produces the waste heat. The arrangement indicated in the diagram is typical of a variety of applications where the boiler and dryer are operating in a closed loop. The wet bagasse feed is the beginning of the process and the boiler stack discharge is the end of the process, with steam as the product. The boiler flue gas can go to the dryer as needed, with the surplus going directly to the stack.

Specifically at this symposium we are concerned with "cogeneration" of electric power and process heat, especially as applied to the cane sugar industry. This is being done in most raw sugar mills today, which burn their own bagasse to generate steam and electric power for their own processing needs. Unfortunately, these systems were designed to be heat inefficient in order to more completely incinerate the waste bagasse. The counterpart beet sugar factory, which must purchase fuel, is much more heat efficiency conscious.

(Illustration No. 7) Utilities, whose sole product is electric power, have developed the most efficient use of steam for that purpose. In these cases, high pressure boilers feed steam to condensing turbines, in order to attain the greatest pressure drop. Compare the percent recoverable heat of the high pressure boiler versus that of the low pressure boiler. Again, note the percent recoverable heat where the low pressure boiler supplies a back pressured turbine, as used by many sugar factories.

(Illustration No. 8) In spite of a sugar factory's relatively inefficient heat process, which uses only some 8-1/2% of the available heat from its low pressure boiler to produce electric power, it also uses another 76-1/2% for process heating by condensing the exhaust steam at atmosphere pressure. The latent heat of vaporization liberated by condensation is obviously the largest portion of the available heat from a low pressure steam process.

(Illustration No. 9) The sugar factory with its low pressure boiler and back-pressured turbine generates all of the electricity and process steam that it needs for its own operation and if in balance, blows little exhaust to the roof or requires little exhaust make-up. However, most sugarcane factories do not burn all of their bagasse, and would need to burn even less bagasse if they practiced some of the steam economies of the beet sugar factories.

If a balanced sugar mill were to have installed a high pressure boiler with a suitable back-pressured turbine, it could generate additional saleable power, as represented by the area above the 160 psig level on the left side of the tall bar on the graph. If the extra bagasse were burned in a high pressure boiler and the additional steam were run through a condensing turbine, it could generate additional power as represented by the right side of the tall bar. The heavy line on the right side of the tall bar represents the additional heat available by pre-drying the bagasse (or conversely, the heat recovered from the boiler waste gases).

In conclusion, the cogeneration of a large amount of saleable electric power, in conjunction with sugar production, is now a reality. The Hilo Coast Processing Company of Hawaii now operates a very efficient power generating plant with its raw sugar mill and supplies a large part of the electricity used on the island. It uses bagasse from other mills in addition to its own, and has a high pressure boiler supplying steam to a condensing turbine; automatic extraction from the turbine supplies process steam to the sugar mill.

The dehydration of the bagasse not only increases its heating value as a fuel, but more especially increases the system's total output by making it operate at higher input temperature and exhausting smaller quantities of waste heat at lower temperature.

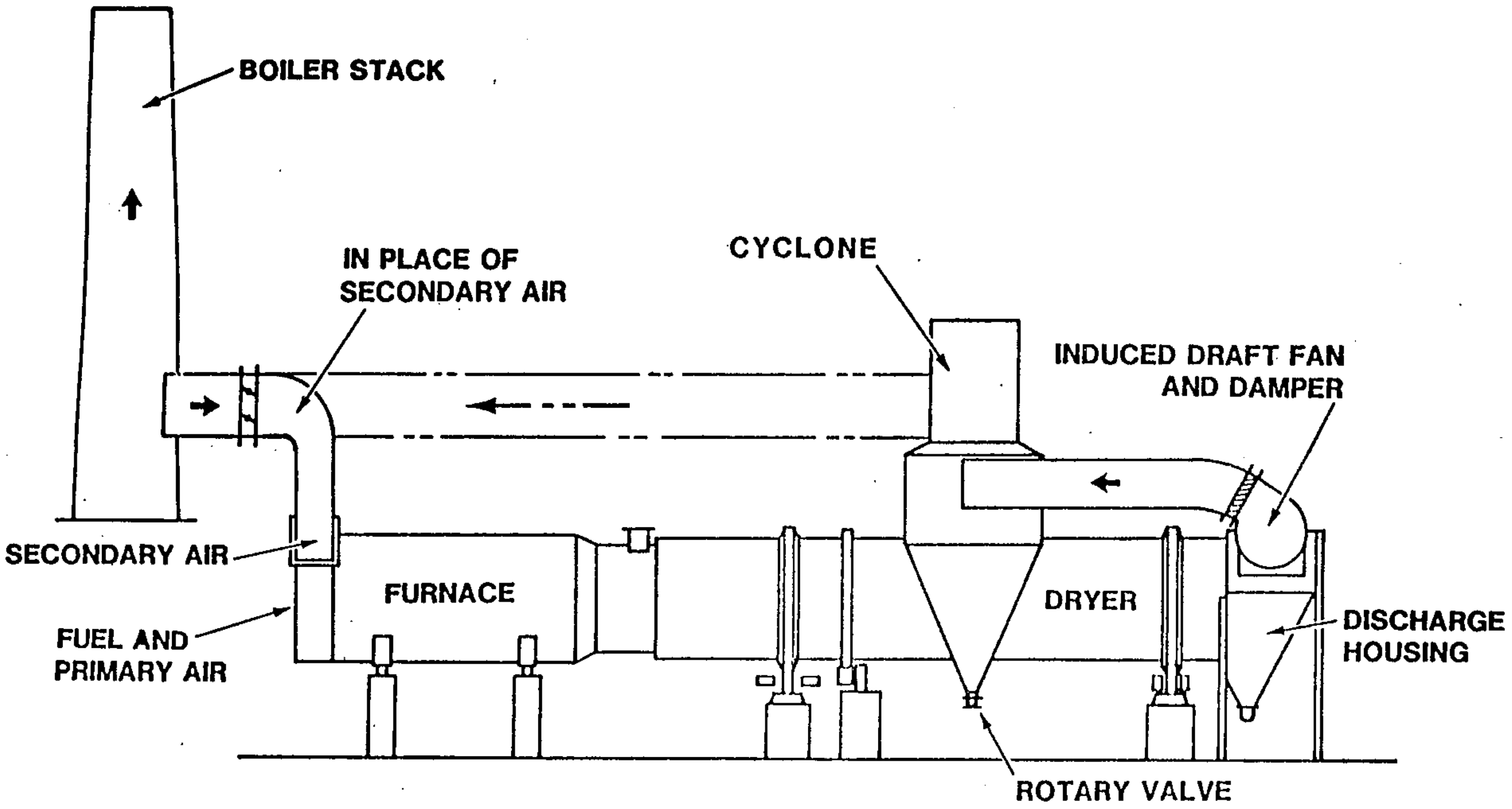


FIG. 1
ROTARY DEHYDRATOR WITH EXHAUST GAS RECYCLE

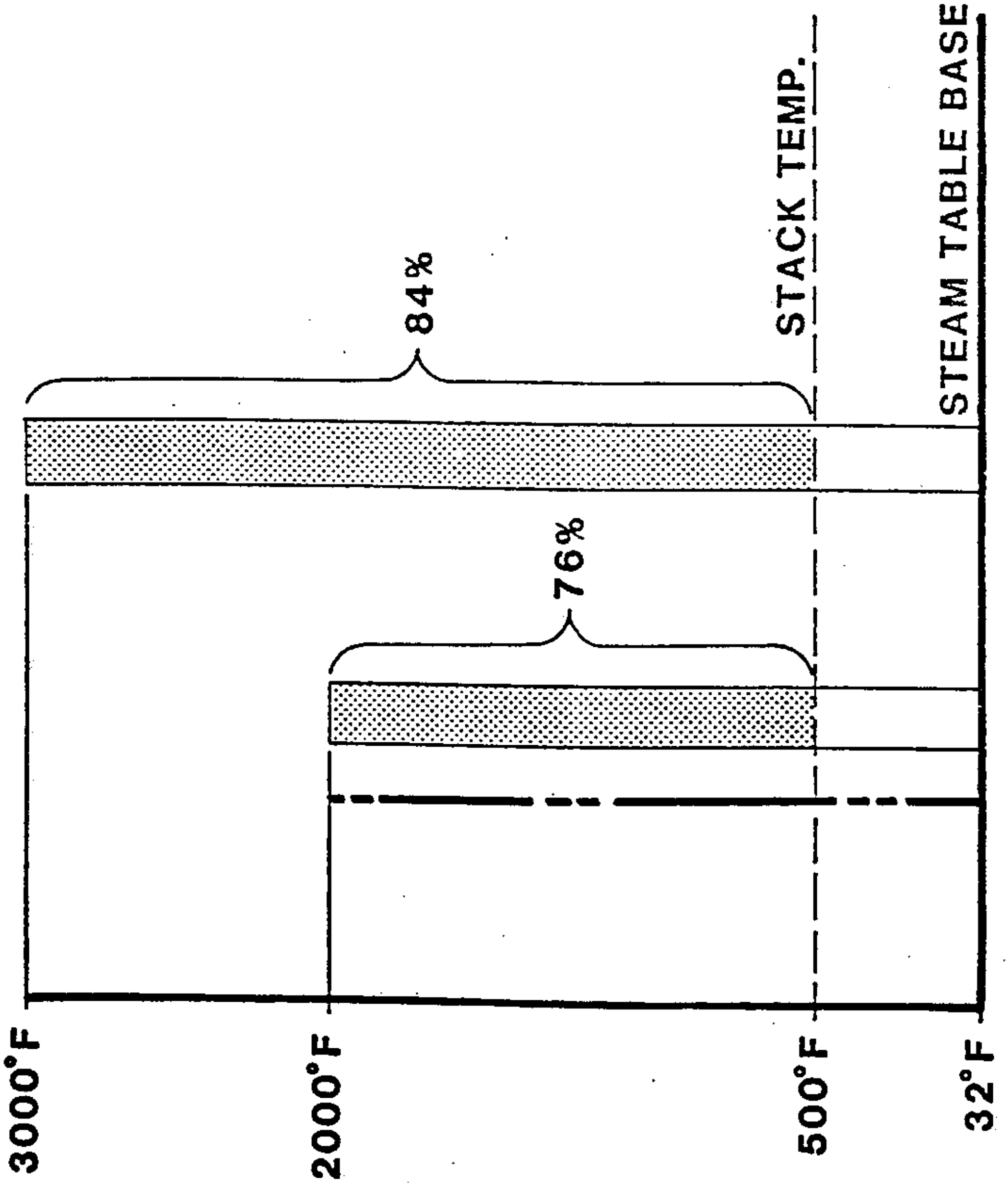


FIG. 2
COMBUSTION TEMPERATURE vs. RECOVERABLE HEAT

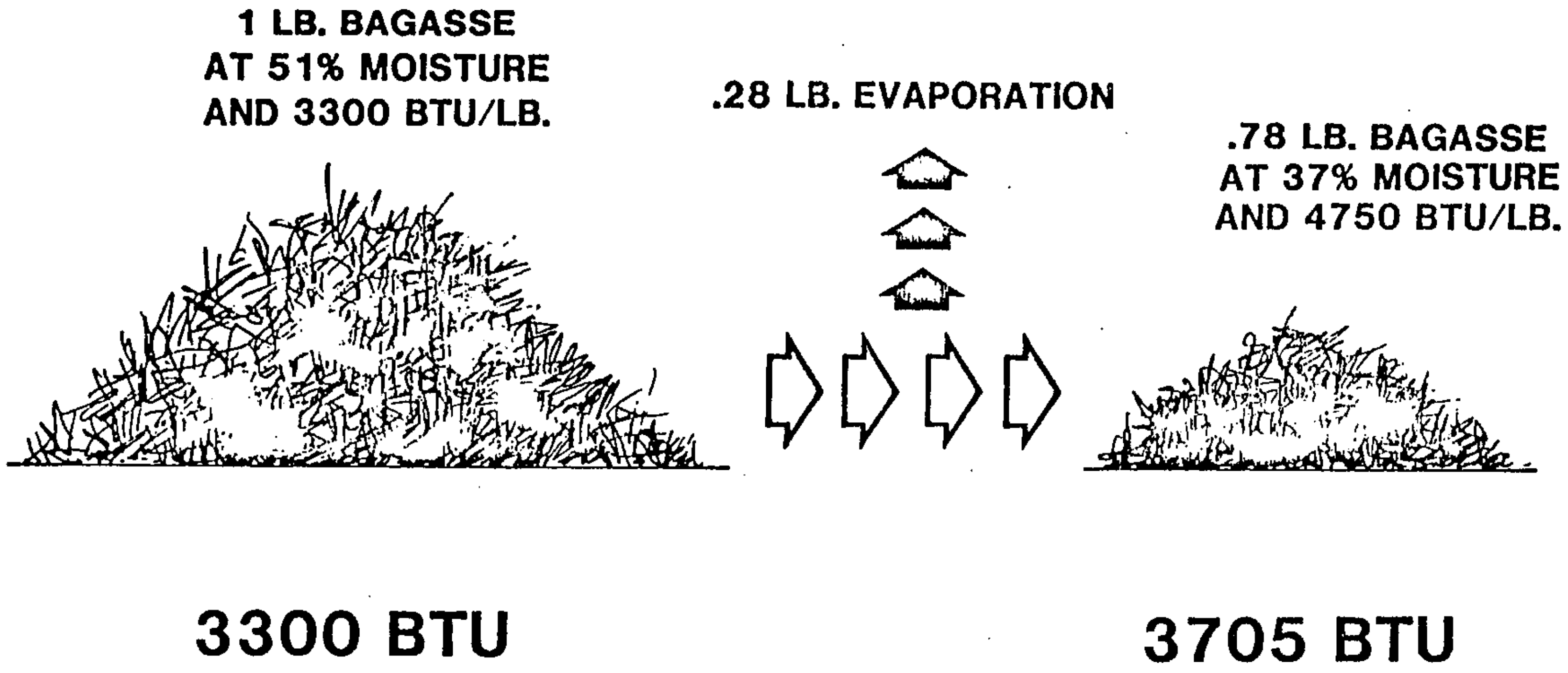

1 LB. BAGASSE
AT 51% MOISTURE
AND 3300 BTU/LB.
.28 LB. EVAPORATION
.78 LB. BAGASSE
AT 37% MOISTURE
AND 4750 BTU/LB.
3300 BTU
3705 BTU

FIG. 3

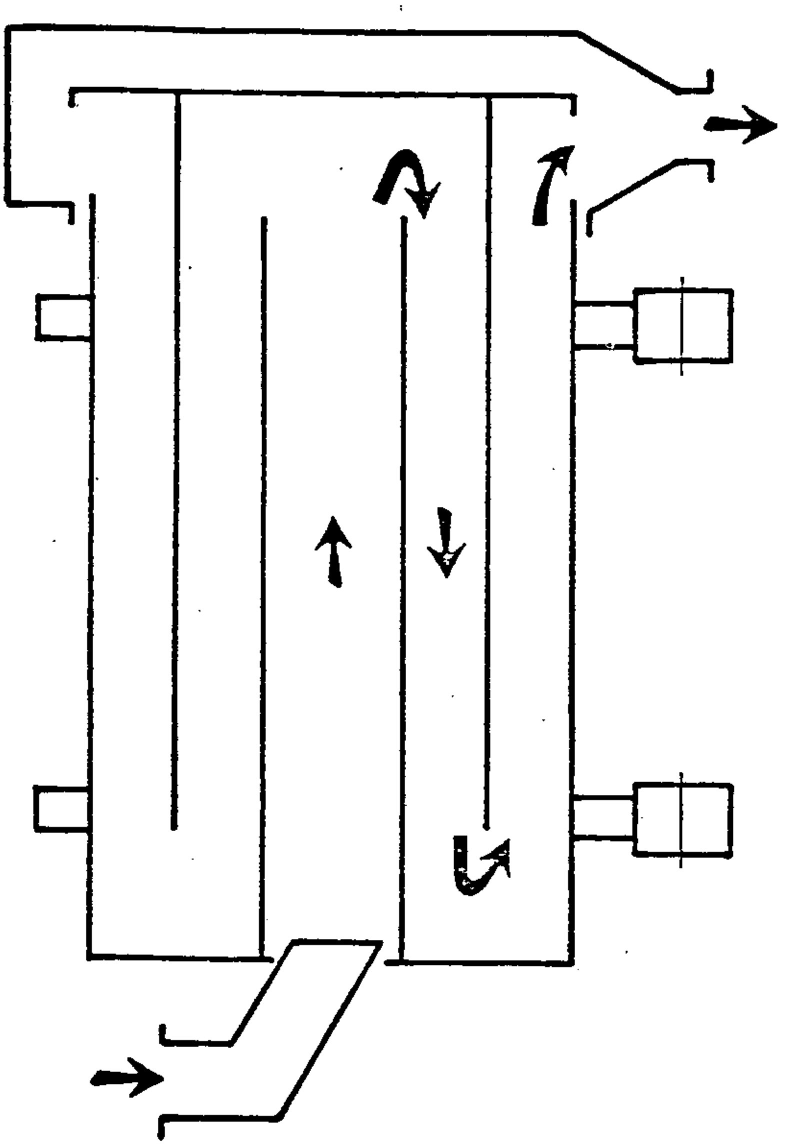
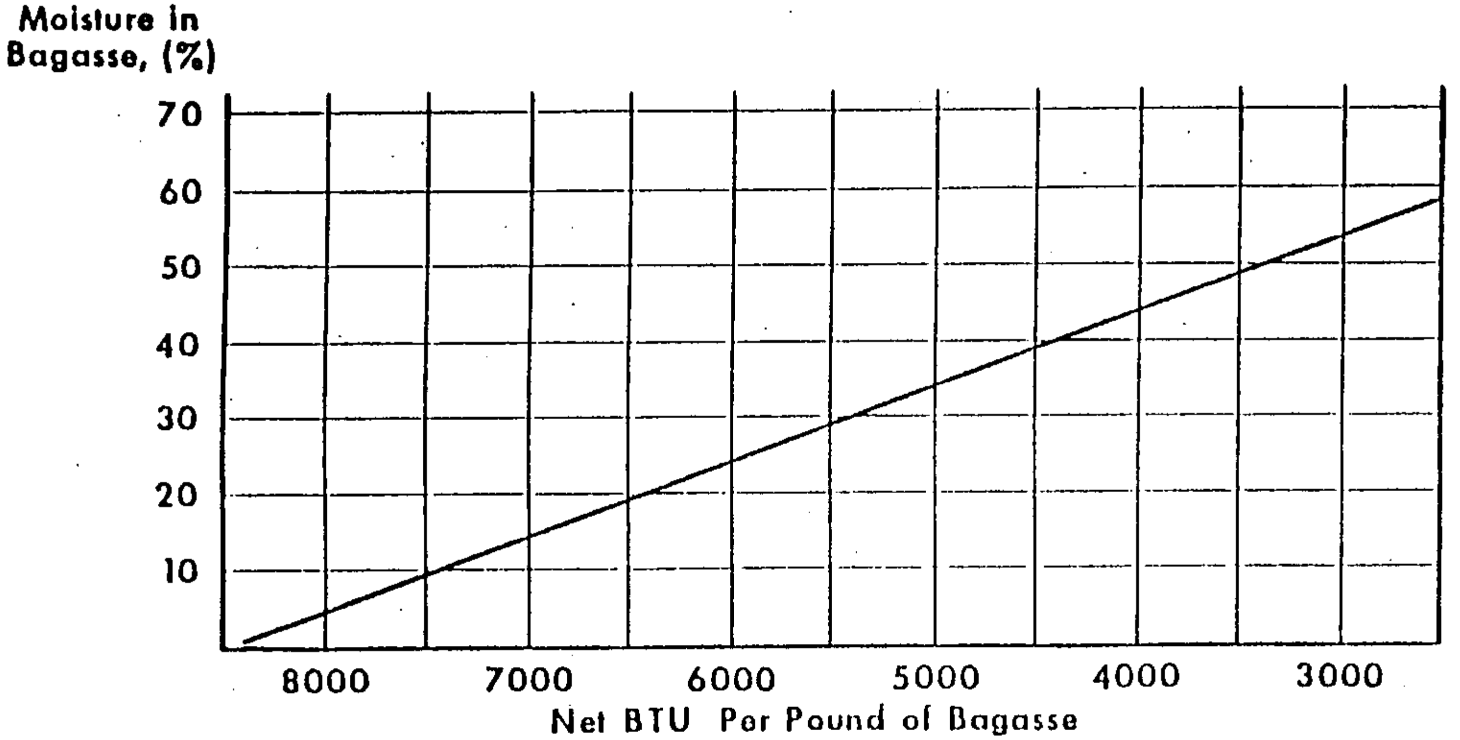


FIG. 4
THREE PASS DRYER

BAGASSE HEATING VALUE
VS.
MOISTURE CONTENT



FROM: Louisiana Bulletin No. 128
June, 1911
By: E. W. Kerr

FIG. 5

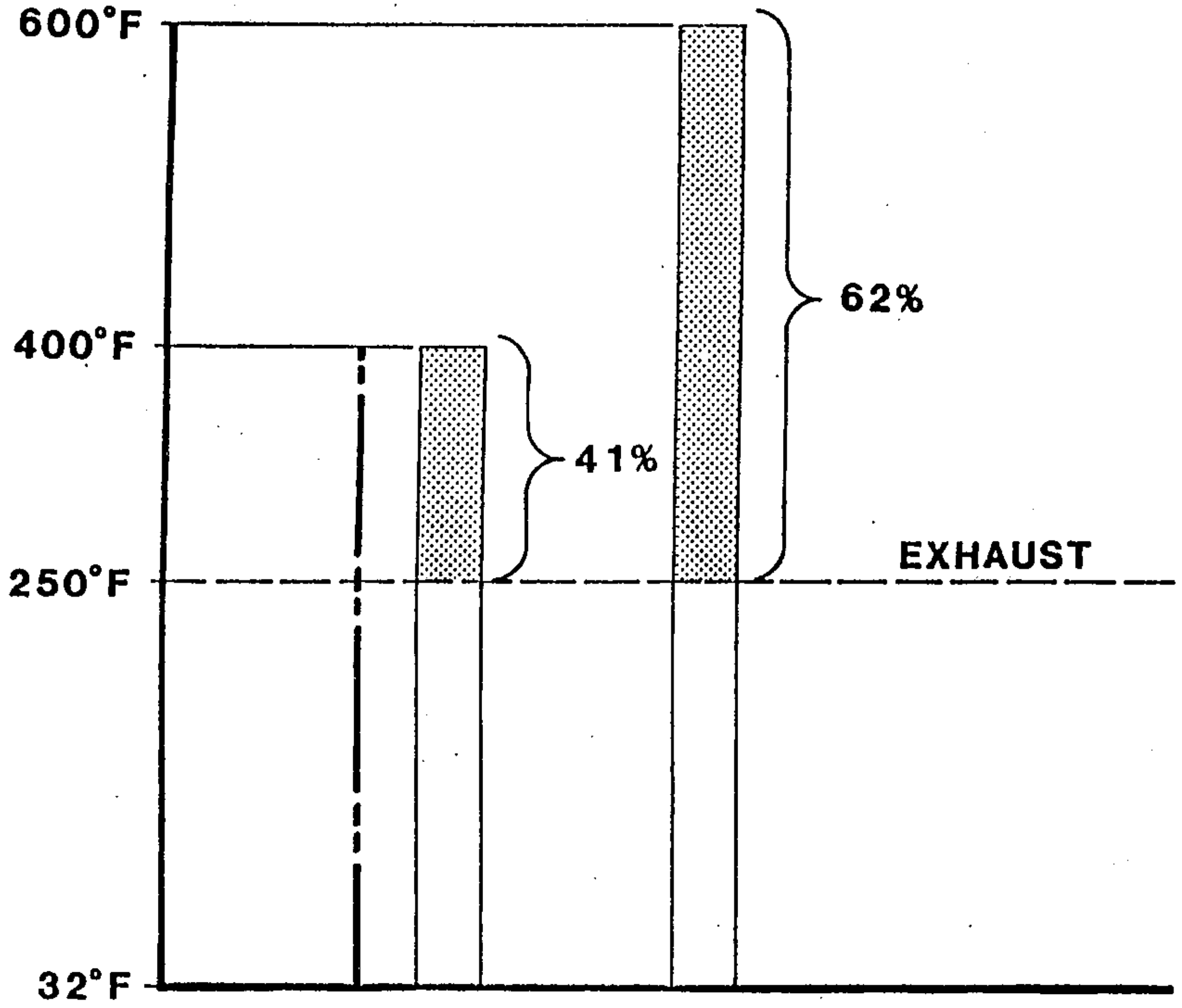


FIG. 6
WASTE HEAT TEMPERATURE vs. RECOVERABLE HEAT

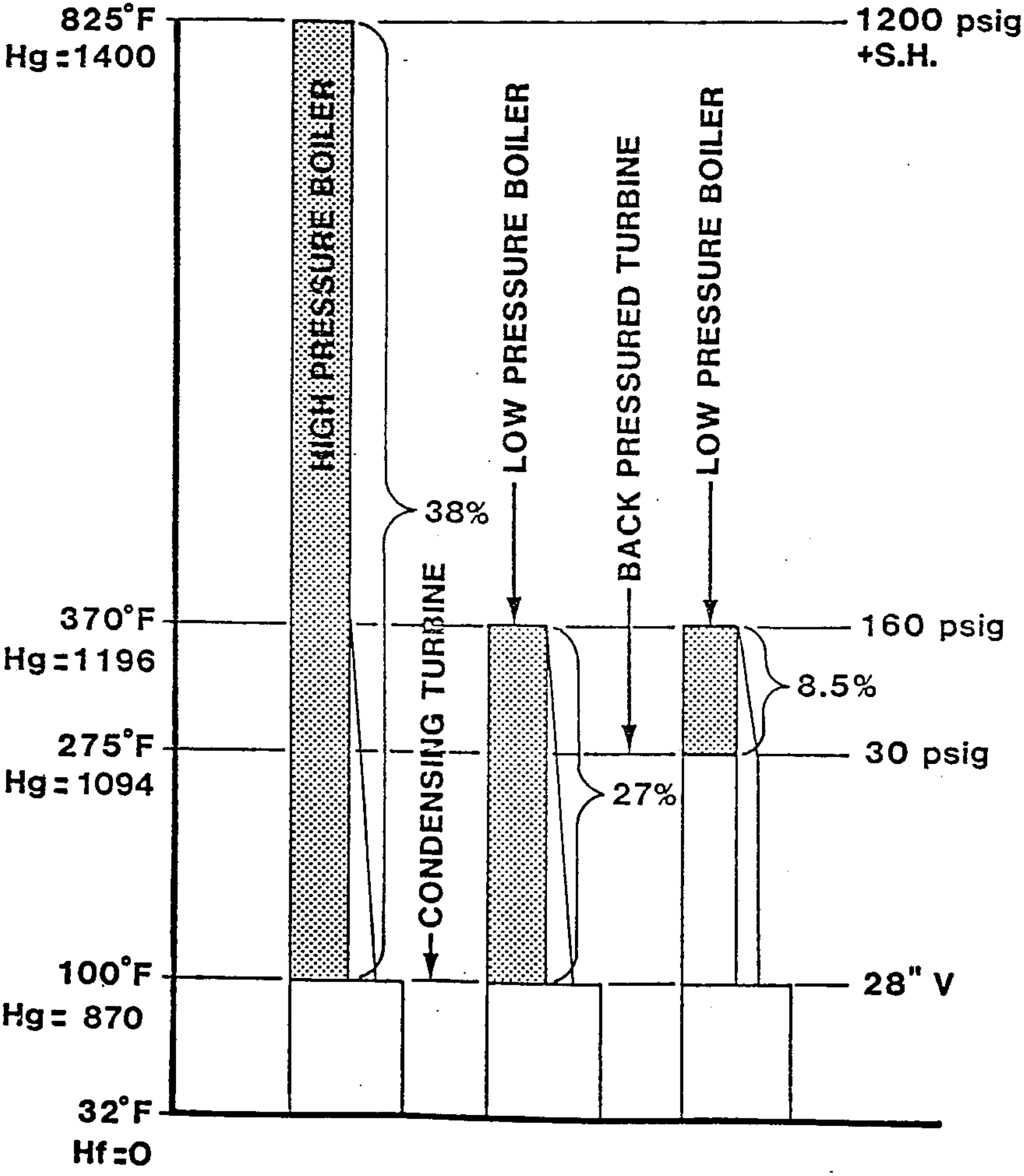


FIG. 7
STEAM TEMPERATURE vs.
RECOVERABLE HEAT

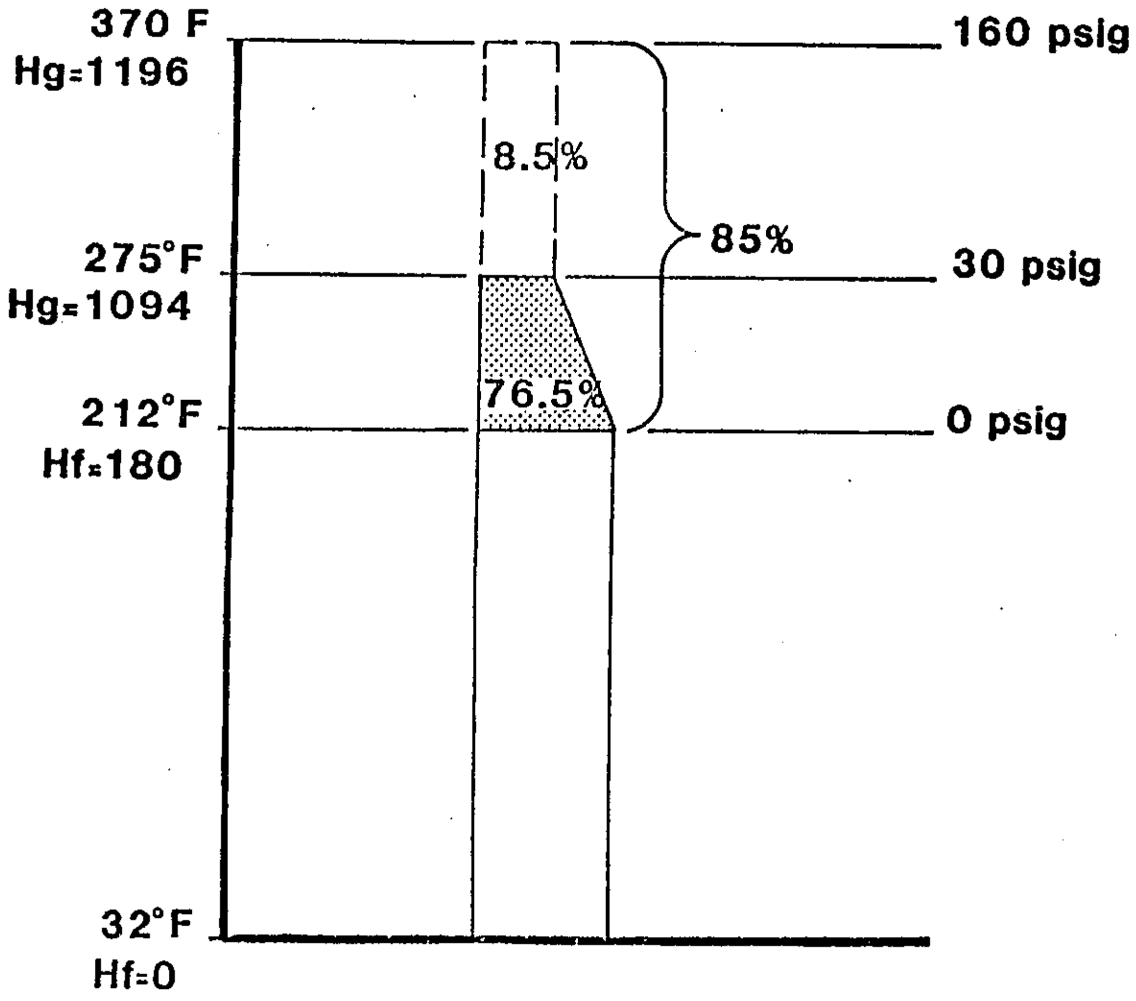


FIG. 8
ADDITIONAL HEAT RECOVERED FROM LOW PRESSURE BOILER FOR HEATING

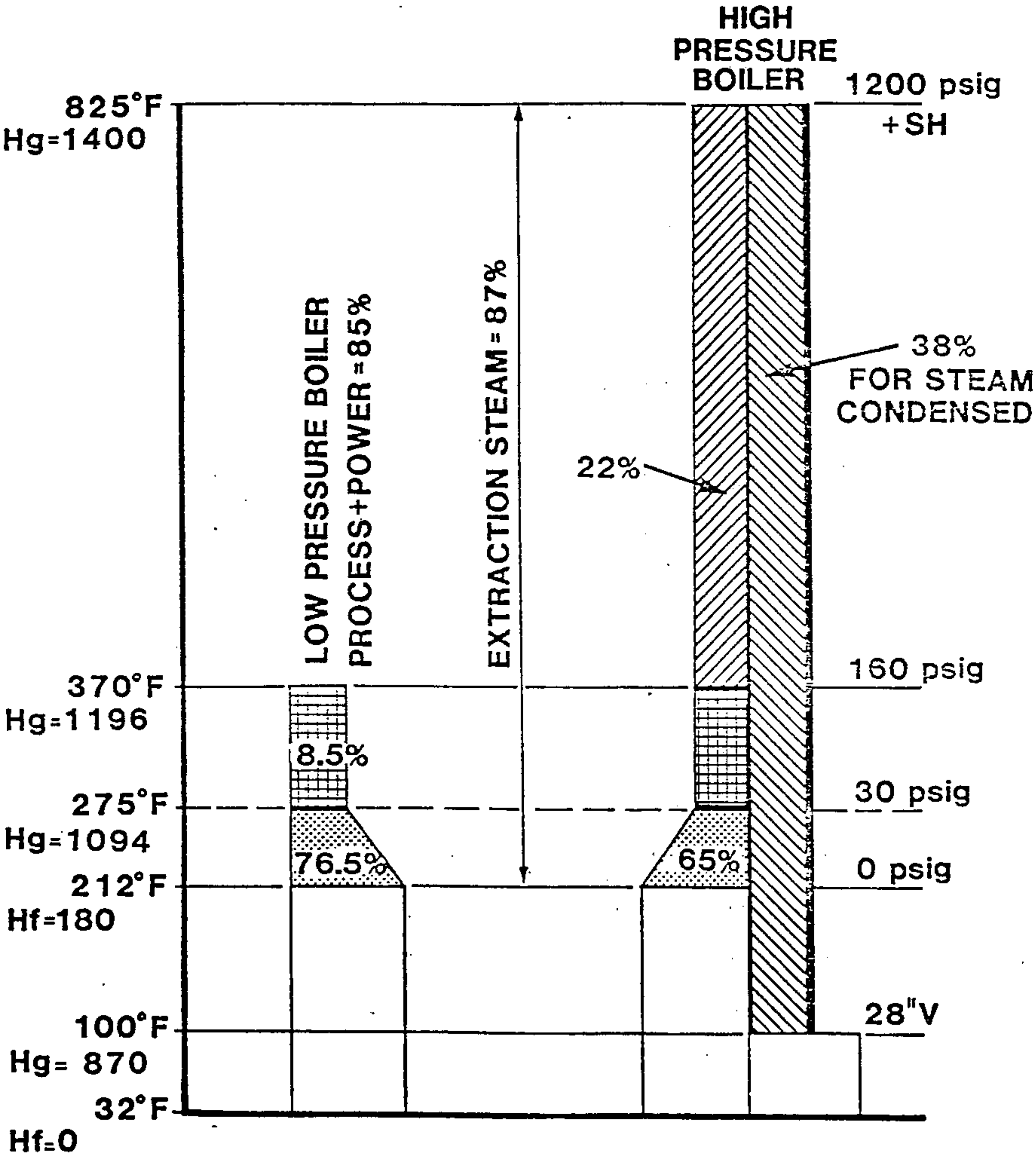


FIG. 9
RECOVERABLE HEAT
WITH COGENERATION

FUEL PREPARATION SYSTEM POSITIVE AIR SYSTEM

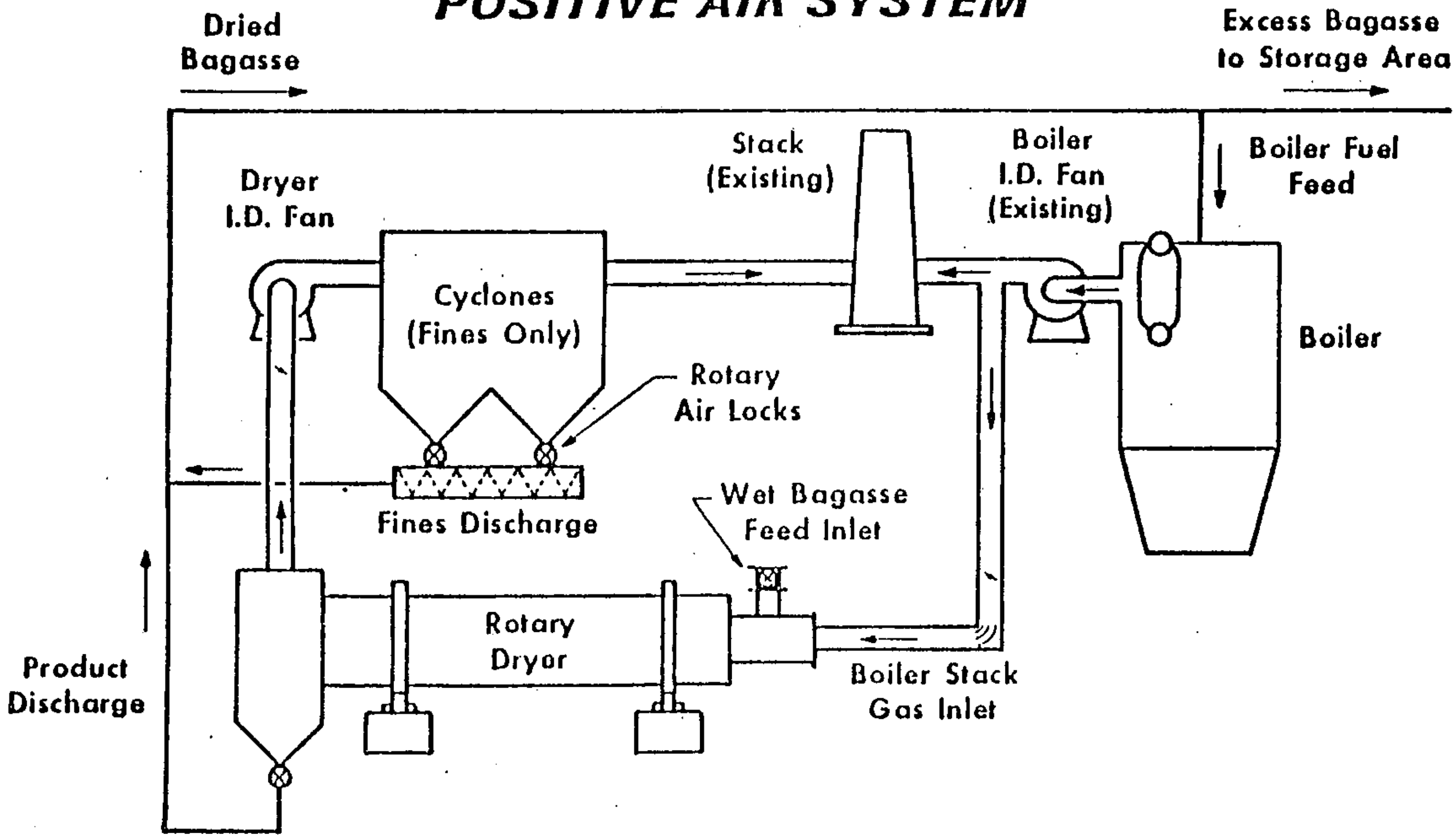


FIG. 10

UTILIZATION OF BIOMASS/OIL FUEL BLENDS IN PETROLEUM-FIRED BOILERS

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

COMBUSTION EQUIPMENT ASSOCIATES, INC.
New York, N. Y.

UTILIZATION OF BIASS/OIL FUEL BLENDS IN PETROLEUM-FIRED BOILERS

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UTILIZATION OF BIOMASS/OIL FUEL BLENDS IN PETROLEUM-FIRED BOILERS

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ABSTRACT

THE DRASTIC increase in oil prices has changed the economic value of biomass crop residues and created incentives toward increased energy recovery and power generation efficiencies. The highest efficiencies can be achieved by burning dry, powdered biomass fuels such as ECO-FUEL™ and AGRI-FUEL™ in utility boilers.

Co-firing of ECO-FUEL in suspension with oil in Bridgeport, Connecticut has already been demonstrated at up to 50% of boiler heat input with highly satisfactory results: no loss in plant efficiency, acceptable stack emissions and minimal tube fouling.

AGRI-FUEL has been produced in a CEA pilot plant in Connecticut. Indications are that dry, powdered fuels prepared from crops and crop wastes have a significant potential as a storable, transportable fuel for co-firing with oil in new and existing boilers and cement kilns.

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UTILIZATION OF BIOMASS/OIL FUEL BLENDS IN PETROLEUM-FIRED BOILERS

INTRODUCTION

BIOMASS offers a renewable alternative to petroleum oils as an energy source, especially in tropical islands, and the possibility of energy self-sufficiency.

In the past, biomass, such as bagasse and crop wastes, has been burned in boilers with the disposal of waste as the major objective, together with generating only the thermal and mechanical energy required by the sugar mill. This marriage of objectives resulted in both wasteful use of heat in the sugar mill, and inefficient recovery of energy from the bagasse. An effort to remove more energy from the bagasse would result in excess energy which the plant could not use.

The export of power from sugar mills has attracted greater interest in recent times as the price of oil increased many fold. Utilities are now becoming willing to pay for export power at rates which reflect the cost of oil, and governmental regulations are more and more being changed to include the capital cost of new power plants in the price paid for exported power.

This new economic situation has created new areas of interest, including:

- Improved efficiency of existing sugar mills to maximize the export of power.
- The outright production of fuel from biomass for transport to utilities and industry as a means of reducing dependance on oil.

INCREASING POTENTIAL FOR BIOMASS FUEL

As a consequence of increased revenues from export of power we now see an effort to use less power in the sugar mill, to increase boiler efficiency, to increase the thermal efficiency of power conversion in the mill, to employ heat recovery devices where practical, and to improve the thermal efficiency of the sugar refining process itself.

These measures have been carried out extensively in Hawaii, Florida and other places where the utilities are now required to show an active interest, whereas in the past they were only offering a pittance for excess power.

As power production rather than heat generation becomes the economic objective, increasing thermal efficiency of power generation becomes important: low pressure boilers and turbines produce only a fraction of the power, from the same heat energy, as high-pressure high superheat boilers. Drying the bagasse before firing, using stack gas heat recovery becomes attractive. Recovery of stack gas heat by air preheat economisers becomes justified.

We also see a shift toward molasses and alcohol production which results in different energy balances and economics.

Direct production of fuel from biomass, without necessary association with sugar production has become more attractive as oil prices fluctuate and continue to rise. Over the last few years, CEA has been closely following the interesting and exciting "energy cane management" concept which has been developed by the Center for Energy and Environment Research, University of Puerto Rico. The implementation of this concept would materially increase the amount of biomass available for the production of energy.

As sugar becomes a less rewarding crop, the same land can be converted to growing crops for energy. To do this, however, we must find the energy users which can burn this fuel as a partial or even full replacement for oil, since the sugar mill is no longer the major user.

As previously mentioned, sugar industry boilers historically had been designed as a bagasse incinerator, the less efficient the better, so as to dispose of all the excess bagasse. By and large, if electricity is generated with these inefficient low pressure boilers, it would require between 15 and 20,000 BTU's per KW Hr. On the other hand, if electricity is generated in a modern efficient power plant the heat rate would be in the range of about 10,000 BTU's per KW Hr. In other words, biomass burned in existing sugar mill boilers for the purpose of generating electricity rather than for the purpose of getting rid of the biomass, would waste about 50% of the energy in the biomass.

For this reason CEA has developed a fuel from biomass which can be burned in efficient utility boilers and in general act as a direct oil replacement in cement kilns or other applications.

LIMITATIONS OF SUGAR MILL COGENERATION

While cogeneration in a sugar mill has some obvious advantages to the extent that it serves the purpose of providing power and low pressure steam for the mill, the sale of excess electricity to a utility is a decidedly unattractive proposition from the utility's point of view unless such excess electricity is available in relatively large quantities at predictable and desirable times. In the case of Puerto Rico where the grid capacity is about 2000 MW, the task of accepting and absorbing relatively minute amounts of electricity from sugar mill cogenerators presents more of a problem than it's worth. Typically, a sugar mill would have an excess of 5 to 10 MW at varying and unpredictable times and the cost of dealing with it would probably be greater than the cost of the fuel oil saved, if there are any savings of fuel oil at all.

In the case of Hawaii or other places where efficient biomass power plants are being built for the specific purpose of generating excess electricity, the situation is somewhat different and the efficiency of those boilers and power plants approximates the efficiency of a regular modern power plant. While it is true that under the new energy regulations coming out of Washington, the utilities will have to buy excess electricity from cogenerators, it would be much more desirable for excess biomass to be converted into a comparable, storable and transportable fuel so that it can be burned in more efficient applications so that the waste of biomass energy can be minimized.

You may be aware of the fact that CEA, jointly with CEER-UPR, has applied to the U.S. Department of Energy (DOE) for a grant to finance a feasibility study that would document such a biomass fuel concept. We look to utilities and industries, such as the cement industry, as major users since they consume energy all the time, not being seasonally affected. Industry, while an interested customer for biomass fuel, could not consume the full potential production, hence may be the tail of the kite.

So far, so good: We see a great potential for biomass as an alternative to petroleum in power generation, especially in efficient boilers with efficient power cycles. What stands in the way? Are there any reasons why biomass cannot be burned as an alternate fuel, replacing oil?

BIOMASS CONSTRAINTS AS AN ALTERNATIVE FUEL

There are many reasons why this hasn't been widely done, some trivial, some surmountable, and some of which limit the range of application. These include the following:

(a) Boilers designed for one fuel cannot necessarily burn fuels with different characteristics.

(b) Boilers designed for one fuel cannot necessarily burn two different fuels at once.

(c) The ash content of biomass fuels requires flyash collectors not needed for petroleum firing.

(d) Tube-fouling, slagging and erosion are caused by biomass fuels; boilers designed for oil many not be able to tolerate this.

(e) Furnace and superheater temperatures are affected by the nature of the fuel: This is why the fuel affects boiler design.

(f) Control of boilers burning multiple fuels may be difficult, inefficient or ineffective, if not impossible.

(g) Reliable production of power requires a dependable supply of fuel, and reliable combustion. This often means that oil must be burned whenever the biomass fuel is insufficient, whether for an instant, an hour, a day, week or month.

(h) Oil can be readily stored. Biomass fuels must also be stored to assure steady supply to follow power demand.

There are obviously many problems and questions which can be raised. What proof or answers can we offer?

There are many bagasse-burning plants which demonstrate that oil can be used to sustain the combustion of bagasse in sugar mill boilers. Some modern bagasse-burning boilers use high steam pressures and temperatures. There are reports that some of these boilers have experienced tube failures when operated near their ratings when oil is fired, attributed to the hotter flame produced by oil. These faults are probably correctable, but the contradiction between wet and dry fuels remains.

There are reports that, with substantially improved control systems, bagasse firing with oil assist can generate reliable exportable power. There are reports that drying the bagasse before firing improves reliability and reduces the need for supplementary oil. These reports indicate oil can be co-fired with bagasse to a certain extent in sugar mill boilers associated with fairly efficient power cycles, and that this course of action will continue to progress.

BIOMASS AS A PREPARED FUEL

Bagasse is a prepared waste fuel. The grinding was needed to extract the sugar. The product is over 50% water and contains large fibers which are slow-burning, needing a large combustion chamber to minimize char and black particulate. It is reasonably stable. Other types of biomass would have to be ground to permit feeding to the boiler. Their variable moisture content would cause problems in firing the boiler and maintaining reliable, efficient power production.

We can draw an analogy here with the urban waste-to-energy experience of recent years. Consider the following points:

- Municipal Solid Waste (MSW) and Refuse-Derived Fuel (RDF), are essentially biomass (albeit heavily contaminated).
- Experience with RDF has shown that moisture, ash content, and particle size are problems in proportion to their extent in the fuel.
- Experience has shown that dry powdered RDF (ECO-FUEL™) can be burned in a utility boiler firing with beneficial results. The boiler was for coal, and had adequate emission controls (ESP).
- Wood has been burned in bark boilers with or without oil.
- Ground wood and sawdust have been fired in an industrial packaged boiler designed for oil, with and without oil assist.

The above considerations indicate that dry, powdered biomass-derived fuels can be burned in industrial packaged boilers and utility boilers much more readily than wet, unprepared fuels.

The principal reasons for this are the following:

- Small particles ignite quickly (at low temperatures).
- Biomass is highly volatile (burns like gas).
- High combustion temperatures and rapid combustion permit smaller combustion chambers.
- The ash in biomass is fine particulate which does not cause excessive slagging, fouling or tube erosion when properly fired.

What we see here is that highly processed biomass fuels can be substituted for petroleum oil in some existing boilers and certainly in properly designed boilers. A dry powdered fuel is much more compatible with oil firing than a large-particle moist fuel.

CEA has developed processes to reduce both MSW and crop wastes such as bagasse to dry powdered fuels which are storable, transportable, and readily conveyed by conventional powder handling systems. They open up entirely new potentials for biomass-to-energy.

SLIDE LEGENDS FOR CEA PROCESSES

A few slides will illustrate these plants:

Figure 1. The Bridgeport MSW To ECO-FUEL Process

This process has trommel screens to remove glass, magnets to remove metals, and an air classifier/dryer to remove moisture prior to final milling to ECO-FUEL II, which is similar to pulverized coal.

Figure 2. The Bridgeport ECO-FUEL II Storage And Transfer System

Here we see conventional pneumatic conveying blowers used to convey the powdered fuel brought from the plant in trucks to silos, and from the silos direct to the burners, under precise control of feed rates. Three such systems serve three burners.

Figure 3. The United Illuminating Boiler

This BEW boiler has cyclone furnaces which burn the fuel prior to the main furnace. These remove about 10% of the fuel ash. The remainder of fuel ash is removed by the ESP, after the air preheaters. This boiler needs only 10,000 BTU/KW Hr, which means the power is produced at about 30% thermal efficiency. (Low pressure boilers such as in sugar mills may require 16 to 20,000 BTU/KW Hr).

Figure 4. AGRI-FUEL Pilot Pilot Plant, Glenbrook, Connecticut

Figure 5. Physical Characteristics of MSW, RDF, ECO-FUEL II and AGRI-FUEL

This table shows that the heating value of MSW, RDF, ECO-FUEL and AGRI-FUEL is almost the same on a moisture and ash-free basis. The moisture and ash in the fuel determines the "dead weight."

Figure 6. Boiler Efficiency Versus Moisture

These slides show how much moisture and ash reduce heating value, and reduce boiler efficiency.

Figure 7. Combustion Characteristics of Coal, Oil and ECO-FUEL

This slide shows the rapid release of energy from ECO-FUEL to be similar to that of oil.

Figure 8. Packaged Boiler Burning Powdered Wood

Boilers of this type, designed basically for oil firing, have been used to burn sawdust and ground wood without major modification, when equipped with double-vortex and other suitable burners.

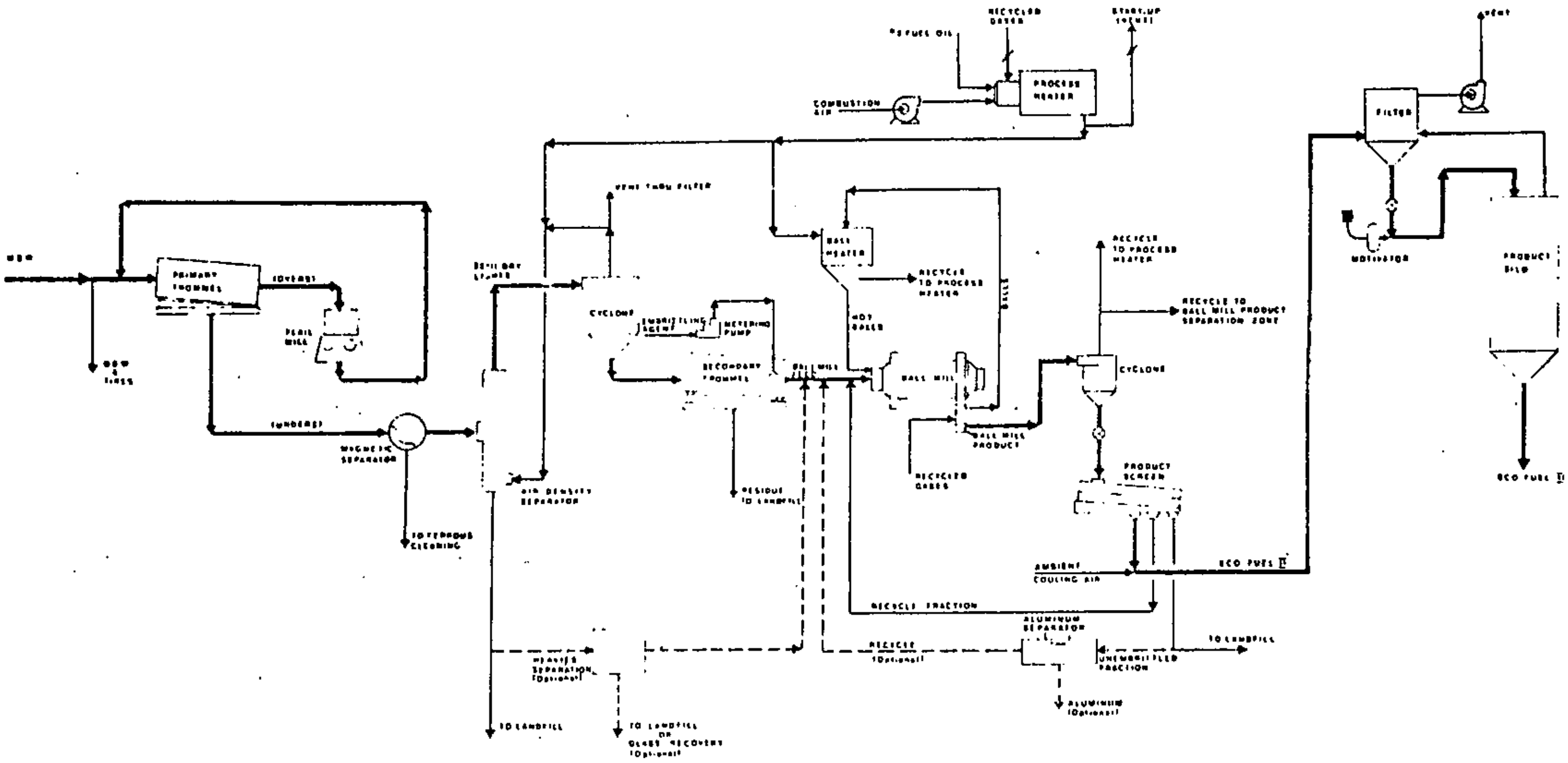
Figure 9. Fuel Preparation Plant for Wood Waste

Figure 10. Histograms of Emissions of Fuels

SUMMARY

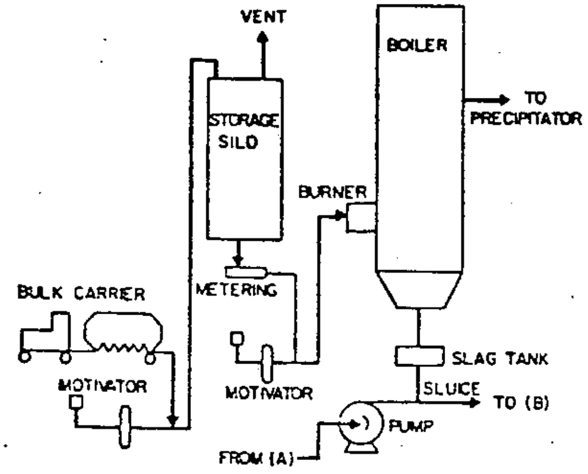
Past practice has been to burn crop wastes inefficiently, with minimum processing. As the cost of oil increases, economics dictate investment in more drying and size-reduction of biomass wastes and ultimately toward production of dry, powdered biomass fuels such as ECO-FUEL and

AGRI-FUEL, which can be burned with or without oil in boilers essentially designed for oil. This new technology is still in the state of development but has already been partially demonstrated.

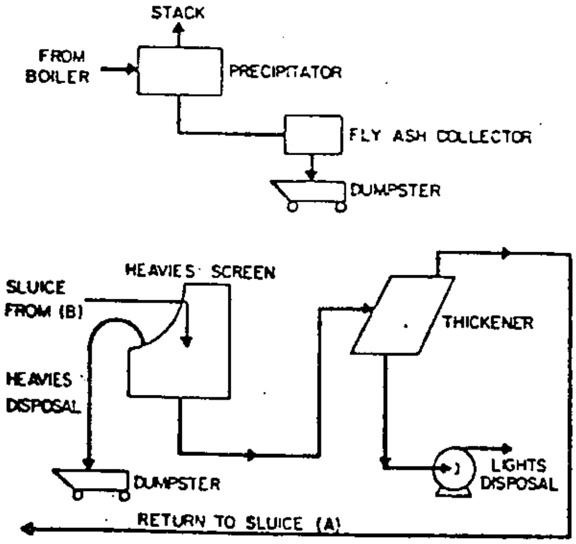


FLOWSHEET OF FLAIL MILL LINE

FIGURE 1 : The Bridgeport MSW to ECO-FUEL Process

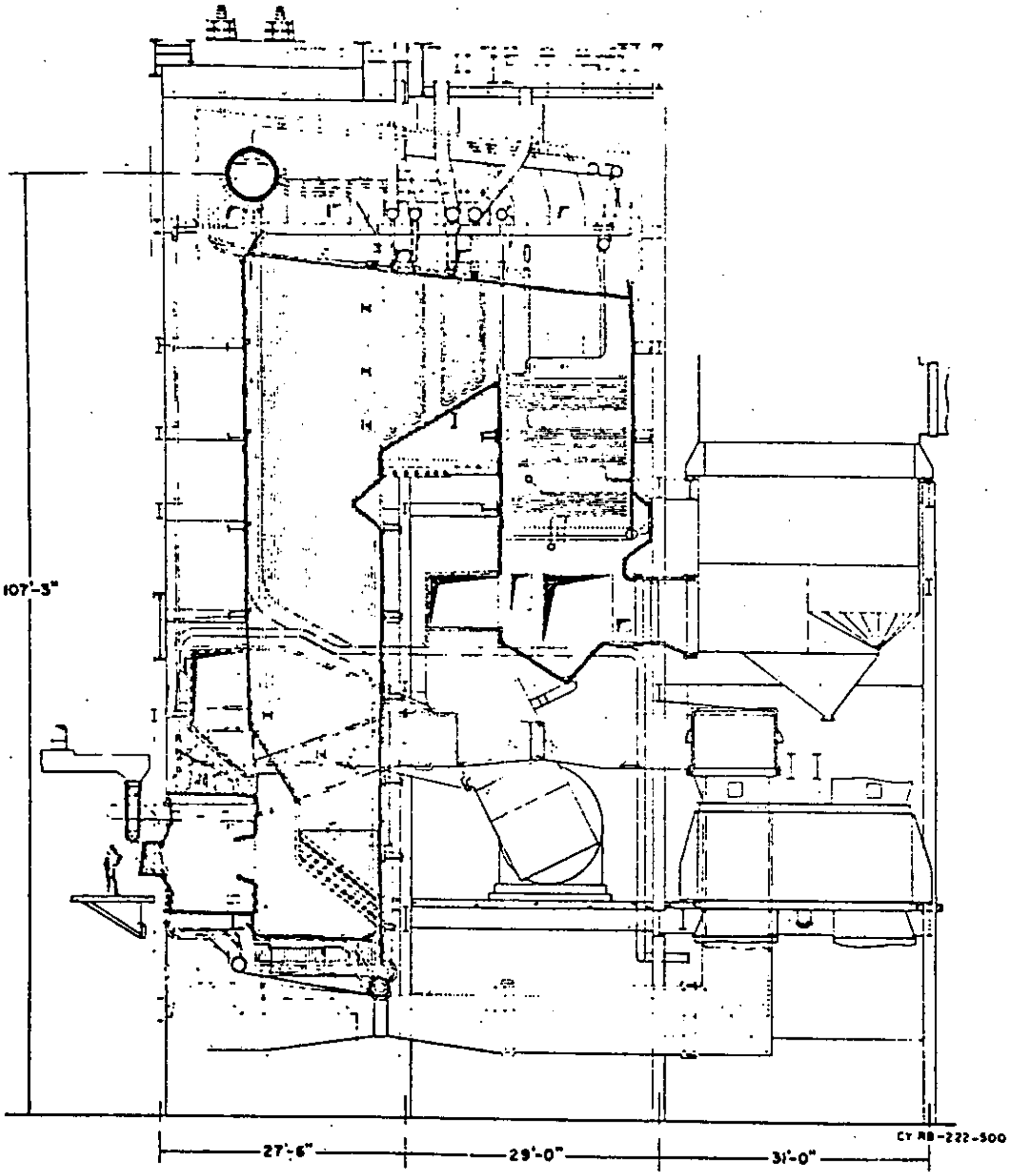


FUEL HANDLING SYSTEM



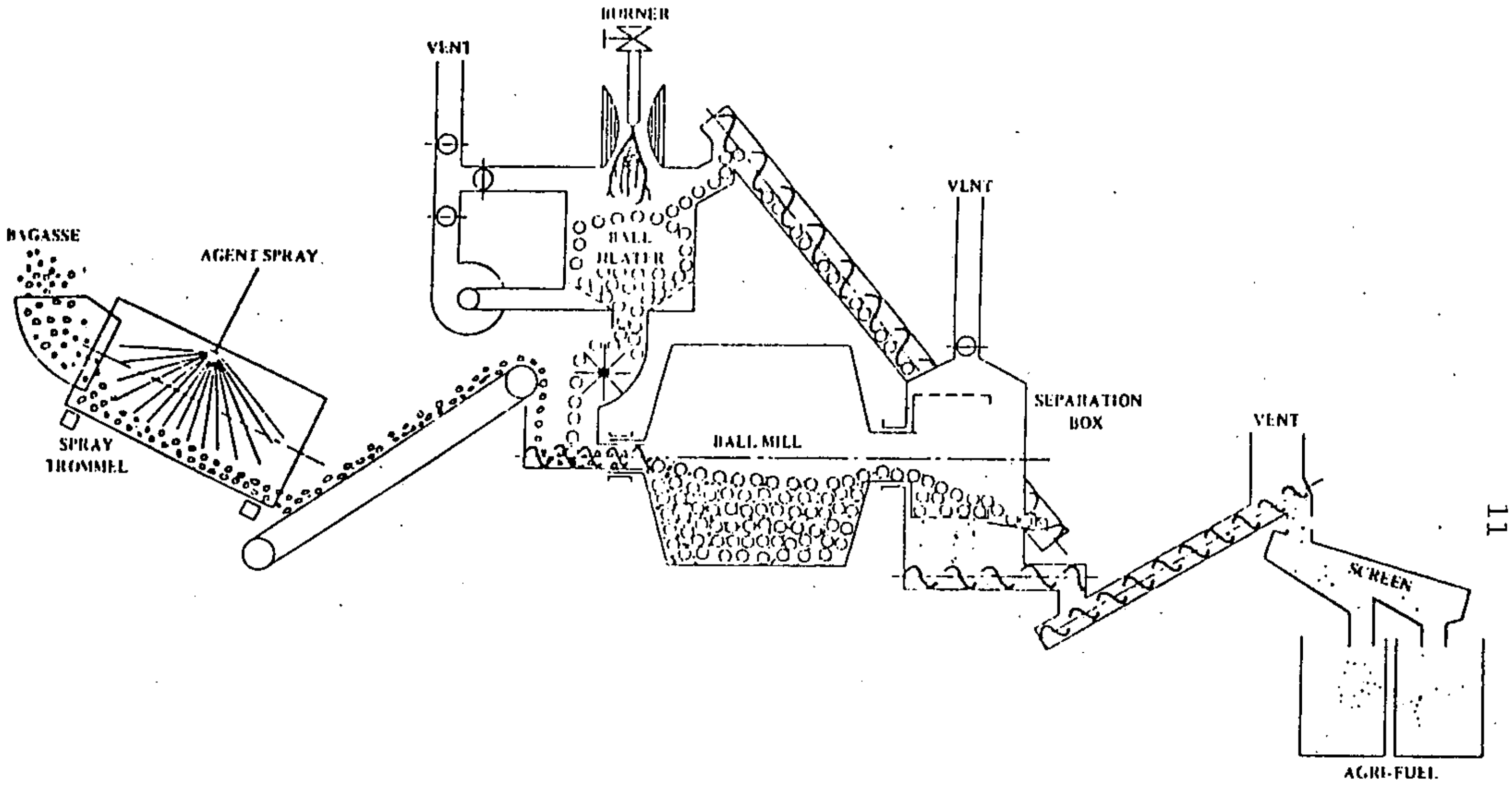
ASH REMOVAL SYSTEM

FIGURE 2: The Bridgeport ECO-FUEL II Storage and Transfer System



ELEVATION SECTION OF UTILITY BOILER AT UNITED ILLUMINATING COMPANY
BRIDGEPORT HARBOR STATION

FIGURE 3: The United Illuminating Boiler



NOTE: THIS PILOT PLANT IS CURRENTLY IN OPERATION AND WILL BE USED TO VERIFY ANALYTICAL DATA

FIGURE 4: AGRI-FUEL Pilot Plant, Glenbrook, Connecticut

FIGURE 5: Comparison of Fuel Properties

(dry basis)	Pine Bark	Oak Bark	Western Coal	Penn. Coal	ECO-FUEL	AGRI-FUEL	Resid. Oil
Proximate							
Volatile	72.9	76.0	43.4	37.7	74	83	
Fixed Carbon	24.2	18.7	51.7	52.2	13	15	
Ash	2.9	5.3	4.9	10.1	12	1.1	.5
Ultimate							
Hydrogen	5.6	5.4	6.4	5.0	5.7	5.0	11
Carbon	53.4	49.7	54.6	74.2	42	43.9	88
Sulfur	.1	.1	0.4	2.1	.7	.2	1
Nitrogen	.1	.2	1.0	1.5	.6	0.46	
Oxygen	37.9	39.3	33.8	7.1	29.0	48.8	
Heating Value	9030	8370	9420	13,310	8200	8132	18,000
Ash Analysis							
SiO_2	39	11.1	30.7	49.7	50.7	21.9	
Fe_2O_3	3	3.3	18.9	11.4	18.6	9.9	
TiO_2	.2	0.1	1.1	1.2	-	-	
Al_2O_3	14	0.1	19.6	26.8	11.3	2.8	
Mn_3O_4	-	-				1.3	
CaO	25.5	64.5	11.3	4.2	8.0	-	
MgO	6.5	1.2	3.7	.8	1.2	29.0	
Na_2O	1.3	8.9	2.4	2.9	5.8	0.6	
K_2O	6.0	.2	-		-	-	
SO_3	.3	2.0	12.2	2.5	2.2	-	

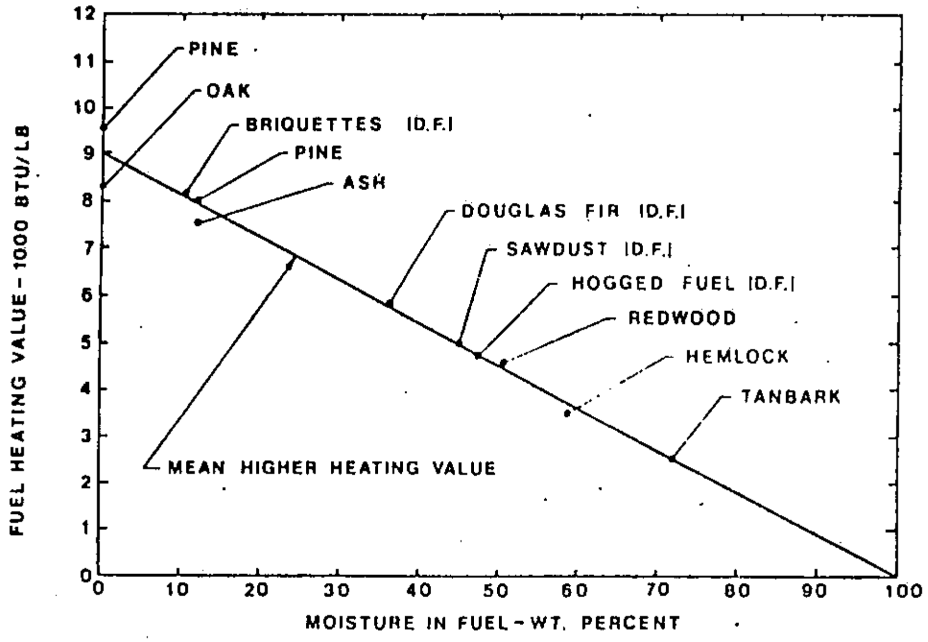
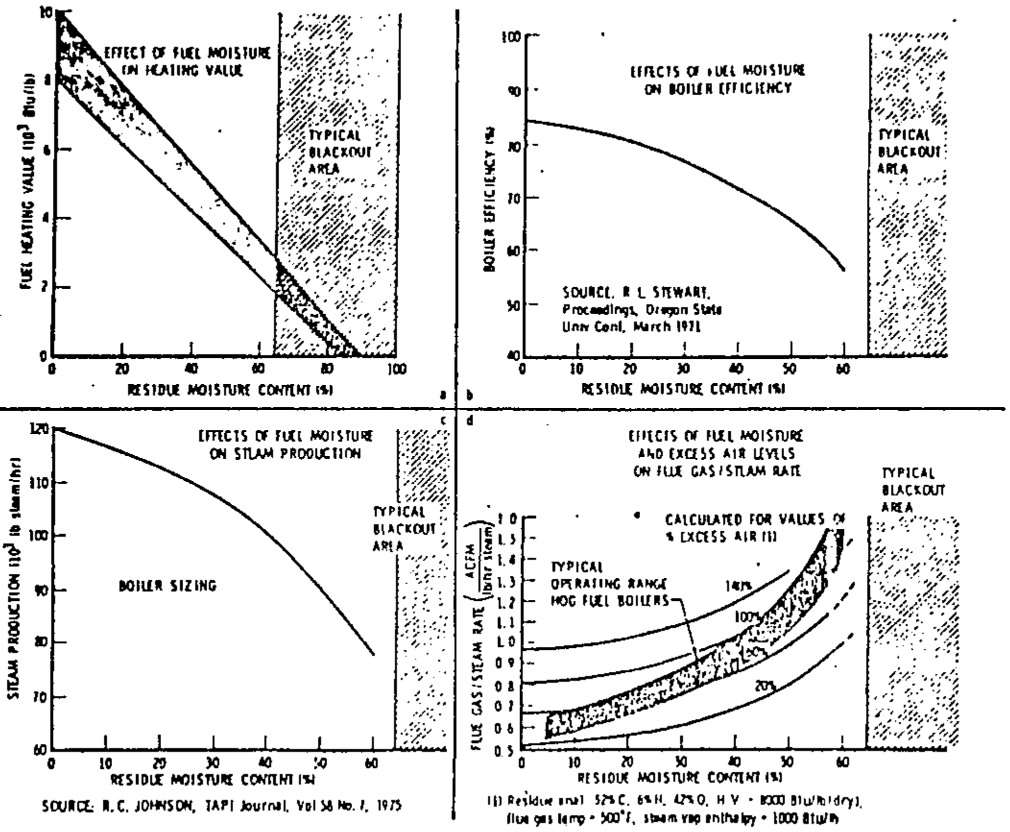


Figure 6.--Higher heating value of wood fuel.

FIGURE 6: Heating Value of MSW, RDF, ECO-FUEL and AGRI-FUEL Versus Moisture and Ash



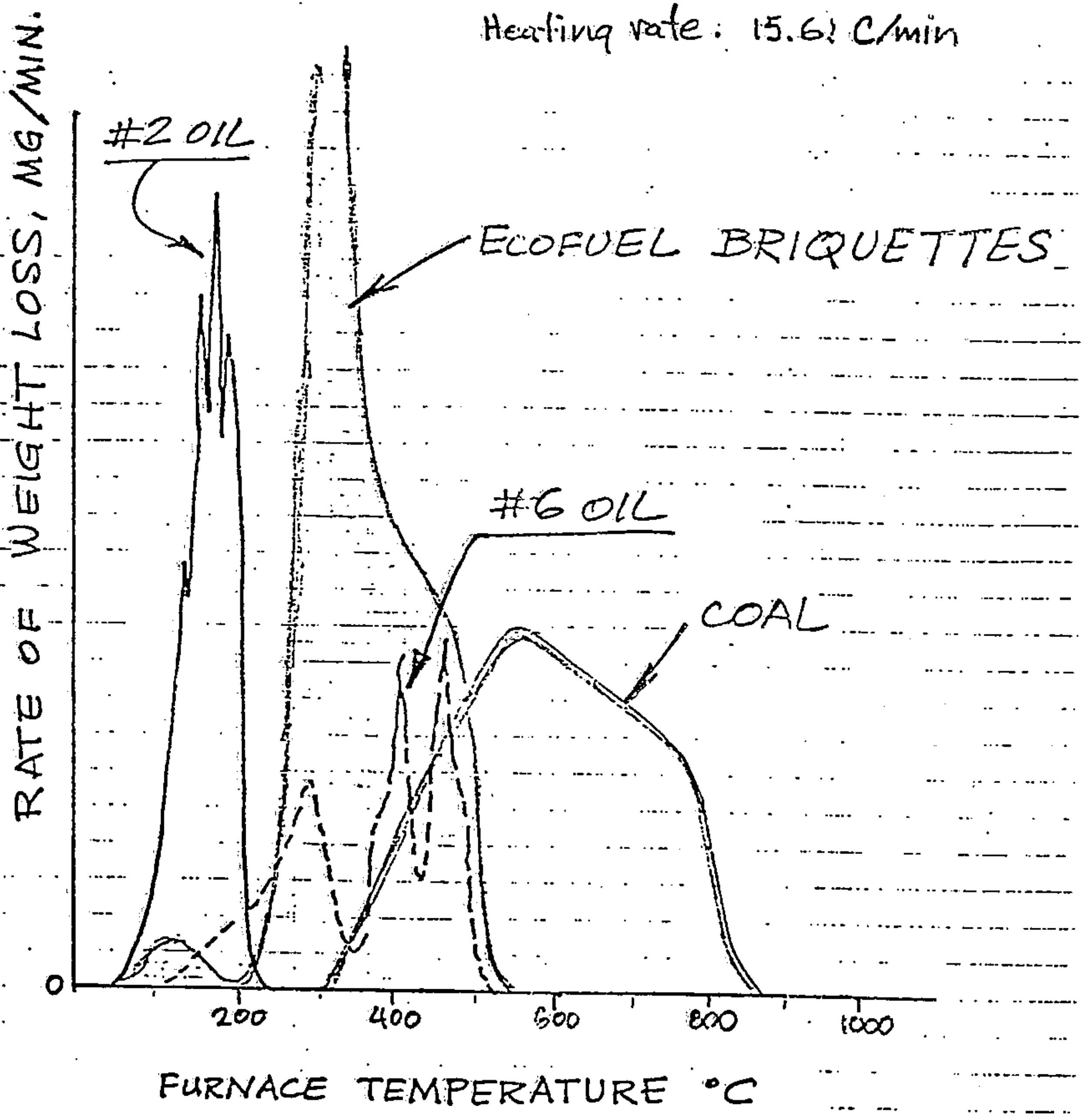
SOURCE: R. L. STEWART, Proceedings, Oregon State Univ Conf, March 1971

SOURCE: R. C. JOHNSON, TAPI Journal, Vol 58 No. 7, 1975

(1) Residue anal 52% C, 6% H, 42% O, H.V. = 8000 Btu/lb (dry), flue gas temp = 500°F, steam vap enthalpy = 1000 Btu/lb

Figure 7.--Residue Fuel Moisture

FIGURE 7: Boiler Efficiency Versus Moisture



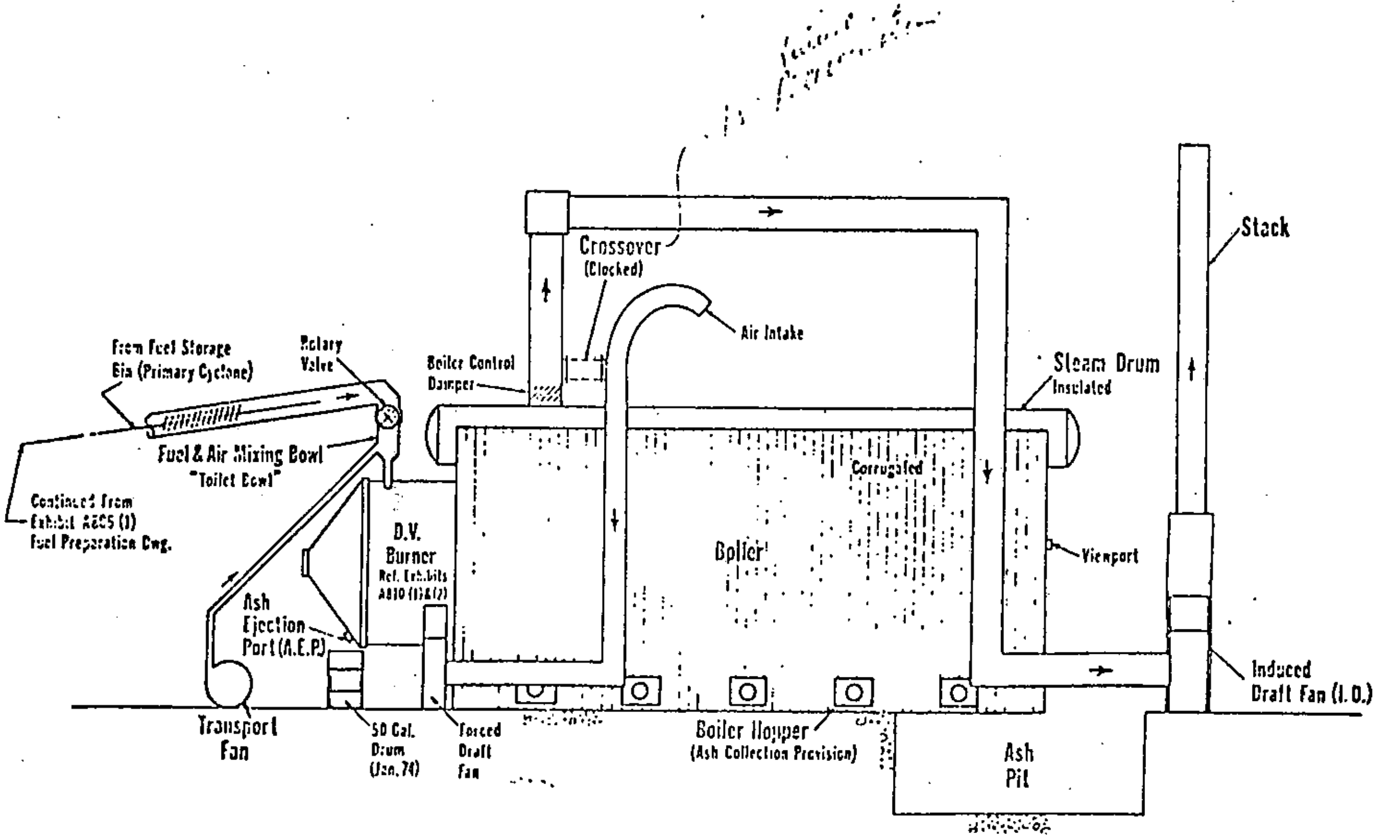
BURNING PROFILES OF FUELS

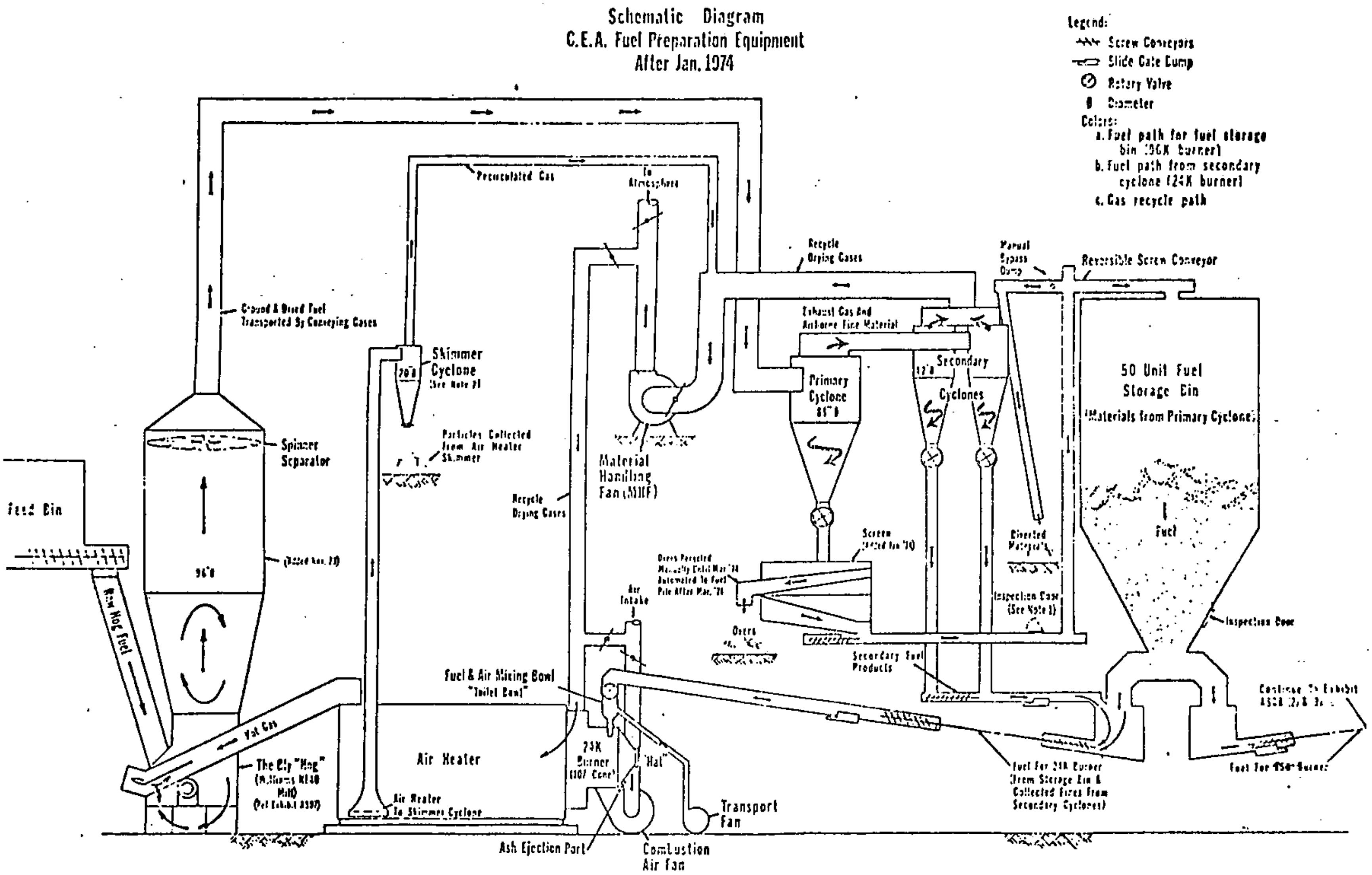
Babcock & Wilcox

FIGURE 8: Combustion Characteristics of Coal, Oil and ECO-FUEL

FIGURE 9: Packaged Boiler Burning Powdered Wood

96K DV Burner
107' Configuration On Boiler
Oct. '73 - Jan. 1974





Notes:
1. Injection point of Klamath Falls fuels. (Used Oct. '73 & Feb. '74)
2. All cyclones ref. exhibit A509

FIGURE 10: Fuel Preparation Plant for Wood Waste

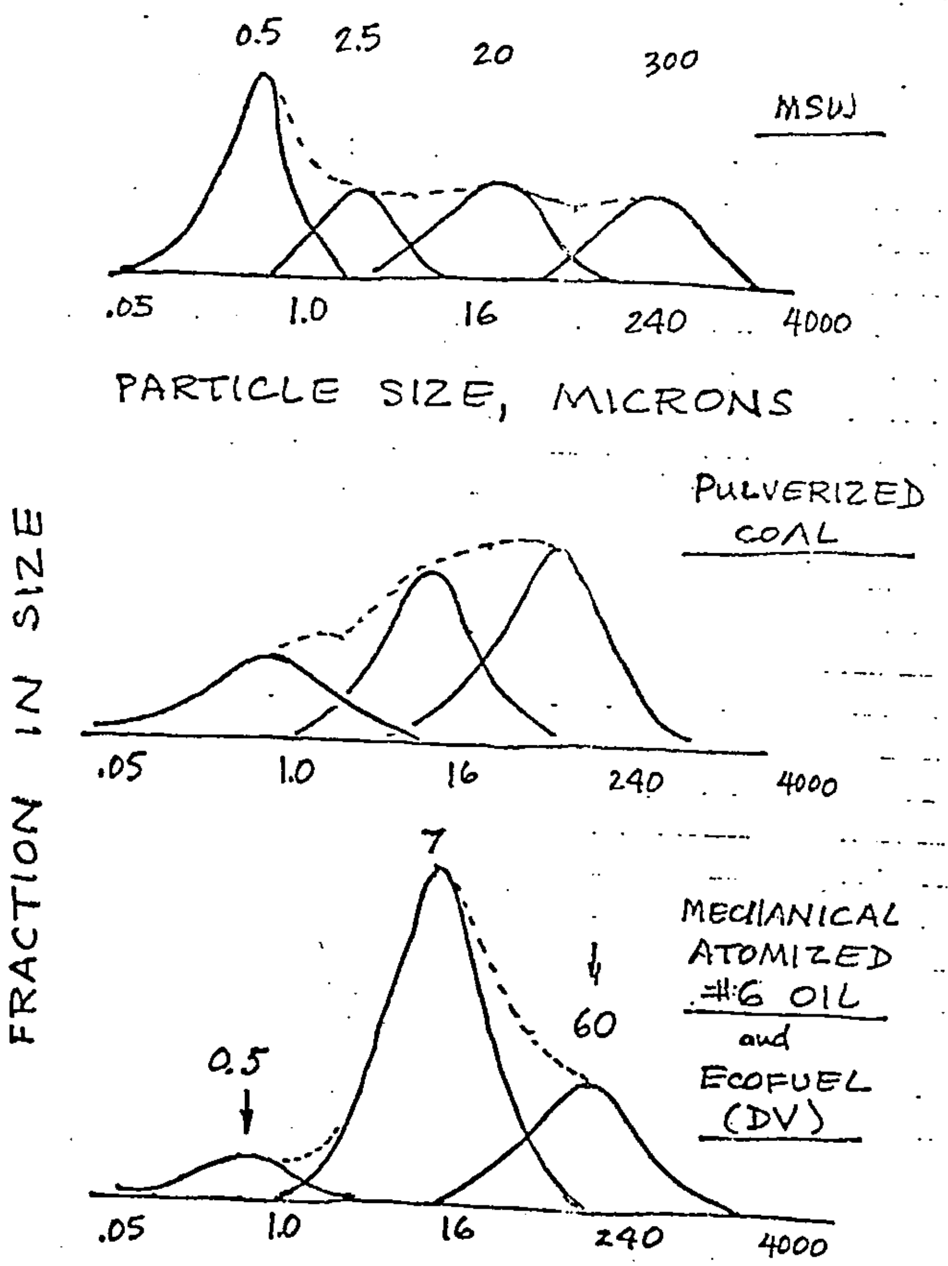


FIGURE 11: HISTOGRAMS OF EMISSIONS OF FUELS

PREPA ANALYSIS OF FOSSIL, FOSSIL/BIOMASS, AND BIOMASS BOILER FUEL OPTIONS

Presented To the Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
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Contributed By

THE PUERTO RICO ELECTRIC POWER AUTHORITY
Planning and Engineering Division
San Juan, Puerto Rico

PREPA ANALYSIS OF FOSSIL, FOSSIL/BIOMASS, AND BIOMASS BOILER FUEL OPTIONS

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PREPA ANALYSIS OF FOSSIL, FOSSIL/BIOMASS AND BIOMASS BOILER FUEL OPTIONS

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ABSTRACT

ELECTRICITY costs have risen to unprecedented levels in Puerto Rico during recent years because of increases in the price of imported oil. Because of this fact the Puerto Rico Electric Power Authority decided to use an alternate fuel for its next generating unit and is analyzing other sources of energy for possible utilization in the near future.

In this study we present some of the advantages and disadvantages of these alternate sources of energy which come about when making a fuel utilization decision. The discussion is divided into three parts: (a) Alternate sources for base load units; (b) alternate sources which could serve as backup fuel to these units; and (c) strictly bagasse-fired units.

We conclude that, although there are problems and obstacles in these alternate sources of energy, these are modest in comparison to the problems surrounding oil, at present and in the future.

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PREPA ANALYSIS OF FOSSIL, FOSSIL/BIOMASS AND BIOMASS BOILER FUEL OPTIONS

INTRODUCTION

ELECTRICITY costs have risen around 150 percent during the last six years in Puerto Rico (1). This is strictly due to the fact that 99 percent of our electricity is generated via thermoelectric power plants that use imported oil derivatives as fuel.

As we all well know, the cost of these imported fuels has jumped in an unprecedented way during the last seven years. In Table I (2) we present the price paid, the barrels consumed, and the total cost for oil used in the production of electricity during the last ten years.

Our load forecasts are also predicting that by the end of this decade at least 900 megawatts of capacity will have to be added to our system to satisfy the demand for electricity on the Island (3).

ANALYSIS

1. Fossil Fuels

Given these two hard facts about our electrical energy situation, what fuel are new units going to use? The Authority had only two choices; either nuclear or coal. The nuclear alternative was discarded because, apart from the uncertainties that exist at this moment with regard to nuclear plants and especially their radioactive wastes, it would have taken too long to be put into operation (mainly because of the licensing requirements). So the only alternative we had was coal (4).

Nevertheless, one has to be very careful when utilizing coal. For instance, some problems could arise if the properties and quantities of impurities are not considered in the design and operation of the generating equipment. Take for example the coal ash; if it is not properly considered in the design and operation of the boiler it can deposit not only on the furnace walls and floor, but also through the convection banks. This not only reduces the heat absorbed by the unit, but increases draft loss, corrodes pressure parts, and eventually causes irregular or unscheduled shutdown of the unit for cleaning and repairs (5).

Another aspect that must be carefully considered in coal usage is that although boilers are often designed and equipped to use a wide range of coals satisfactorily, no boiler installation will perform equally well with all types of coals. All coals have certain properties which place limitations on their most advantageous use (6).

To define the limitations of various types of coal burning equipment in service, specifications covering several important properties of coal are necessary. For example, in pulverized-coal firing, which will probably be the type of firing to be used by the Authority's units, it may be necessary to specify ash-slagging and ash-fouling parameters for a dry-ash installation.

2. Fossil/Biomass Fuels

Boilers that use coal as fuel can be designed to use other fuels as backup. PREPA's units are going to be designed so as to use oil as backup fuel. The decision was made based on the fact that if there should be any interruption in supplies of coal (although there will be a three month coal supply storage system) the unit would be able to continue its operation (7).

Oil will be stored in tanks with a capacity for 30 days usage. At this point we could ask ourselves, should the Authority have considered other fuels such as bagasse or solid waste to use as backup for these units? Let's analyze this situation.

According to our studies (8), coal (for a 300 MW capacity unit) will be consumed at rate of $756{,}000 \frac{\text{tons}}{\text{year}}$ (based on a heat rate of $9145.77 \frac{\text{BTU}}{\text{KWH}}$)for

$$7{,}352 \frac{\text{hours}}{\text{year}} \text{ or: } 7{,}352 \frac{\text{hours}}{\text{year}} \div 24 \frac{\text{hours}}{\text{day}} = 306.33 \frac{\text{days}}{\text{year}}$$

then the rate of consumption per day is:

$$756{,}000 \frac{\text{tons}}{\text{year}} \div 306.33 \frac{\text{days}}{\text{year}} = 2{,}467.93 \frac{\text{tons}}{\text{day}}$$

Based on the fact that if the heat content of coal is $24 \times 10^6 \frac{\text{BTU}}{\text{ton}}$ and coal is consumed at a rate of $2{,}467.93 \frac{\text{tons}}{\text{day}}$, then the heat content needed per day is:

$$(24 \times 10^6 \frac{\text{BTU}}{\text{ton}})\ (2{,}467.93 \frac{\text{tons}}{\text{day}}) = 59.23 \times 10^9 \frac{\text{BTU}}{\text{day}}$$

Oil

How many barrels of oil will we need per day in order to replace coal? Since there are $6.087 \times 10^6 \frac{\text{BTU}}{\text{Barrel}}$ and we need to meet $59.23 \times 10^9 \frac{\text{BTU}}{\text{day}}$ then:

$$59.23 \times 10^9 \frac{\text{BTU}}{\text{day}} \div 6.087 \times 10^6 \frac{\text{BTU}}{\text{Barrel}} = 9.73 \times 10^3 \frac{\text{Barrels}}{\text{day}} \text{ or } 9{,}730 \frac{\text{Barrels}}{\text{day}}$$

For a 30-day storage of oil this is equivalent to:

$$(9{,}730 \frac{\text{Barrels}}{\text{day}})\ (30 \text{ days}) = 291{,}900 \text{ barrels of oil.}$$

Bagasse

How many tons of bagasse would be needed to replace coal? Assuming that sugarcane bagasse has a heat content of $14.00 \times 10^6 \frac{\text{BTU}}{\text{ton}}$ and we need $59.23 \times 10^9 \frac{\text{BTU}}{\text{day}}$, then:

$$59.23 \times 10^9 \frac{\text{BTU}}{\text{day}} \div 14.00 \times 10^6 \frac{\text{BTU}}{\text{ton}} = 4.23 \times 10^3 \frac{\text{tons}}{\text{day}} \text{ or } 4230 \frac{\text{tons}}{\text{day}}$$

If we were to maintain the 30 day storage as in oil then we would need to store in bagasse:

$$(4{,}230 \frac{\text{tons}}{\text{day}})\ (30 \text{ days}) = 126{,}900 \text{ tons of bagasse}$$

Solid Waste

How many tons of solid waste would be needed to replace coal: Assuming that solid waste has a heat content of $9.248 \times 10^6 \frac{\text{BTU}}{\text{ton}}$ (11), and we need to meet $59.23 \times 10^9 \frac{\text{BTU}}{\text{day}}$, then:

$$59.23 \times 10^9 \frac{\text{BTU}}{\text{day}} \div 9.248 \times 10^6 \frac{\text{BTU}}{\text{ton}} = 6.41 \times 10^3 \frac{\text{tons}}{\text{day}} \text{ or } 6{,}410 \frac{\text{tons}}{\text{day}}$$

Maintaining as in the previous case the 30 day storage requirement, then we would need to store in solid waste:

$$(6{,}410 \frac{\text{tons}}{\text{day}})\ (30 \text{ days}) = 192{,}300 \text{ tons of solid waste}$$

As we can observe from the previous analysis, if we were to use either bagasse or solid waste as backup fuel to coal in this 300 MW capacity unit instead of oil, we would need to store 126,900 tons of bagasse or 192,300 tons of solid waste in order to meet the 30-day oil storage criteria (see Table 2).

We also have to take into consideration that both bagasse and solid waste are more complicated than oil in terms of handling, storage, transportation and preparation before combustion (both bagasse and solid waste have a high moisture content; therefore drying is essential, see Table 3). But the most important factor to consider is whether the boiler will be able to burn either bagasse or solid waste to replace the coal. That is, can a pulverized-coal fired boiler be designed so as to burn bagasse or solid waste as a backup fuel?

Preliminary research indicates that it is possible that such fuel backup can be used, but that extensive modifications to the boiler would have to be made. These alterations to the boiler would elevate substantially the original price of the boiler (12).

3. Biomass Fuel

As for a strictly bagasse-burning unit, the Authority has taken its first steps in that direction by analyzing the alternatives that exist within our system to develop a plant on an experimental basis (13). Among the alternatives being considered are the former experimental nuclear power plant at Rincón, on the western part of the Island, with a turbo-generator capacity of 17 megawatts, and the San Juan Power Plant Units No.1, No.2 and No.4, each with a 20 megawatt capacity. Some of the aspects which the analysis is considering are: (a) The equipment available; (b) the sugarcane plantation vis-a-vis the unit location; (c) transportation; (d) storage of the bagasse and the fiber; and (e) heat content of the bagasse to be used in the boiler.

An important aspect to consider in this experiment is the moisture in the bagasse. Gas produced from bagasse has a high moisture content whose weight is about twice that produced from oil and one and one-half that from coal. This high gas weight causes a high draft loss and requires either extremely high stacks or large fans to obtain the required steam capacity from the boilers. A low draft-loss boiler can alleviate these conditions (14). Bagasse drying via a mechanical dryer, or solar dried, could be a solution.

Another answer might be to use the existing gases of a high-pressure boiler. This, apart from increasing the heat content of the bagasse, would reduce the amount of gases in the furnace, producing a cleaner operation in the boiler (15).

CONCLUSION

We have shown some of the problems we could encounter when shifting from oil, our traditional source of electrical energy, to other fuels such as coal and sugarcane bagasse. Nevertheless, we at the Puerto Rico Electric Power Authority think that these obstacles are small in comparison to the economic burden and supply limitation if we continue our dependance on oil. The Authority is committed to supply, at the lowest price possible, the electricity needed to sustain the economic development of Puerto Rico. In order to do so, we will have to solve all of the problems which are limiting the use of alternate fuels at the present moment.

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Table 1

PRICES, QUANTITIES PURCHASED, AND TOTAL COSTS OF OIL USED FOR THE PRODUCTION OF ELECTRICITY; 1970-1980

FY	Expenditures — $/Bbl	Bbl x 10^6	Total Cost ($ x 10^6)
1970	1.66	11.38	18.9
1971	2.17	13.78	29.9
1972	2.83	16.59	46.9
1973	3.28	20.29	66.9
1974	7.27	20.22	147.0
1975	11.09	18.22	202.2
1976	11.77	20.69	243.6
1977	13.36	22.57	301.5
1978	14.43	23.86	344.3
1979	13.79	23.99	330.8
1980	21.75	23.38	508.5

Table 2

ESTIMATED HEAT CONTENTS, DAILY CONSUMPTION, AND 30-DAY STORAGE REQUIREMENTS FOR OIL AND THREE ALTERNATIVE FUELS

	Estimated Values For —		
Fuel	Heat Content	Daily Consumption	30-day Storage
Oil	$6.08 \times 10^6 \frac{\text{BTU}}{\text{Bbl}}$	$9{,}730 \frac{\text{Bbl}}{\text{Day}}$	291,900 Bbl
Coal	$24.00 \times 10^6 \frac{\text{BTU}}{\text{Ton}}$	$2{,}468 \frac{\text{Tons}}{\text{Day}}$	—
Bagasse	$14.00 \times 10^6 \frac{\text{BTU}}{\text{Ton}}$	$4{,}230 \frac{\text{Tons}}{\text{Day}}$	126,900 Tons
Solid Waste	$9.25 \times 10^6 \frac{\text{BTU}}{\text{Ton}}$	$6{,}410 \frac{\text{Tons}}{\text{Day}}$	192,300 Tons

Table 3

PROXIMATE AND ULTIMATE ANALYSES FOR BAGASSE AND COAL [1]

Analyses [2]	Fuel — Coal [3]	Bagasse
Proximate:		
Moisture	2.5	52.0
Volatile Matter	37.6	40.2
Fixed Carbon	52.9	6.1
Ash	7.0	1.7
Ultimate		
H_2 (Hydrogen)	5.0	2.8
C (Carbon	75.0	23.4
S (Sulfur	2.3	Trace
N_2 (Nitrogen)	1.5	0.1
O_2 (Oxygen)	6.7	20.0
H_2O (Water)	2.5	52.0
A (Ash)	7.0	1.7

[1] Source: Steam: Its Generation And Use. Babcock & Wilcox. 1972.

[2] As fired; % by weight.

[3] Pittsburg Seam Coal; West Virginia.

THE MOLASSES CRISIS IN THE PUERTO RICO RUM INDUSTRY

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

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THE MOLASSES CRISIS IN THE PUERTO RICO RUM INDUSTRY

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THE MOLASSES CRISIS IN THE PUERTO RICO RUM INDUSTRY

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ABSTRACT

IN 1978 the Puerto Rico rum industry provided 85% of the U.S. rum market, returning to the P.R. treasury $200 million in Federal excise taxes. The diminishing P.R. sugar industry is not able to supply sufficient blackstrap molasses (BSM) to the expanding P.R. rum industry, and at present imports from foreign suppliers amount to 88% of its needs. These imports place the rum industry in jeopardy, as these suppliers can boycott Puerto Rico to protect their own rum production, or they can insist by treaty that all rums claiming geographic origin (ie, "Puerto Rico" rum) must be distilled from molasses produced in that country. The purpose of this paper is to present possible solutions to improve domestic molasses production to eliminate these threats.

The use of high-test molasses (HTM) would answer the present and future needs of the rum industry if produced by the energy cane (or biomass) concept. This is a management concept stressing total growth potential rather than sugar. It would permit doubling cane production per acre and produce sufficient HTM on 70,000 acres for the projected rum industry requirements.

Considerations of HTM production show that problems exist with the marketing price rather than in the field or factory. The economics of HTM pricing will have to be worked out by the interested parties: The rum industry, the sugar industry, and the government.

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THE MOLASSES CRISIS IN THE PUERTO RICO RUM INDUSTRY

INTRODUCTION

PUERTO RICO rum has become the favorite rum in the United States, capturing 85% of the rum market in 1978-79. Sales increases of 43% and 147% have been projected for 1983 and 1988, respectively (1). Rum production and exports have increased greatly in the past 15 years (Table 1). The taxes from rum sales are an important and growing source of Puerto Rico's Government revenue. For every proof gallon1/ of rum produced in Puerto Rico and shipped to the mainland there is a return of the U.S. $10.50 excise tax to the Puerto Rico Treasury Department. For each proof gallon sold in Puerto Rico there is a local tax payment of $9.50. The Federal excise tax returns for 1978-79 were about $200 million, and Puerto Rico's tax was about $34 million. The $234 million total returned to General Fund revenues amounted to 14.4% of the total revenues received by the Puerto Rico Treasury. This means that of every seven dollars going into the Puerto Rico Treasury, the rum industry contributed one dollar (2).

The Puerto Rico rum industry is threatened by a problem which jeopardizes its future. This threat is posed by the lack of sufficient domestic molasses, the basic raw material for rum production. A declining Puerto Rico sugar industry has failed to meet rum industry demands for molasses since 1972. This deficit has been made up by importing molasses from other parts of the world. For 1980, the rum industry will have to import 87% of the molasses it uses. The cost of importing molasses from foreign sources adds to the Island's balance of payments deficit. Dependence on imported molasses leaves the rum industry at the mercy of foreign rum producers, who, by adopting a multi-lateral definition of rum, can decree that rum must be distilled from molasses produced in the country of origin. This claim of geographical designation can eliminate "Puerto Rico" rum. A decision of the molasses-producing countries not to sell molasses to Puerto Rico would destroy most of the Puerto Rico rum industry (2).

The local production of sufficient molasses for the Puerto Rico rum industry can eliminate the "foreign threat" and reduce the balance of payments deficit. It is the purpose of this paper to present possible solutions for improving molasses production in Puerto Rico.

1/ A proof gallon of rum is defined as one gallon of rum at 100° proof (50% alcohol).

MOLASSES

1. The Raw Material

Sugarcane molasses is the basic raw material used in manufacturing rum. It is the end product of either raw sugar manufacture or refining. It is usually designated as "final" or "blackstrap" molasses (BSM). It is the heavy, viscous liquid separated from the final, low-grade massecuite from which no further sugar can be crystallized by the usual methods.

The chemical composition of BSM varies with sugarcane varieties, weather, soil conditions, harvesting methods, and processing conditions in the sugar factory (3). The main BSM constituents are water (17-25%), total solids (77-84%), Brix (85°-92°), sucrose (30-40%), total reducing substances (10-25%), other carbohydrates (2-5%), and ash (as carbonates, 7-15%).

One BSM gallon contains about 6.75 pounds sugar, and it will produce about 0.75 proof gallons of rum. One ton of cane will produce about 6 BSM gallons (for Puerto Rico this varied from 5.9 gallons per ton of cane in 1954 to 6.4 gallons in 1980).

High-test molasses (HTM) is the name given to a clear, light brown, heavy, partially-inverted cane syrup having 85° Brix. The term HTM is a misnomer, because it is made directly from the concentrated, clarified cane juice and no sugar is removed. The term "molasses" is generally used to designate material from which sugar has been removed by crystallization. However, HTM will be used herein as it is the term used in the sugar industry.

Milling, clarification, and evaporation for HTM follows the same steps as in raw sugar production. The syrup is inverted and then evaporated to 85° Brix. A typical HTM analyses shows 85° Brix, 27% sucrose, 50% reducing sugars, 2.25% ash, and 5.5% water (3). There are about 9.8 pounds of sugar per HTM gallon (the range being from 9.4 to 10.2) and 17.6 HTM gallons per ton of cane (the range being from 13.3 to 21.8). Some confusion exists in the designation of sugar in HTM, as it contains sucrose and reducing sugars which combine to form the fermentable solids, or sugars, in HTM. One gallon HTM is equivalent in sugar to about 1.5 BSM gallons. A HTM gallon will yield about 1.20 proof gallons of rum.

2. Quantity

The Puerto Rico sugar industry was the major molasses supplier for Puerto Rico rum producers until 1971 (Table 2) when the increased needs of the booming rum industry surpassed the declining molasses supply. From 1971 onward the rum producers were forced to import molasses to offset the dwindling supply of domestic BSM. Imports have come from the Dominican Republic (major supplier), Haiti, Jamaica, Guyana, Brazil, Colombia, Panama, Mexico and South Africa. In 1972, some 16% of the rum distiller's BSM was imported. By 1979 this figure had increased to an estimated 88%.

By virtue of research, quality control, and advertising the Puerto Rico rum industry has captured 85% of the U.S. rum market. Beginning with 296,300 proof gallons shipped to the U.S. in 1936, Puerto Rico rum shipments increased to 20.1 million proof gallons in 1979. Projections indicate that about 50 million proof gallons will be produced in Puerto Rico by 1985. This output will require about 75 million gallons of blackstrap molasses.

3. Storage and Transportation

Domestic HTM production for the rum industry will present certain problems of storage and transportation. Storage of HTM at extremely high temperatures will result in sugar losses. Experiments indicate that 100°F is the maximum temperature at which HTM can be stored without sugar losses (3, p. 377).

Since 1972, when BSM was first imported into Puerto Rico, a specific pattern of shipments has been followed to maintain steady supply throughout the year and to minimize storage. Molasses is received from local sugar mills, and the Dominican Republic and other Caribbean areas, from January to June. Shipments are received from Brazil, Colombia, and other sources in the July to December period when these countries are harvesting sugarcane. Increased storage capacity will be needed to store the domestic HTM for the off season when mills are not grinding. Usually, cane is harvested from January to June in Puerto Rico. Adoption of the energy cane concept (4) proposed by CEER-UPR scientists would enable the grinding season to be extended to about 8 months, ie, from December through July. Thus, HTM storage would be reduced to a 4-month period.

Transportation is a factor which must be considered with domestic HTM production. The principal rum distillers, which produce over 88% of the Puerto Rico rum, are located on the north coast. Bacardí, at Cataño, produces 72%, and Puerto Rico Distillers, at Arecibo, produces 16%. The remaining distillery, Distillería Serrallés at Ponce, on the south coast, produces 12%. A major part of the proposed HTM production will probably be located on the south coast. To move the HTM by truck will prove too costly. It now costs about 1.2 cents per gallon per mile to move imported BSM from the dock in San Juan to the Bacardí plant in Cataño, approximately 9 miles away (5). The most economical method would be to move the HTM by barge. Dock facilities are available for this purpose in San Juan and Ponce.

POSSIBLE SOLUTIONS

There are several possible means for eliminating Puerto Rico's reliance on foreign molasses. This section will present these solutions from the standpoint of technical feasibility. The economic feasibility of solving the molasses problem will require a later publication.

1. Produce Sugar And BSM.

The normal routine of sugar and BSM production, as now practiced by the Puerto Rico sugar industry, yielded only 14 million BSM gallons in 1980, or about 12% of rum industry needs. It has been estimated that 62 million BSM gallons will be required by the rum distillers in 1981. The sugar industry would require about 359,000 cane acres to produce this quantity of BSM, based on the present yields of 6.4 BSM gallons per ton of cane and 27 tons of cane per acre (Table 3). Even energy cane, at 80 tons per acre, would require about 77,500 acres. These increased acreages will conflict with proposed agricultural needs for food production (6). Thus, BSM is not the proper molasses source to satisfy the requirements of the Puerto Rico rum industry.

2. Maintain The Present Sugar Industry And Produce HTM.

The production of molasses for rum can be increased by a factor of four by diverting all sugarcane production to HTM rather than sugar and BSM. For 1981, about 41.5 million HTM gallons could be produced (equivalent to 62.2 million BSM gallons) on 87,300 cane acres yielding 27 tons cane per acre (Table 3). This would meet the rum industry needs projected for 1981, but it would meet only 83% of the 1985 estimated needs of 75 million BSM gallons. It would not be possible to supply sufficient molasses by this means for the expanding rum industry.

3. Develop The "Modern Agricultural Plan" For The Sugar Industry, Producing HTM Instead of Sugar And BSM.

The Puerto Rico Department of Agriculture, in its "modern" agriculture plan for the Island, has designated 70,000 acres for sugarcane, yielding an average of 3 tons of sugar per acre (6). This plan calls for a yearly production of 200,000 tons of sugar to supply the local market.

If implemented this plan could provide 43 million HTM gallons, equivalent to 64.7 BSM gallons, which would satisfy the 1981 rum industry needs. By 1988, the rum industry requirements (based on a 5% yearly growth) would climb to about 90 million BSM gallons. A deficit of about 28% in molasses production would be anticipated with this plan.

4. Develop The Energy Cane Concept And Produce HTM And Boiler Fuel.

A research project proposal entitled "Energy Cane Management for Boiler Fuel and Molasses" was submitted November 4, 1979 to the Office of the Governor, Commonwealth of Puerto Rico. It was prepared by scientists of the CEER-UPR Biomass Energy Program, and was based on sugarcane research data obtained under sponsorship of the U.S. Department of Energy (7). The basic concept of the proposal is a pilot scale demonstration of sugarcane's value as an energy crop and a source of HTM. By applying modern agronomic techniques based on sugarcane's real growth potential rather than sugar, millable cane yields in excess of 80 tons per acre year were demonstrated (4). Juice quality data indicated that over 1700 HTM gallons per acre could be recovered from this cane.

Critics of this project, and of the energy cane concept in general, have been reluctant to believe that sugarcane production can be increased by a factor of three as claimed. It is difficult for people who have dealt with Puerto Rico's sugarcane all of their lives to accept the production of 80 tons of millable can per acre, even on experimental plots. Actually, even when managed for sugar rather than biomass, sugarcane has often produced more than 60 tons per acre on the fertile, irrigated, and well-managed soils of Puerto Rico's south coast. By selecting high-tonnage varieties and managing them for maximum growth, yields in the order of 80 tons per acre year are not at all exceptional.

The quantity of molasses produced on 70,000 acres, about 59 million gallons, would supply the fermentable solids needed by the rum industry in 1981. For future molasses needs of the rum industry, various combinations of HTM, and lower quality HTM, could be produced while simultaneously accommodating some sugar production during periods of high sugar values. From 70,000 acres of energy cane, a HTM yield of 99 million gallons (equivalent to 148 million gallons of BSM) could be obtained.

The use of 40,000 acres of irrigated cane lands on the south coast, yielding about 80 tons of energy cane per year, could provide about 56 million HTM gallons. This is approximately 85 million BSM gallons (Table 3, solution 4A).

CONCLUSION

The use of energy cane methodology to produce HTM on 70,000 acres can supply more than enough molasses to meet the needs of the Puerto Rico rum industry. This cannot be accomplished by present sugar industry methods aimed at raw sugar and BSM[1/].

There could exist a pricing problem for HTM as regards the use of current sugar values or BSM equivalent prices. The economics of HTM pricing will have to be worked out by the interested parties: The Puerto Rico rum producers, the HTM producer (Puerto Rico's sugar industry), and the Puerto Rico Government. Cooperation by all parties is needed to resolve the pending crisis in the Puerto Rico rum industry.

ACKNOWLEDGEMENTS

Thanks are given to Prof. William Allison, Head, Department of Agricultural Engineering, University of Puerto Rico at Mayaguez, and Mr. Mariano A. Romaguera, Puerto Rico Sugar Corporation, Mayaguez, for supplying opinions and data on HTM composition and production. Thanks are also expressed to Mr. René F. Rodríguez, Caribbean Industrial Molasses Company, San Juan, for data concerning BSM and HTM pricing, and to Mr. Carlos L. Yordán, Puerto Rico Rum Producers Association, Inc., San Juan, for data on rum production and exports.

[1/] The excess HTM capacity allows for the possibility of producing sugar as well as HTM when sugar prices are favorable.

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TABLE 1. Puerto Rico rum production, sales, and taxes 1965-79 [1]

Year	Production PG [2] x 10^6)	Sales (PG x 10^6) US	PR	Taxes ($ x 10^6) [3] Federal	PR
1965-66	14.5	3.9	3.7	-	-
1966-67	13.4	4.6	2.8	-	-
1967-68	15.0	5.4	3.3	58.9	25.2
1968-69	17.3	7.1	3.6	73.9	27.6
1969-70	15.5	6.6	3.5	70.1	26.7
1970-71	18.0	7.4	3.8	80.3	29.5
1971-72	24.0	8.4	3.8	91.0	32.3
1972-73	21.2	9.1	3.4	96.2	30.7
1973-74	19.8	9.3	3.9	85.6	33.2
1974-75	18.4	10.2	2.9	104.0	27.7
1975-76	24.9	12.0	4.0	127.1	38.7
1976-77	27.7	13.7	3.1	134.1	31.8
1977-78	28.1	17.0	3.4	176.5	35.4
1978-79	37.5	20.1	3.2	199.9	33.9

[1] Production and sales data supplied by PR Rum Producers Association, Inc., San Juan, P.R. Tax data derived from Depto. Hacienda, Oficina de Estudios Económicos y Financieros, Estado Libre Asociado de P.R., Santurce.

[2] PG = Proof Gallon (50% alcohol).

[3] Federal excise tax return $10.50 per proof gallon exported to US; P.R. taxes $9.50 per proof gallon sold locally.

TABLE 2. The relation between molasses production and consumption in Puerto Rico (millions of gallons), 1964-79 1/.

Year	Molasses produced	Molasses consumed			% deficit molasses needed by rum industry 3/
		Total	Rum industry	Others 2/	
1964	64.3	26.0	16.0	10.0	0
1965	57.2	27.1	17.1	10.0	0
1966	60.6	30.3	20.3	10.0	0
1967	52.1	29.8	18.8	11.0	0
1968	43.9	32.6	21.0	11.5	0
1969	41.6	36.6	24.2	12.4	0
1970	45.4	32.7	21.8	10.9	0
1971	30.9	36.2	25.2	11.0	21.0
1972	28.3	44.7	33.7	11.0	48.7
1973	24.9	40.7	29.7	11.0	53.2
1974	22.9	38.8	27.8	11.0	57.2
1975	23.6	36.8	25.8	11.0	51.2
1976	21.0	45.9	34.9	11.0	71.3
1977	21.1	49.8	38.8	11.0	74.7
1978	17.4	50.4	39.4	11.0	83.8
1979	14.2	60.5	52.5	8.0	88.2

1/ Data supplied by P.R. Rum Producers Association, Inc., San Juan.

2/ Animal feeds and pharmaceutical uses primarily.

3/ 100-(molasses produced - others ÷ rum industry needs) x 100.

TABLE 3. Blackstrap molasses (BSM) and high-test molasses (HTM) available from suggested possible solutions for molasses needs of Puerto Rico rum producers.

Possible solution	Acres in cane	Tons cane per acre	Molasses production (gallons x 10^6)	
			HTM 1/	BSM equivalent 2/
1	359,000	27	0	62.0
2	87,300	27	41.5	62.2
3	70,000	35	44.4	64.7
4	70,000	80	98.6	147.9
4 A	40,000	80	56.3	84.5

1/ Based on 17.6 gallons HTM per ton cane.

2/ Based on 1.5 gallons BSM (6.75 pounds sugar/gallon) = 1 gallon HTM (9.8 pounds sugar/gallon).

TABLE 4. Percent of Puerto Rico rum industry molasses needs provided by high-test molasses (HTM) for 1981, 1985, 1988

Possible solution	1981	1985	1988
Conventional	101	83	70
Modern Agricultural Plan	105	86	72
Energy cane (70,000 acres)	241	198	165
Energy cane (40,000 acres)	137	112	93
HTM needed (gallons x 10^6)	41	50	60

CELLULOSE CONVERSION TO FERMENTATION FEEDSTOCKS; AN OVERVIEW

Presented To The Symposium

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Troy, New York

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CELLULOSE CONVERSION TO FERMENTATION FEEDSTOCKS; AN OVERVIEW

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ABSTRACT

THE MAIN principles of economical production of fuel alcohol from biomass are: 1. Pretreatment to loosen the structure for efficient hydrolysis; 2. Avoiding excessive dilution so that expensive concentration steps are unnecessary; 3. Recycling to minimize waste; and 4. Deriving benefit from all components. Very effective pretreatments have been found, and hydrolysis of cellulose to glucose commonly gives yields in the range of 90 percent of theoretical. Another major component, hemicellulose, is easily hydrolyzed to sugars for which new methods for conversion to ethanol have been devised. The other major component, lignin, is not converted to useful products by any biological process with commercial prospects. However, native lignin will probably attract an excellent price for applications in polymers or binders, and byproduct lignin from an ethanol factory has ideal properties. A new, gigantic biomass industry should develop quite rapidly.

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CELLULOSE CONVERSION TO FERMENTATION FEEDSTOCKS; AN OVERVIEW

INTRODUCTION

THE PAPER by Dr. Berger has covered a wide scope of biomass programs for this symposium, so a restricted review of the conversion of crude biomass to fermentation feedstocks is now appropriate. Although the symposium focuses on tropical biomass, almost all of the research in North America on hydrolysis of cellulose has used non-tropical woods or agricultural residues. Even sugarcane bagasse which is available in a few of the United States has had little testing. Nevertheless, tropical materials have many similarities to the materials that are being emphasized, thus yields for hydrolysis are quite predictable.

Much research has dealt with conversion of cellulose to fermentable sugars, but it is obvious that cheap fuels cannot be obtained if non-cellulosic components are wasted. Not only are credits for possible products lost, but it is costly to treat the large amounts of wastes after using only the cellulose. There is little margin for profitable hydrolysis to glucose for fermentation to ethanol if only cellulose is utilized. The economics are much more favorable when the other biomass constituents are also utilized. Fermentation of the sugars from hemicellulose to various organic compounds has commercial possibilities, and there have been recent improvements for the production of ethanol. No bioconversion of lignin appears to be practical because the linkages and aromatic rings are broken only in aerobic processes in which organic intermediates do not accumulate. However, native lignin should command high prices and find fairly large markets as a component of wood binders and plastics.

Hydrolysis of hemicellulose to mono- and oligo-saccharides is easily accomplished with either acids or enzymes under mild conditions. Native cellulose resists hydrolysis for two reasons: (a) Its highly ordered crystalline structure; and (b) a physical barrier of lignin surrounding cellulose fibers. Some of the most striking advances for the programs supported by the U.S. Department of Energy have been various pretreatments that render cellulose amenable to easy hydrolysis.

ACID HYDROLYSIS

Acid hydrolysis of wood is old technology, and projects during World War II led to the

Madison process which optimized time, temperature, and acid strength. While the process is not economical in the U.S., other countries, particularly the U.S.S.R., have many plants for hydrolyzing wood to sugars. A few plants produce alcohol by fermenting the sugar, but single-cell protein for animal feed is the most common product. Furfural is sometimes derived from the pentose fraction from hemicellulose.

Acid hydrolysis leads to a sequence of reactions. Hydrolysis is approximately 1000 times faster for hemicellulose than for cellulose. The sugars from each are degraded by acid to resins, polymers, and furfural derivatives. Reaction conditions are thus set for a compromise between hydrolysis and degradation such that the final mixture contains unreacted biomass, unwanted products, and the desired sugars. Since the sugars from hemicellulose are formed early, there is time for considerable degradation leading to major losses. The maximum yield of fermentable sugars is about 55 percent by weight of starting cellulose.

Hemicellulose can be removed by dilute acid treatment with very little effect on the cellulose. Adequate conditions range from 0.1% sulfuric acid at 170°C to 1 percent at 120°C with times up to one hour.

Knappert et al. (1980) have reported the yield of sugars from cellulose as a function of time and temperature. Best yields are obtained at high temperatures for very short times. However, times less than 0.1 minutes can be dismissed from practical consideration because there would be insufficient mixing time for acid solution and biomass. The predicted yield does not exceed 55 percent of theoretical, thus acid hydrolysis must be improved or replaced with a different technology. There are indications that pretreatment of the feedstock can greatly increase the hydrolysis reaction rate coefficient. This would raise the yield of glucose by reducing the time for degradation.

ENZYMATIC HYDROLYSIS

Active cellulase preparations are seldom obtained from microorganisms which thrive on decaying plant materials, probably because cellulase producing cultures work synergistically, and few organisms secrete adequate levels of all the components of the complex of enzymes. It is uncommon to find a bacterium that is a potential commercial source of cellulases, but several molds produce high concentrations of enzymes in fermentation tanks. Production of cellulases has advanced to the point where fermentation titers are sufficiently high that there is no need to purify or concentrate the product.

Enzymatic impurities can catalyze recombination of glucose units so that the product is contaminated with small amounts of oligosaccharides. For hydrolysis of native cellulose, the proportions of various cellulases in a given enzyme preparation may not be suitable. Analytical procedures are now available for resolving the components of cellulases, and some understanding has been gained of factors which shift their production. If no one organism can produce an optimum mix of enzymes, it should be possible to blend cellulases from various sources.

There are many thermophillic organisms which attack cellulose, but those with highest activity are actinomycetes, clostridia, and sporocytophaga (Bellamy, 1979). Rate of cellulose hydrolysis is slow unless the feedstock is pretreated. Cellulase from the thermophillic soil fungus, *Thielatia terrestris*, (SRI International, Chem. Eng. News, Aug. 7, 1978) are functional between 60° and 70°C which means a faster reaction rate and less chance of contamination. *Clostridium thermocellum* is a bacterial candidate for supplying cellulases. It thrives at 60°C and completes its fermentation in 2 days whereas *Trichodema reesei*, the most widely used mold, requires one to two weeks. The proportions of isoenzymes and enzymatic activities vary for different organisms.

Catabolite repression is a feed back control whereby excess product slows its formation rate, thus high yields are impossible. Mutants can be isolated in which repression is weakened or inoperative. Often mutants which hyperproduce enzymes are still subject to catabolite repression. Further mutation of these hyperproducing strains to obtain less catabolite repression can give higher yields of enzymes.

The saccharification of cellulose with enzymes can take many days if no pretreatment is used. With mild pH and slightly elevated temperature, contaminants can thrive on the sugars that are formed. Antiseptics or antibiotics can be added to reduce contamination, but cellulase activity may be impaired (Spano, 1976). Removal or destruction of the protective agent may be needed prior to the fermentation of sugar to ethanol. Even if the fermentation culture is unaffected by the protective agent, there is a pollution problem if a toxic agent is present in the final effluent. It seems advisable to omit these agents and carry out saccharification quickly so that contaminants have insufficient time to reach troublesome concentrations.

Ryu et al. (1979) have operated two-stage continuous cultures of *T. ressei* for production of cellulases. The first stage was for rapid cell growth; lactose was the carbon source and served as an inducer for cellulase formation. Cellulase productivity was best when the second stage dilution rate was 0.026 to 0.028 hr^{-1}. This is roughly equivalent to 1-1/2 days of fermentation and is a significant improvement over slow batch fermentation.

The University of Pennsylvania team effort with the General Electric Company has been using an organism identified as *Thermoactinomycetes* sp. (Hagerdal, et al 1980a,b). Further testing, plus confirmation by workers at Rutgers University, has corrected the identification, and the proper designation is *Thermonospora* sp. (perhaps *T. alba*). At 55°C, this organism elaborates active cellulases; yields are nearly comparable to those of good mutants of *T. reesei.* Mutation should lead to higher yields, but continued improvement of other species which produce cellulases means that comparisons must continually be updated. The beta-glucosidase activity for *Thermonospora* is associated with culture solids while the cellulases are released to the medium. This could be an advantage if fractionation is desired or a disadvantage if by requiring a step for releasing beta-glucosidase, an enzyme mixture is being prepared. The beta-glucosidase is unusual in that there is very little inhibition by glucose. Glucose syrups approaching 20 percent concentration were made from cellobiose using only *Thermonospora* cells (Pye and Humphrey, 1979).

It is very important to obtain high sugar concentrations for the fermentation step so that products are not too dilute in the broth. Recovery by distillation of dilute solutions means that excessive water would be heated, vaporized, and condensed. Evaporation of the hydrolysate is feasible but it too is costly. Thus it is best to strive for high sugar concentrations directly. The product inhibition of cellulases as previously mentioned causes a lowering of hydrolysis rate; high sugar concentrations can be achieved by using excess enzyme or allowing a prolonged detention time. A different means of avoiding high glucose concentrations during cellulose hydrolysis has been demonstrated at a number of institutions and is exemplified by the Gulf process. The saccharification and fermentation are performed simultaneously with cellulases and yeast. Glucose does not accumulate because the yeast converts it to glucose, thus hydrolysis can approach its maximum rate.

As enzyme is a major expense, large excesses are intolerable. However, reuse of recovered enzymes is possible; the hydrolysate may be rich in enzymes that can be recovered by well known methods. A problem arises from the very tight binding of cellulases to cellulose. In order to reach high sugar concentrations, the feed concentrations of cellulose must be high. This leads to considerable unreacted cellulose and enzymes are adsorbed. Agents such as urea which weaken hydrogen bonds can desorb enzymes from cellulose and increase recovery yields by a factor of two or more. Unfortunately, enzyme recovery is expensive. If urea or some other agent is to be used, it too must be recovered and reused.

Immobilization of beta-glucosidase for splitting cellobiose to glucose makes a great deal of sense because this enzyme is usually present in insufficient proportions in natural cellulases. In nature, sugars from cellulose do not tend to accumulate because feedback control turns off the enzymes producing them. Small levels of beta-glucosidase are adequate for cellular metabolism which uses sugars as they are produced. Supplemental beta-glucosidase works well in vitro when immobilized since its substrate is a soluble, relatively small molecule.

Issacs and Wilke (1978) have immobilized beta-glucosidase from *Aspergillus phoenicius* on phenol-formaldehyde resins by coupling with glutaraldehyde. Up to eighty percent of starting soluble enzyme activity was retained. When columns with immobilized enzyme were operated in conjunction with hydrolysis of cellulose by cellulases, there was little difference in the rate at which reducing sugars were formed. However, cellobiose was split to give a higher yield of glucose which is acceptable to most yeasts while cellobiose is not fermented. A group at the University of Connecticut has also demonstrated advantages of using immobilized beta-glucosidase.

PROCESSES

The most important processes for producing ethanol from biomass are shown in Table 1. The grain alcohol process is very popular presently because of the high subsidy provided by the Federal government and by several states for ethanol blended with gasoline. This program was intended to prop up the price of corn by creating more demand, but the drought of 1980 was of a serious nature and caused major price perturbations. There is little or no margin for profit at the prevailing price of corn in the Fall of 1980. Sugarcane juices and molasses are being fermented to ethanol in

Brazil on a large scale, and there are factories in other countries. With excess bagasses to fuel the factories and with low labor costs, the production of fuel alcohol is a good way to reduce requirements for imported oil. There have been several small technological advances, but the process relies on rather old technology. The wide distribution of cellulose and its relatively low price make it likely to become the main alcohol feedstock displacing corn and sugarcane.

The Natick process was the first significant advance in using cellulose to produce ethanol. Pretreatment has been various types of grinding which have proved too consumptive of energy. The molds which produce cellulase have been studied intensively by Reese, Mandels, and coworkers, and these efforts plus contributions of other groups (especially at Rutgers University) have led to excellent strains in terms of producing high titers of enzymes. The Berkeley process is derived from the Natick process and has contributed engineering solutions to most of the problems. The economic prospects are good if uses can be developed for lignin and hemicellulose.

The Purdue group headed by Tsao showed great ingenuity in devising pretreatments and thus achieved nearly theoretical yields of glucose from cellulose. There are now several competing schemes for pretreatment, but most resulted from the stimulus of the Purdue work. Other accomplishments are better dehydration methods for ethanol, better and varied fermentations for the sugars from hemicellulose, different fermenter designs, and improvement of the solvent pretreatment to the point where good yields are obtained by acid hydrolysis. Enzymatic hydrolysis is more expensive, thus acid hydrolysis is presently featured at Purdue although yields are somewhat lower. Corn stover is probably the best cellulosic feedstock in the midwestern farm states.

The Gulf process appeared to be in the technological forefront just a few years ago, but newer processes have demonstrated superior yields. The concept of simultaneous hydrolysis and fermentation is excellent, but the individual steps have different pH and temperature optima, thus process conditions require a compromise. Nontheless, the simultaneous process deserves further research, and improvements such as a better pretreatment of the biomass could revitalize its prospects.

A team effort of groups at the University of Pennsylvania and the General Electric Company has led to a process based on solvent extraction of lignin for better hydrolysis of cellulose and new thermophillic cultures to supply the cellulases. This is another highly promising process, and there are plans to get significant credits for byproduct lignin by such measures as dissolving it in alcohol or other solvents to create a diesel fuel.

The Iotech process uses steam explosion for pretreatment. High pressure steam permeates the biomass, and sudden release through a die shreds and disintegrates the structure. Hydrolysis of cellulose and fermentation to ethanol proceed nicely. The biggest advantage, however, is development of high-value uses for lignin as a wood binder or specialty chemical. When there are many factories for fuel alcohol, the coproduct lignin will greatly overwhelm the foreseeable markets, but the first few factories selling lignin will be highly profitable. The search for new applications for lignin should be very rewarding because enormous quantities of material with properties superior to lignin from paper pulping will be available.

The M.I.T. process has more simultaneous steps than does the Gulf process. Carefully selected mixed cultures are added directly to coarsely ground biomass. Enzymes hydrolyze both the cellulose and the hemicellulose while the organisms ferment the resulting sugars to ethanol. The organism which ferments the sugars from hemicellulose may be added later after the first organism has nearly completed the hydrolysis and has consumed most of the glucose. The really clever feature of this approach is investing very little in feedstock preparation and not being overly concerned with a high efficiency of feedstock utilization. This means that much of the feedstock is unreacted, but the residue does not represent much money. It would be burned to supply energy for the factory. Some improvement in efficiency of feedstock utilization would be desirable, however, because the fuel value of the residue far exceeds the needs of the factory; steam or electricity would be products of about equal importance to the ethanol. There does not appear to be an opportunity to recover valuable lignin from the residue although it is enriched with respect to the other polymers. There are other problems such as inability of the present strains to reach high concentrations of ethanol, but the rate of accomplishment by the M.I.T. group has been outstanding.

Kelsey and Shafizadeh (1980) have still another simultaneous operation whereby the grinding of the feedstock is performed in the presence of cellulases. The rate of hydrolysis and the concentration of glucose were both improved.

RECENT ADVANCES

Flickinger (1980) has reviewed selected areas of research on fermentation of cellulosic materials with emphasis on the present status and the potential for improvement. In the brief time since this assessment, two groups have independently announced a remarkable improvement in fermentation of sugars from hemicellulose to ethanol (Wang, et al, 1980 a, 1980 b, Gong, et al, 1980). There are bacteria, molds, and yeast that ferment these sugars to ethanol, but other products are usually present and poor tolerance of ethanol prevents its accumulation. The best producers of ethanol are certain yeasts and the bacterium *Zymomonas*. Xylose, the predominant sugar from hemicellulose, is not fermented by the good ethanol producers, but xylulose, a keto sugar derived from xylose, is fermented well. When the enzyme glucose isomerase is added, xylose is isomerized to xylose, but an equilibrium mixture is reached at prolonged times. This enzyme is widely used to convert glucose to fructose for commercial sweeteners and it is inexpensive. A serious drawback is the need to recycle unreacted xylose back from the fermentation step to the enzyme to again approach the concentrations of the equilibrium mixture. Work is underway to create mutants which have isomerase activity and thus need no supplemental enzyme. Furthermore, organisms which have the inherent ability to ferment xylose such as those being used at M.I.T. may soon be so improved that they merit commercial consideration. Utilizing hemicellulose to produce additional ethanol will mean a 50 to 60 percent improvement in productivity in factories using biomass.

Other significant improvements are in fermenter design. There are several advantages to retaining organisms in the fermenter or capturing them in the effluent and recycling them. First, there is less diversion of substrates to growth. The other main advantage relates to ethanol tolerance. All producers of ethanol can become inhibited as ethanol accumulates; this is shown by a decrease in the production rate per microbial cell as ethanol concentration rises. The decrease in rate per cell can be overcome by having more cells. Several new designs retain the cells to achieve very high populations. One method uses heavily flocculated cultures which settle back as clear effluent is withdrawn from the top, and other designs have physical means such as immobilization or encapsulation to hold the cells in the fermenter. A group at Oak Ridge National Laboratory is having good success with *Zymomonas* held in a column reactor, and there is a good chance that this bacterium will outperform yeast in the future because improvements through genetic manipulation are easier and bacteria grow faster than yeast and lead to shorter processing times.

Engineering problems are being solved by novel means for handling materials. Dilution is troublesome in several steps in the biomass processes because extraction yields are low unless excessive volumes of liquids are used. When biomass is mixed with water, the slurry concentration must be kept low or else stirring becomes impossible. Several groups are experimenting with contacting and extracting in columns with the liquid percolating through a solid bed. The solutions can be relatively concentrated so as to minimize the need for costly subsequent evaporation.

CONCLUSION

Fractionation of biomass is leading rapidly to utilization of all its components. Hydrolysis of cellulose has improved in just a few years from yields in the range of 50 percent of theoretical to over 90 percent. Hemicellulose hydrolysis has always been easy, and there are highly promising ways for its conversion to ethanol. Lignin from the various biomass processes does not seem attractive for conversion by biological means, but it has great value in its native state because reactivity is much superior to lignin from paper pulping. Tropical biomass has not had sufficient testing in the processes covered in the review, but there is little doubt that it would work well. The climates of most tropical countries are much better than is that of the U.S. or Canada for growing high yields of biomass, so tropical biomass could soon support major new industries.

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TABLE 1
PROCESSES FOR MANUFACTURING ETHANOL

Process	Description	Remarks
Grain alcohol	Corn grain is malted to hydrolyze the starch. Yeast produce ethanol and stillage is concentrated for cattle feed.	Profitability can be destroyed by high corn prices or collapse of cattle feed market
Sugarcane	Juices or molasses are fermented directly by yeast which are washed and recycled.	Stillage too high in salts for cattle feeding. Credits for cane fiber could be high.
Natick Process	Cellulosic materials treated with Trichoderma enzymes to get fermentable sugars.	Pretreatment by grinding too expensive. Has not focussed on using hemicellulose.
Berkeley Process	Derived from Natick process and also uses hemicellulose.	Strong candidate for large-scale operations.
Purdue Process	Removal of cellulose and hemicellulose permits excellent hydrolysis with acid or enzymes.	Regeneration of solvent may be costly, but this is a very high yielding process.
Gulf Process	Enzymes added for simultaneous saccharification and fermentation.	Hydrolysis yields not outstanding and good use of hemicellulose undeveloped.
Pennsylvania/ General Electric Process	Solvent extraction of lignin gives excellent hydrolysis.	Costly recovery of organic solvents.
Iotech Process	Steam explosion fractures biomass for good hydrolysis.	Very valuable lignin byproduct.
M. I. T. Process	Mixed mold cultures hydrolyze biomass and produce ethanol.	Simple but effective; highly promising.

ALCOHOL FUELS FROM SUGARCANE IN BRAZIL

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ALCOHOL FUELS FROM SUGARCANE IN BRAZIL

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ALCOHOL FUELS FROM SUGARCANE IN BRAZIL

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ABSTRACT

A SURVEY is made of the state of the art of the production of ethanol from sugarcane as compared with other crops in Brazil. The economical and political implications of the "Programa Nacional do Alcohol" are described together with the present achievements and future prognostics.

The improved efficiency of modified internal conversion engines fueled by pure ethanol is compared with the performance of conventional engines that use ethanol-gas blends; some economical discussions follow this presentation.

The energy balance for the production of ethanol from sugarcane is evaluated, taking into account agricultural and industrial energy expenses, and compared with the energy requirements for gasoline production. Real cost of ethanol from sugarcane, under present Brazillian conditions, is US$12.69/GJ as compared with gasoline which is US$12.19/GJ. Considering that ethanol when used as an octane booster has an efficiency 25% higher than gasoline, the final conclusion is that ethanol has reached the break-even point as compared with gasoline in Brazil.

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ALCOHOL FUEL FROM SUGARCANE IN BRAZIL

1. INTRODUCTION

Any assessment of the energy needs of the world population by the year 2,000 shows the insufficiency of the present energy resources. The continual population growth, the larger "per capita" energy consumption expected in the future, mainly in developing nations, and the finite oil resources have been the chief source of worldwide concern, specifically after the oil crisis in 1973.

A historical analysis of the main sources of energy used by the developed countries shows the possibility of oil being replaced by some other source of energy in the near future. This has already happened with wood and coal, as can be seen in Fig. 1. Several analyses performed in the last two decades showed that oil would be replaced by the intensive use of nuclear fuels. (1-3) After several accidents with the operation of nuclear reactors and the strong public opinion consensus taken against their use, particularly the incident at Three Mile Island, several reviews of the world's energy future have been published which predict new sources; mostly in renewable energy. (4-6)

In many developing countries the renewable sources still supply most of the energy used as can be seen from Table 1. The crescent search for technology that allows the utilization of renewable sources in an economical way, even in developed countries, is explained by the lack of large quantities of fossil fuels (except coal) and by the large concern with the environment. Pollution can be avoided for all products, except for the CO_2; its concentration level in the atmosphere is continually growing and will be a serious problem in the near future. (7)

The technical difficulty for the production of alternate fuels is quite small as was proven historically with the use of alcohols by Germany (8) and Japan (9) and water gas by several developed (10) and underdeveloped countries during the second World War (Sweden, Brazil, etc.). The economical difficulty was unsurmountable up to 1973 as evidenced by the efforts of coal gasification developed in South Africa (11) for more than a decade, but as the oil price increases the problem nears a solution. Countries with little or no oil and with large areas of unused land have a greater possibility of producing alternate fuel derived from biomass at costs very competitive with present day oil prices. In Brazil, where a large ethanol program based on sugarcane is being developed costs of alcohol have probably reached the break-even point, as we intend to show in this paper. Even when the ethanol cost is still higher than gasoline, the continuous trade deficit of many less developed, non-oil producing countries does justify the gasoline replacement by an indigenous product. Another important reason to compete economically with gasoline is the surplus of grain crop, particularly corn in the United States, which is the main feedstock for the production of the ethanol, sold in a 10% blend with gas under the name of "gasohol." It is necessary to keep in mind that the price a consumer can pay for fuel is not necessarily the same price a country can afford to pay.

All efforts for the economical production of fuels from biomass are directed to improvements in the crop yield and reduction in energy costs of the industrial processing of the feedstock. Photosynthetic average yields for sugarcane in Brazil is approximately 0.2%. This number can be increased four fold as shown by the sugarcane productivity in Australia (12), Hawaii (13), Puerto Rico (14) and a few specific cultures in Brazil (15). Nevertheless, special care must be taken to avoid excess energy utilization in fertilizers and artificial irrigation. The industrial costs can be significantly reduced if new techniques for the distillation process (16-18) are used.

2. FEEDSTOCKS

A) Sugarcane

Up until now the ethanol derived from sugarcane is the most intense, commercially exploited, fuel alternative. The main reasons for this are:

1) Brazil is the leading nation in the production of fuels derived from biomass, with a total annual production in 1979 of 3.5 billion liters (19) (equivalent to 60,000 barrels of oil/day);

2) The well-developed sugar industry in this country, which is the largest world producer exporter, underwent a severe crisis due to the low international price of sugar when the National Alcohol Program (PNA), i.e. the program for the use of ethanol as a fuel for automobiles, was proposed in 1975 by the federal government. This fact immediately triggered the interest of the sugar producers who were able to bring a large idle fraction of the distilleries into full operation and detour a significant amount of sugarcane beer from the sugar market to the ethanol production (approximately 0.7 billion liters/year of this product are being produced using this method) (20);

3) The technology required to convert sugarcane into alcohol is quite simple and requires equipment that can be built in many of the developing countries;

4) The total amount of capital required to operate an ethanol processing plant is very small when compared with all the other fuel alternatives. The typical cost of a distillery with a 120,000 1/day capacity is not precisely known, since different authors quote different figures, as can be seen

from Table 2, but a reasonable number is 10 million dollars (21). An economical feasible unit of synthetic fuel from coal or oil shale requires large scale production (over 50,000 barrels/day) and capital investment over a billion dollars (22). Even a methanol plant, using biomass as a feedstock requires a large scale plant, with a capacity of handling 2,000 tons of wood/day to become economically competitive; this translates into a cost of 300 million dollars (23). Furthermore, ethanol distilleries in Brazil can be delivered and put into operation twelve months after the order is placed, which is a very short time span as compared with any other investment in energy. Developing nations, in which the shortage of capital is the bottleneck of the industrial growth, are very appreciative of the two aforementioned factors;

5) Ethanol is a very common product and its effect on man is very well known. It is accepted by the human organism even in large concentrations in the atmosphere (1,000 ppm)(24), that is, two times higher than gasoline (500 ppm); therefore the possibility of inducing diseases is quite small. Since it is an organic product, very little impact on the environment is expected.

6) It is the only commodity that can be immediately produced on a large commercial scale to replace gasoline; old cars ran with this fuel and it is still used in race cars when large engine power is the main goal.

The alcohol is now being produced by autonomous and annexed distilleries. The annexed distilleries are extensions of the sugar processing units, built to displace part of the feedstock from sugar to alcohol commodities. These units were built very quickly and for a low price since they used same basic installation for the processing of sugar. The first autonomous distillery, that is, the one designed specifically for the production of alcohol, came into operation in the beginning of 1977.

B) Ethanol from other crops

The possibility for use of other feedstocks in ethanol production has been frequently investigated. Table 3 presents the energy costs in Brazil for some of the most promising crops.

Cassava, often considered a source of ethanol, does not compete with sugarcane when checked through an energy balance. The fundamental reason is the difficulty of using the aerial part of the crop as a fuel for the generation of steam and electricity. The aerial part has large amounts of moisture (>72%) and cannot be used as fuel for boilers without a drying process (25,26). Sweet sorghum is a very competitive crop, mainly because it can provide two harvests per year in most of the tropical areas. Unfortunately some genetic improvements in this culture are still required in order to grow the plant in areas with large insulation (27). Table 3 also presents an energy evaluation for corn crop. The corn stover can be used as a fuel for the ethanol processing industry, but its amount is not sufficient to supply all the energy required.

3. THE NATIONAL ALCOHOL PROGRAM

As was already described in the introduction, just after the fourfold increase in oil price, i.e. at the second semester of 1974, the Brazilian government prepared a program for the replacement of all oil derivatives to be accomplished in four steps. Table 4 shows the goals set for each step at that time. A time limit was determined for the first of the four steps. It would be possible to replace 20% of all gasoline in use in the country by 1980 by addition of ethanol. The use of gasoline-ethanol blends has been common in Brazil since 1950 and in some cases blends containing as much as 16% of ethanol were used in some cities (28). From this previous observation it appears feasible to use conventional gasoline engines to run with a higher level of ethanol, even if the total efficiency was reduced. The second stage of the program, the complete replacement of gasoline by ethanol, would require research and technical changes to reach good performance. Furthermore, economical problems would have to be solved since the oil refineries were designed to supply a market with an almost non-existent seasonal fluctuation, demanding almost the same amount of gasoline, Diesel oil and fuel oil. The reduction in gasoline demand would not be accomplished by the existing oil refineries without imposing restrictions on the supply of Diesel oil and fuel oil. The third phase imposed even more difficulties since it would require not only a change in the oil refining structure but also technical development very hard to assess at that time as Diesel engines had never used any alcohol blend before.

To enhance the ethanol production in Brazil, a large economic program was developed. The federal government supplied 80% of the capital (and in some less developed areas, 90%) and private enterprise 20% or less. The federal mortgage had to be returned to a negative interest rate, i.e. interest and monetary correction below the official index of inflation. With this added advantage, the industrial background of the country was already developed enough to accept any orders for new distilleries. Until now, (February, 1980), more than 250 new units have received funds from the government and nearly 200 are already in commercial operation (29). The most common unit has a production capacity of 120,000 1/day with a cost very near ten million dollars (21). By the end of 1980 the total production of ethanol should reach the goal set in 1975 (4 billion liters/year) and from this total, a little over 3 billion would be produced by the units installed under the National Alcohol Program at a cost of two billion dollars. Another part of the economical program was the indirect subsidy received by the alcohol through the elimination of the taxation that was applied to the price of gasoline and responsible for an over price of almost 30% of its final price to the consumer as can be seen in Figure 3. It is worthwhile to note that gasoline was always overpriced to compensate for the lower prices of Diesel oil (used only for commercial applications) and the fuel oil (used only in industrial applications). The present price of some oil products is shown in Table 5.

With all this preferential treatment, the price of ethanol, since 1975, has always been lower than gasoline, independent of the higher production cost (at least up to the last increase in crude oil price). Presently as we will try to indicate in section 5, the real price of both products seems very similar with a small advantage for ethanol.

In 1979, the success of the PNA was so obvious, mainly because of the constant increase in oil price, that the federal government set an upper limit for the accomplishment of another phase of the program, but less ambitious than the one proposed in 1975. An agreement between the car manufacturers and the government was performed for the production of 900,000 new cars, 100% of which would be fueled by alcohol in the next three years (80-82), plus the retrofitting of 280,000 gasoline cars to run also with the new fuel. The government guarantees the fuel supply up to a level of 10.7 billion liters/year (≃210,000 barrels/day) by the year 1985 (30); a total amount of 5 billion dollars will be available to private investors in new distilleries.

The main conclusions drawn from a fleet of 100% ethanol fueled cars are as follows:

a) engine modifications are very small, the most important being the change in compression ratios from 1:6 to 1:12; the carburetor has to be redesigned since the stoichiometric fuel to air ratio for alcohol is quite different from gasoline; an additional system for the cold start is required on days in which the temperature drops below 10°C (31). Kits for the retrofitting of gasoline engines to run with a 100% ethanol fuel are already available (32).

b) the ethanol consumption, per liter, is 20% higher than with gasoline, even after the compression ratio is increased (31).

The goal set for 1985 will impose several difficulties for the oil refining industries if the production of Diesel oil and fuel oil are to be achieved. Today, the country already processes more gasoline than is consumed and the excess is sold in the international market. The market is very small, mainly for a low quality product as the one produced. As it is unlikely to discover a larger market, another possibility which is under consideration is the exportation of alcohol to be used as an octane booster in countries where environmental concerns limit the use of lead. This solution is quite interesting from the energy point of view. The American market demands that 46%

of the oil be converted into gasoline. The average energy required for processing a barrel of crude oil is 740 MJ (33) distributed among several operations. Reforming and alkylation are mainly conducted to obtain high quality lead free gasoline. Significant energy economy can be obtained if medium quality gasoline is used in place of the high octane gasoline. Figure 4 shows that the apparent consumption decreases with the increase in the octane number, but the real consumption presents a minimum energy cost for different octane numbers as a function of the total amount of lead, since the energy required for processing high quality gasoline also increases. Even more beneficial is the conclusion obtained from Figure 4a which clearly indicates that lead free gasoline requires a real consumption of 600 kcal/10km over what is required for the production of the same octane gasoline with a lead content of 0.6 g/l.

Figure 5 obtained for methyl alcohol is nevertheless a reasonable indicator for ethanol and shows that the addition of 10% alcohol to gasoline increases the octane level by three numbers, which is the same effect as the addition of 0.3 g/l of lead. From this figure and from Figure 4a approximately 400 kcal/10km could be saved (this number is obtained by extrapolation from data from Figure 4a; in the case of minimum gas consumption with 0.4 g/l of lead, 11250 kcal/10km is necessary and the minimum for a gas with 0.15 g/l of lead is 11650 kcal/10 km). Then a mixture with 9 liters of medium gasoline plus 1 liter of alcohol can yield an energy savings of 11,500 kcal (3,600 + 7,800) in the real consumption of oil less the costs for the production of 1 liter of alternative fuel. For the typical case of Brazil, this figure is not bigger than 2,000 kcal as we will show in section 4. Therefore the real economy is 9500 kcal; meaning that the use of one liter of alcohol displaces at least two liters of gasoline.

This calculation could be repeated for blends with 20% of ethanol with the final conclusion that 1 liter of alcohol displaces 1.8 liters of gas. This result is also derived from data shown in Figures 4 and 5 from where we see that the real consumption of gas does not reduce linearly with the increase of the lead content. Following this trend, but in the other extreme, pure ethanol replaces only 0.8 liters of gasoline. So the net energy savings for the world would be two times bigger if alcohol gas blends are used, instead of 100% alcohol fueled cars.

A third option for Brazil would be the use of ethanol in Diesel engines together with the replacement of a part of the fuel oil by some other feedstock suitable as a boiler fuel. The use of ethanol-Diesel blends has been under investigation in the last three years (34,35) and engines have already run with blends as high as 70% ethanol (36). The largest difficulty is due to the high resistance presented by alcohols to self-ignition when compressed, which is measured technically by the cetane number of the fuel. A possible solution is the increase of the cetane number of alcohol through the addition of chemical products with explosive behavior like amyl nitrate.

4. THE ENERGY BALANCE FOR THE PRODUCTION OF ETHANOL

Several papers deal with the problem of assessing the amount of energy in ethanol production. The question is far more important since the basis of the discussion is the amount of oil required to generate the alcohol. If a large amount of energy derived from oil is required, we can conclude that alcohol is a net oil consumer instead of an oil alternative.

Several sources of biomass can be used for ethanol production. In this paper we will analyze the ones that are under commercial use or that have a higher chance of becoming used in the near future. They are sugarcane, cassava, sweet sorghum, corn and wood.

4-I Yields and Productivity

To carry an energy balance it is necessary to assess the ethanol and by-product yields from the feedstocks. The alcohol volume assessment is made from the composition of typical crops, its conversion to sugar and ethanol taking into account the practical limits and the crop productivity as will be described in detail for sugarcane.

Sugarcane is practically the only commercial source of ethanol in Brazil mainly because it can be produced very easily by traditional fermentation techniques and the high energy value of the bagasse. Table 6 shows typical composition of the most common species of sugarcane planted in the southeast part of Brazil.

The classical fermentation process for hexoses (glucoses and fructoses) and sucrose are described by equations A and B respectively.

$$\underset{180\text{g}}{C_6H_{12}0_6} \longrightarrow \underset{92\text{g (64.3m ml at 15°C)}}{2C_2H_50H + 2CO_2 + \text{heat}} \qquad (A)$$

$$\underset{}{C_{12}H_{22}O_{11}} + H_2O \longrightarrow \underset{\substack{\text{glucose fructose}\\ 360\text{g}}}{C_6H_{12}O_6 + C_6H_{12}O_6} \longrightarrow \underset{184\text{g}}{4C_2H_5OH} + 4CO_2 + \text{heat} \qquad \text{(B)}$$

A practical evaluation of the total amount of ethanol obtained must assume an extraction efficiency of 95% for the mono and disaccharide sugars from the crop and also a 95% efficiency in the fermentation process. This means that one ton of sugarcane, with an average composition shown in Table 6, yields 90 liters of ethanol. Using the typical productivity for commercial crops listed in Table 7 we arrive at 4700 liters of ethanol/ha-year.*

4-II Agricultural Expenses

Table 3 presents the energy required for the exploitation of several crops in the southeastern part of Brazil. Sweet sorghum was included using experimental data, since it is not yet exploited on a commercial scale in Brazil.

The energy listed includes direct and indirect expenses; so the energy built-in a liter of Diesel oil is assumed to be 10% higher than its heat value since this is the minimum energy required by the oil refining industry (33,37). More accurate evaluations can be made with the utilization of an input-output matrix already available for the Brazilian economy (38). Labor energy is systematically neglected in the energy evaluation following the prescription of some energy schools (39). However, even in a developing country like Brazil, the human expense in agricultural production is never larger than 5% and its inclusion does not change our results.

The main conclusion derived from Table 3 is that the least energy intensive crops are wood (Eucalyptus and Pinus) with a consumption four times less than any other crop analyzed and seven times less than sugarcane. Using the productivity of each crop it is possible to assess the energy per liter of alcohol required in the agricultural phase for several feedstocks. The result is presented in the last column of Table 8. The expenses account for soil preparation, plantation, harvesting and transportation of the feedstocks up to a distance of 20 km from the farm.

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*This figure is well above the average 3600 liter/ha-year commercially obtained in Brazil distilleries. Inefficient sugar extraction and unavoidable losses associated with large scale production should be the reason for the lower figure.

4-III Industrial Expenses

The conversion of biomass in ethanol is made by several techniques according to the feedstock specie. To evaluate these energies, a complete flow sheet of the plant is required together with a reliable way for computing the built-in energy in the equipment and buildings. The case of sugarcane is the easiest one to evaluate since many industrial units are in operation. It is more difficult to prepare a detailed analysis for the other feedstocks, nevertheless important conclusions can be drawn from the sugarcane flow sheet evaluation, as shown in Figure 2. The input-output Brazilian matrix (38) was used to assess energy built-in capital goods, operation, maintenance and fuel. Table 9 presents the results for a typical unit, with an annual capacity of 18 million liters and assuming an average life of 20 years. As can be seen, the energy expenses come mainly from the fuel required. Fuel is such a large part of the total expenses that it is almost useless to make an accurate assessment of all the other energies. So for a modest precision we can use the fuel energy, usually computed as kg of steam/liter of ethanol as a good means for comparison between different crops. Operational costs are not expected to vary from one feedstock to another but the case of wood deserves a more careful analysis. Table 10 quotes fuel costs for the biomass under analysis.

A comparison drawn between Tables 3 and 9 clearly shows that industrial expenses are at least 3 times larger than the ones in agriculture in the case of corn and almost 50 times more for wood. The amount of energy is so large that it is almost impossible to use noble fuels (oil, natural gas and electricity) in the ethanol processing. This is the main reason for the success of sugarcane as a source of ethanol: as a by-product of the beer, large quantities of fiber are available to be used as a fuel for steam and electricity generation.

Other feedstocks like cassava and corn do not compete with sugarcane either because their by-products are unsuitable as a fuel or the amount of fiber is small. Wood could be used as a feedstock for ethanol and fuel for boiler. One fraction would undergo hydrolysis and the other would supply the energy. Table 10 shows the amount of energy required as being much higher than for sugarcane. Plants in operation in Russia require 25 kg of steam and in Switzerland turn-key plants require 13 kg of steam (40). Even for such high figures, a reasonable amount of wood can be used for hydrolysis because of the large heat value of wood together with the small amount of moisture (20%).

5. THE ECONOMIC PROBLEM

The evaluation of the production of ethanol will be made for only two feedstocks: sugarcane and wood; even so we reclaim calculations to be more precise for sugarcane which is being used extensively in Brazil.

Sugarcane

The evaluation is more realistic for the southeastern part of the country where data is available for the evaluation of the 1976/1977 harvest (21). The size of the investments and of the agricultural yield are presented in Fig. 6 for a hectare of land exploited in a 4 year span. Table 11 presents the costs for sugarcane for three different interest rates.

The capital costs for a distillery have two major components: the fixed investment and the working capital. Working capital includes feedstock expenses and ethanol storage. Table 2 depicts a variation of a factor of 2 in the estimated costs of distilleries. We decided to choose for our base case the price quoted for one of the largest distillery producers (Zanini S.A.): 10^7 dollars for a processing plant of 120,000 1/day, which means 3600 dollars/GJ of ethanol. This price is by far more realistic of the present day market since it is quoted for an autonomous unit and for a large program of fuel replacement, autonomous distilleries being the largest fraction both presently and in the future. Taking this into account we conclude that the cost related with this investment will be in a range between $1.55/GJ up to $3.20/GJ varying with interest rate and pay back time, as shown in Table 12. Operation costs represent $2.20/GJ (21).

As was shown in section 4-I, one hectare produces 226/GJ year of biomass (assuming 18 GJ/ODT) and yields 4700 liters of ethanol or 99 GJ. There is a bagasse excess that will not be considered in the economical evaluation since it is not being used in present day operation. The conversion efficiency of biomass to ethanol is 43.7%, that is, to produce 1 GJ of ethanol it is necessary to buy 2.3 GJ of feedstock. The cost for sugarcane is $3.05/GJ (adding some value to the land and assuming an interest rate of 6%), meaning that the cost of feedstock will add to $6.96/GJ. The other costs are also quoted in Table 13.

Wood

Figure 7 presents the magnitude of fixed investments required for typical Eucalyptus plantations carried in the state of Sao Paulo. Assuming the same interest rate as for sugarcane (6%) we arrive at a cost of $27.60/ODT or $1.55/GJ. Including the land cost, this price will increase to $1.75/GJ; this is a consequence of the high cost of land in the state of Sao Paulo and is characteristic of a very small fraction of the area of the country. For wood farms developed in areas far away from urban centers, the land price decreases significantly and we obtain the same price for the feedstock with or without the addition of cost of land. It is important to notice that this cost estimate is much higher than the cost of wood sold presently in small farms; it is very easy to find wood at a price of $16.5/ODT (including loading, unloading and transportation to a distance as far as 120 km)—this gives a cost of ≃ $1.00/GJ. We believe that this price is more realistic than the previous estimated cost of large scale wood farms and we will use it in our final evaluation. The total expenses for producing ethanol from wood by acid hydrolysis are shown in Table 14 for an interest rate of 6% per year. As in the case of sugarcane, the cost of feedstock is the major component of the final product. This is a consequence of the low efficiency in converting wood to ethanol due to:

a) low yields obtained due to the presence of hemicellulose and lignin in the raw material;

b) significant fraction of wood is used as a fuel for the processing unit. This is a necessity under the assumption of the self-sufficient hectare and the use of lignin in the pig iron industry.

The Cost of Gasoline vs Ethanol

It is imperative to make a comparison between our previous cost evaluation of ethanol and the present day cost of gasoline. To achieve this we will use data from Ref. 41 which is good for the American market.

As shown in Fig. 8, it is necessary to start with 1.12 GJ of oil to produce 1 GJ of gasoline. Furthermore, 0.12 GJ from external sources, which is most commonly obtained from natural gas, has to be used. To be coherent with our previous analysis for ethanol it is important to add capital and operation costs. Instead of going through all these calculations we use another route well established for the production costs of refined oil products in the U.S.A.—they cost 1.64 times more than the raw material (42) which means that gasoline is produced at a cost of $10.50/GJ assuming $35/barrel for oil. In the case of Brazil, the industrial efficiency is probably lower (a general trend observed when comparing developed and developing countries) and a higher price is most likely. There are no present reliable costs published by the state-owned oil company—but for December, 1978 it was quoted as $6.00/GJ before tax. An indirect evaluation can be carried using the consumer's selling prices which are listed for today's market in Table 4. From these prices, 15% has to be subtracted as the cost of distribution and market network ($6.00/barrel) plus the tax of 26.7% over the final price of gasoline, as shown in Fig. 3. This gives a value for the oil derivates ex-refinery of $28.59/barrel (when the average price of crude oil was $22.00/barrel). However, the high price of gasoline in Brazil is something of an artifact, since there are taxes added to cover the low cost of Diesel and fuel oil. Comparison with other countries* suggest that this spread is very atypical and represents a political, not an economic, price of gasoline. Using the spread in price typical from free market economy we arrived at a price of $12.19/GJ for gasoline ex-refinery.

As a final conclusion, alcohol, at least when used as an octane booster where total efficiency is 25% higher than gasoline, has already reached the break-even point as compared with gasoline in Brazil.

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*Diesel is generally 10% less expensive than gasoline ex-refinery and fuel oil 33% as expensive.

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TABLE I

PARTICIPATION OF DIFFERENT ENERGY SOURCES IN SEVERAL COUNTRIES AS PUBLISHED BY UNITED NATIONS 1976

	PRODUCED ENERGY (10^{15}J)					
Country	Coal and Lignin	Oil	Natural Gas	Hydro and Nuclear	Biomass	Total "per capita" (10^9J)
U.S.A.	17250	20950	21300	1770	615	290.0
Brazil	82	386	32	267	867*	14.6
India	2920	367	37	133	2340	9.6
Sudan	-	-	~1	~1	117	6.7
Sweden	~1	-	258	257	15	33.5

*This figure does not agree with the one published by "Balanco Energetico Brasileiro - 1978" prepared by Ministery of Mines and Energy, Brazil. The reason for the discrepancy is:

a) large quantities of wood do not penetrate the commercial market

b) there is an incorrect evaluation of the wood energy in the publication of the Ministery of Mines and Energy as was pointed out in Ref. 43; the wood energy content is under-estimated by 50%.

TABLE 2[†]

PRICE OF ETHANOL DISTILLERIES QUOTED BY SEVERAL SOURCES

	Annexed			Autonomous			
Source	Capital Investment ($/GJ/day) (1)	Scale (m^3/day) (2)	Operating Season (days/year) (3)	Capital Investment ($/GJ/day) (4)	Scale (m^3/day) (5)	Operating Season (days/year) (6)	$\frac{(4)}{(1)}$
Promon (1977-78)	---	---	---	4920	150	180	---
Almeida (1976)	1720	120	180	1890	120	180	1,1
Average for Authorized Brazilian Projects (end 1976)	1950	110	143	3615	154	164	1,85
Average for Sao Paulo Authorized Projects (end 1976)	2065	170	141	2680	165	154	1,3
Zanini, S.A. (1978)				3570	120	---	---

[†] From Ref. 21

TABLE 3+

EVALUATION OF THE ENERGETIC EXPENSES FOR SOME CROPS EXPLOITED IN BRAZIL

Crop / Energetic Expenses	Sugar Cane (Mcal/ha yr.)	Cassava (Mcal/ha yr.)	Sweet Sorghum (Mcal/ha yr.)	Corn (Mcal/ha yr.)	Eucalyptus (Mcal/ha/year)
Labor	---	---	---	---	
Machinery[1]	402	279	787	65	28
Fuel[2]	2239	1491	4217	987	428
Nitrogen (N)[3]	687	347	1665	580	36
Phosphorous (P_2O_5)	89	45	200	107	
Potassium (K_2O)	96	53	133	27	
Lime	37	50	50	82	
Seed[4]	188	118	23	23	
Insecticide	3	24	145	---	59
Herbicide	55	24	96	69	
Total[5]	3796	2431	7319	1940	551

1) Tractors, trucks and other machines - assuming a half-life of ten years for the tractor and other machines and five for the truck.

2) Fuel energy value includes the expenses for its processing at the oil refinery.

3) These energy expenses are derived from the American economy, since until 1970, very little synthetic fertilizer was produced in the country.

4) Data are evaluated assuming that sugar cane and sweet sorghum seeds require 30% more energy than a commercial **equivalent crop.**

5) The energy evaluation includes feedstock transportation up to a distance of 20 km for its processing.

From Refs. 44 and 45

TABLE 4[†]

GOALS PROPOSED BY THE NATIONAL ALCOHOL PROGRAM IN 1975

Production (liters/year) x 10^9		Area Required for the Sugar Cane Crop (x 1000 ha)
Scenario I	3	1100
Scenario II	16	4400
Scenario III	22	6000
Scenario IV	33	9000

(1) 20% ethanol blend in gasoline plus 10^9 liters for industrial use.
(2) 100% ethanol to replace gasoline plus 10^9 liters for industrial use.
(3) 100% ethanol to replace gasoline and 50% ethanol - Diesel or blend.
(4) 100% ethanol to replace gasoline and Diesel oil.

[†] From Ref. 46

TABLE 5†

RELATIVE COMPOSITION AND CURRENT COST (APRIL 1980) OF THE MORE COMMON OIL DERIVATIVES IN BRAZIL

Oil Derivatives	Percent Fraction (%)	A Amount per Barrel (liters)	B Cost ($1/liter)	A x B
Gasoline	26	36.4	.542	19.72
Diesel oil	32	44.8	.25	11.2
Fuel oil	32	44.8	.125	5.6
LNG	6.5	9.1	.25	2.28
Others	3.5	4.9	.25	1.23
TOTAL		140		40.03

Assuming the useful content of a barrel equal 140 liters. This is a reasonable assumption since significant amounts of oil are expended for the derivatives' processing.

Average price of oil at $22.00/barrel.

†From Ref. 19

TABLE 6[†]
TYPICAL COMPOSITION OF SUGAR CANE EXPLOITED IN THE SOUTHEAST PART OF BRAZIL

Component	% By Weight
Sucrose	12-16
Reducing Sugars (glucose and fructose)	0.2 - 1.5
Total Fermentable Sugars (expressed as % of glucose)	13-17
Fiber	9-13
Moisture	70-73

[†] From Ref. 47

TABLE 7
TYPICAL YIELDS FROM COMMERCIAL CROPS OF SUGAR CANE IN THE SOUTHEAST PART OF BRAZIL[†]

Cycle	Number of Harvestings	Total Production (t)	Production By Harvesting (t)	Yields (t/ha/yr.)	Yields (t/ha/mo.)
4	3	180-240	60-80	45-60	4.3-5.7
		210*	70*	52*	5.0*

[†] From Ref. 47

*Average

TABLE 8

Yields, energy invested in agriculture (planting, harvesting and transportation) and its ratio for some crops in the United States and Brazil.

Crop	Yield (Y) dry mt.ton ha.year	Agricultural Energy (E) (Mcal/ha/year)	E/Y (Mcal/dry/mt.ton)
U.S.A.			
Sugar cane	6.21 2)	6900 1)	1111
Wheat	1.63 2)	2080 1)	1276
Soybean	1.44 2)	7250 1)	5035
Corn	4.90 3)	6596 3)	1346
Forest logging	15.4	570	37 4)
Eucalyptus	---	---	---
Pinus	---	---	---
BRAZIL			
Sugar cane	14.81	3018	204
Wheat	1.06	1378	1305
Soybean	1.85	1882	1018
Corn	2.42	1951	806
Forest logging	---	---	---
Eucalyptus	11.9 5)	530	45
Pinus	14.6 5)	427	29

Notes: 1) From ref. 54
2) From ref. 48
3) Average value from ref. 54, 55, 56 and 57
4) From ref. 58, includes only energy for harvesting
5) From ref. 47

TABLE 9[†]

ENERGY REQUIRED FOR THE INDUSTRIAL CONVERSION OF SUGAR CANE TO ETHANOL -- TYPICAL BRAZILIAN DISTILLERY

Industrial Expenses	Energy $(\frac{10^9\ \text{kcal}}{\text{year}})$	
Capital Goods (average life 20 years)	3.04	
Operation	2.36	
Maintenance	3.04	
Fuel	88.23	A
Total	97.23	
Productivity per Year (x 10^6 l)	18	B
$\frac{\text{Total Industrial Energy - A}}{\text{Alcohol Yields - B}}$ (A/B)	5.4 Mcal/l	

[†] From Ref. 45

TABLE 10†

INDUSTRIAL FUEL EXPENSES FOR THE PROCESSING OF SEVERAL FEEDSTOCKS

Feedstock	Energy (kg of steam/l of ethanol)
Sugar Cane	5.5
Cassava	6.5
Sweet Sorghum	5.5
Corn	6.5*
Eucalyptus Pinus	25 - 13

† From Refs. 25, 40

* This figure is evaluated for the Brazilian technology. In the United States, much more energy is required (see Ref. 48) since stillage is dried to be used as cattle feed.

TABLE 11†

ECONOMICAL EXPENSES FOR THE SUGAR CANE CROP

1. $\bar{E}$		
(average energy value of biomass) I		226 GJ/year
2. $I_a\overline{CRF}_a$	x = 12% (VII)	\$272/year
(clearing & purchasing land levelized annual revenue) II	x = 6% (VII)	\$135/year
	x = 3.5% (VII)	\$32/year
3. $I_b\overline{CRF}_b$	x = 12%	\$105/year
(purchased equipment levelized annual revenue) III	x = 6%	\$88/year
	x = 3.6%	\$79/year
4. $I_c\overline{CRF}_c$	x = 12%	\$217/year
(investment in planting levelized annual revenue) IV	x = 6%	\$166/year
	x= 3.6%	\$147/year
5. $\bar{f}_{OM}$	x = 12%	\$300/year
(operating and maintenance costs) V	x = 6%	\$298/year
	x = 3.6%	\$297/year
6. $\bar{R} = I_a\overline{CRF}_a + I_b\overline{CRF}_b + I_c\overline{CRF}_c + \bar{f}_{OM}$	x = 12%	\$834/year
(total levelized annual revenue requirement)	x = 6%	\$687/year
	x = 3.6%	\$605/year
7. $\bar{C}$ ($\bar{R}/\bar{E}$)	x = 12%	\$3.95/GJ
	x = 6%	\$3.04/GJ
	x = 3.6%	\$2.67/GJ
8. $\bar{R}$	x = 12%	\$630/year
(excluding land purchase) VI	x = 6%	\$565/year
	x = 3.6%	\$531/year
9. $\bar{C}$	x = 12%	\$2.78/GJ
(excluding land purchase)	x = 6%	\$2.50/GJ
	x = 3.6%	\$2.38/GJ

†From Ref. 21

I) Defined as $\bar{E} = \sum_{i=1}^{M} E_i$

E_i... The energy output in i(th) year

II) Assuming a price of land equal to U.S. $1760/ha; clearing costs are estimated to be about $500/ha.

III) From Ref. 49 there are about 12 days of tractor time and 7 days of truck time per hectare over 4 years, or, in practice 42 months. Because of maintenance, weather, and the timing of agricultural operations we estimate that one tractor can cover 50 ha and one truck 100 ha. We estimate a tractor to cost U.S. $20,000 and a truck U.S. $15,000. Auxiliary equipment is estimated at U.S. $10,000 covering 100 ha. We therefore obtain an investment in equipment of U.S. $650/ha. Harvesting is done by hand. Depreciation time is taken to be 10 years.

IV) 25% of labor, fertilizer, machine operation, and other.

V) Includes harvesting and all other costs not stated earlier.

VI) Excludes the land purchase investment (U.S. $1760/ha) plus the interest accumulated on this investment during a six month period when land is idle prior to planting.

VII) All calculations are made for 3 different interest rates; 12% as suggested by Little and Mirrless (50) for a developing country like Brazil; 6% as our base case and 3.6% as the cost of money for a regulated industry in a developed country.

TABLE 12[†]

CAPITAL INVESTMENT COSTS

	Average life of the distillery	15 years	20 years
		Cost ($/GJ)	
Interest (%)			
3.6		1.90	1.55
6.0		2.25	1.90
12.0		3.20	2.90

[†] From Ref. 21

TABLE 13[†]

PRODUCTION COSTS OF ETHANOL DERIVED FROM SUGAR CANE

	($/GJ of anhydrous ethanol)
Fixed investment in distillery	2.25
Operation and Maintenance	2.20
Biomass input	6.99
By-product credit	- 0.70 (I)
Working capital for operation	0.10
Sub-total	12.24
Product inventory	0.45 (II)
Total	12.69

From Ref. 21

[†] Updated to 1980 dollar value from data presented in Ref. 21. Assuming that the large devaluation of Brazilian money occurred in December, 1978 (30%) was enough to offset the dollar inflation in 1978 and 1979.

(I) By-product credit is calculated as the difference between the cost of direct application of stillage as fertilizer and the cost of conventional fertilizers.

(II) If alcohol is to be a major component of the energy supply system for transport its supply must be constant over the year. This implies an inventory equal to at least one half of the output of of a distillery operating 165 days per year. This adds a significant cost to the final product.

TABLE 14[†]

PRODUCTION COSTS OF ETHANOL DERIVED FROM WOOD (ACID HYDROLYSIS PROCESS)

	($/GJ)
Fixed investment in processing plant	3.72
Operation and maintenance	2.00
Biomass input (I)	6.20
By-product credit (II)	- 1.80
Total	10.12

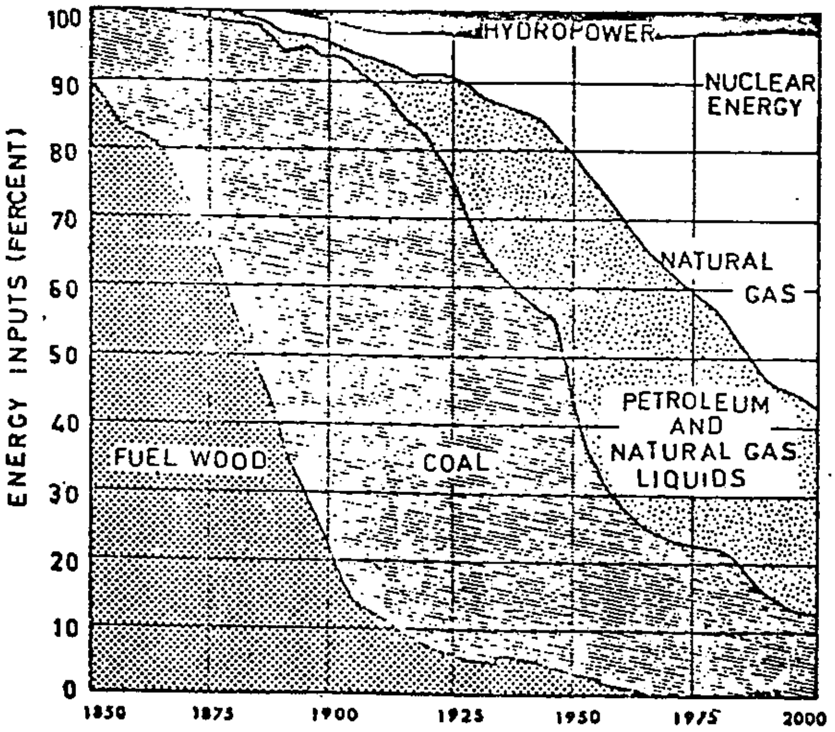
[†] Update to 1980 dollar value from data presented in Ref. 21. Assuming that the large devaluation of Brazilian money occurred in December 1979 (30%) was enough to offset the dollar inflation in 1978 and 79.

I) The cost of biomass is evaluated under the assumption of self-suficient hectare: 60% of wood undergoes hydrolysis and 40% is used as fuel for the industrial plant as suggested by the performance of the swiss factories and presented in fig. 9. 1ODT of wood yields 230 liters of ethanol, and 1 ha yields 12 ODT which means (12x230x0,6 = 1650) 1650 ℓ/ha/year of ethanol.Since the heat contend of ethanol and wood are 21GJ/m^3 and 18GJ/ODT, respectively, the hydrolysis process converts 216/GJ of wood (12ODT x 18GJ/ODT) in 34,5GJ of ethanol with a conversion efficiency of 16%.

II) The model assumed is such that lignin is a by-product sold to the pig iron industry. Lignin is produced at a rate of 1.54 GJ of lignin/GJ of ethanol which means a credit od $1.80/GJ of ethanol.

Figure 1

HYSTORICAL EVOLUTION OF ENERGY SOURCES IN USA*



*From ref. 51

Figure 2

BLOCK DIAGRAM - ETHANOL DISTILLERY

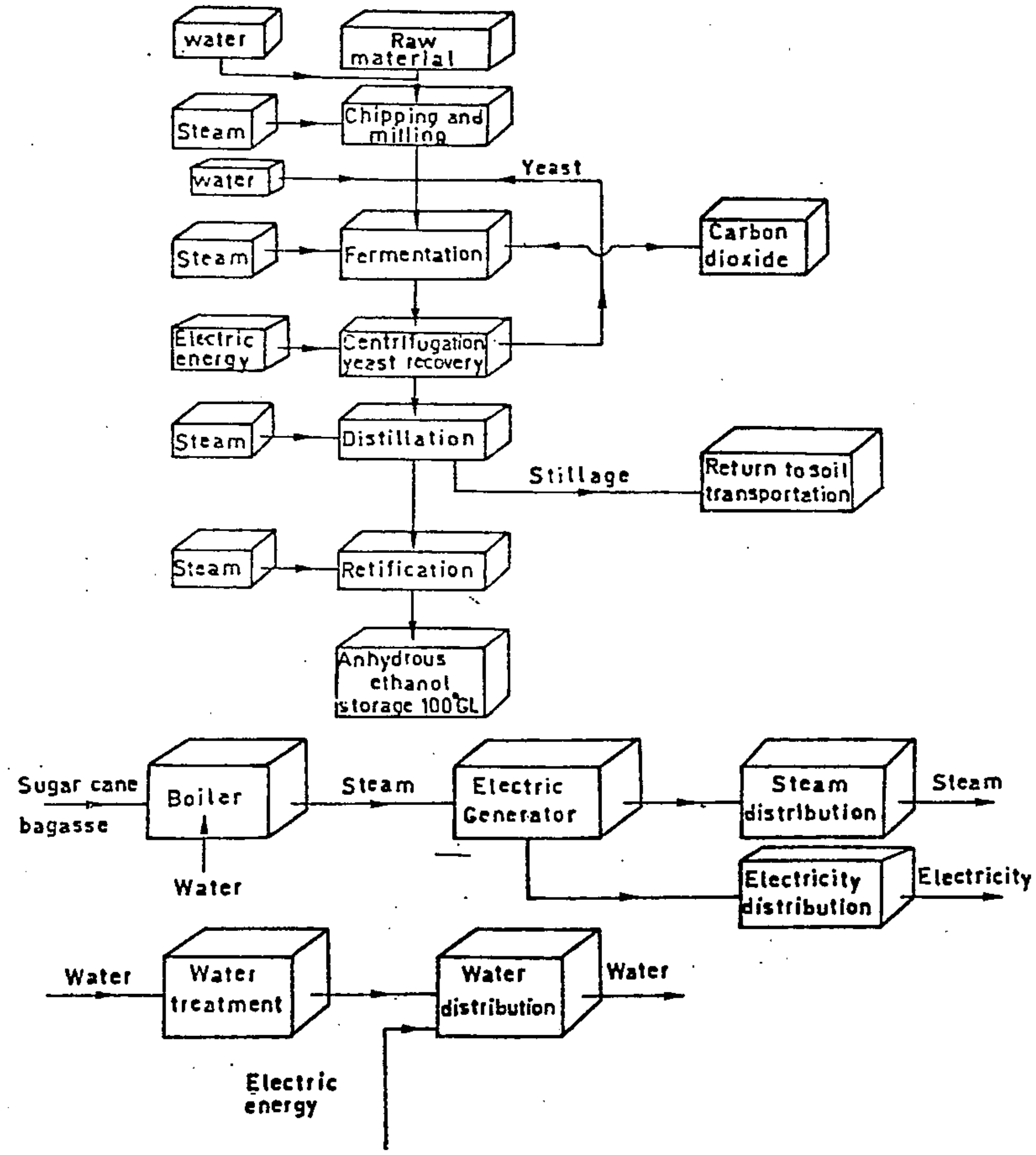
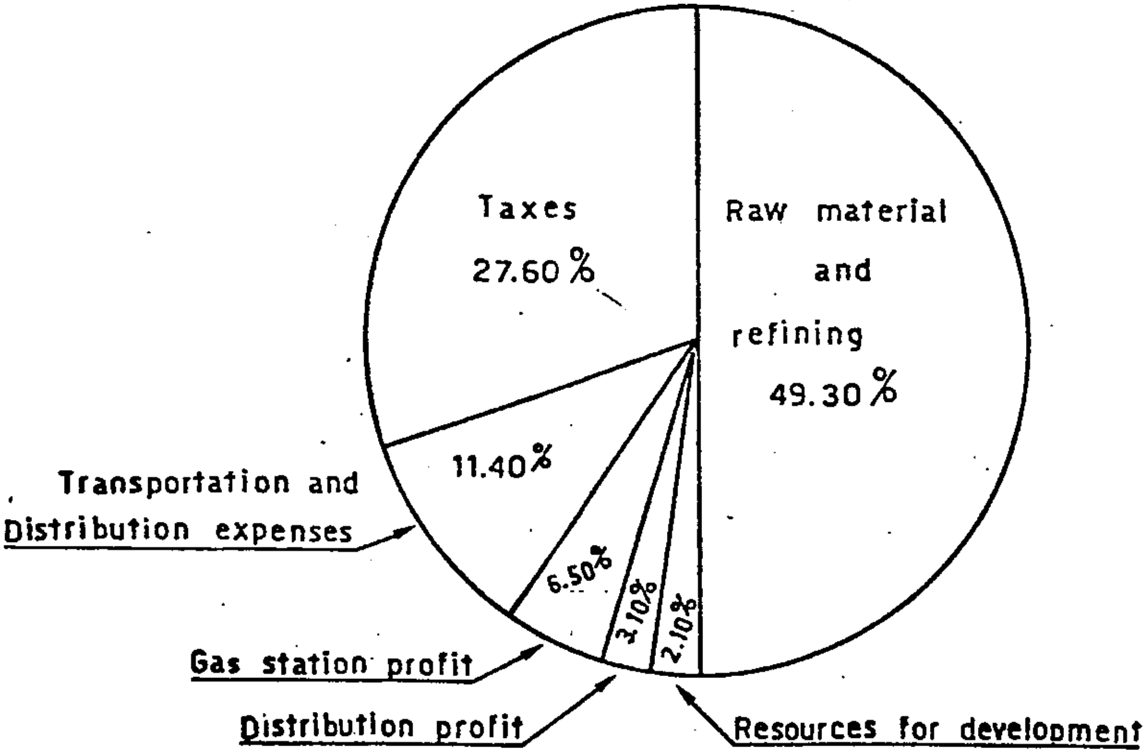


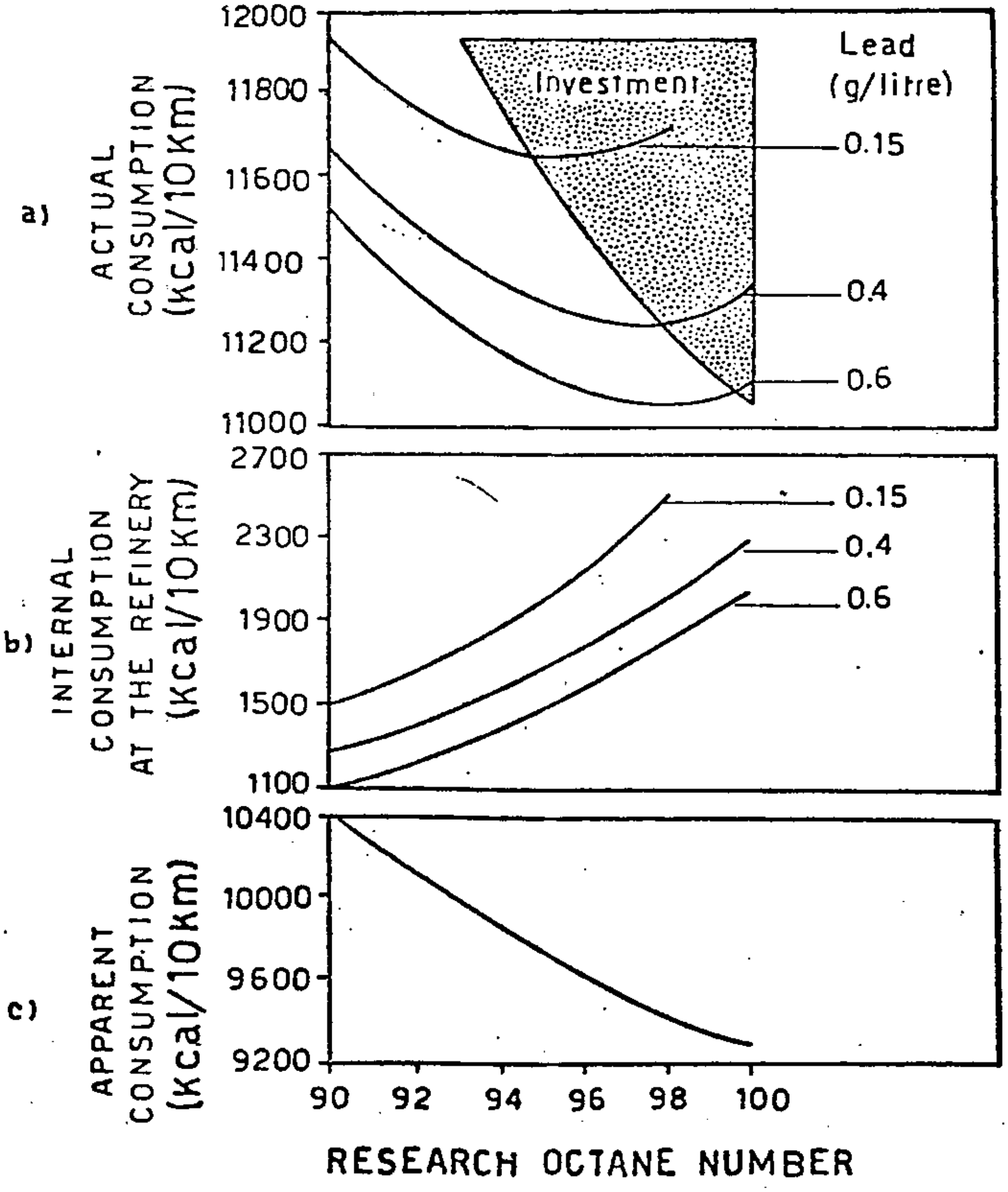
Figure 3

PRICE STRUTURE OF GASOLINE IN BRAZIL [+]



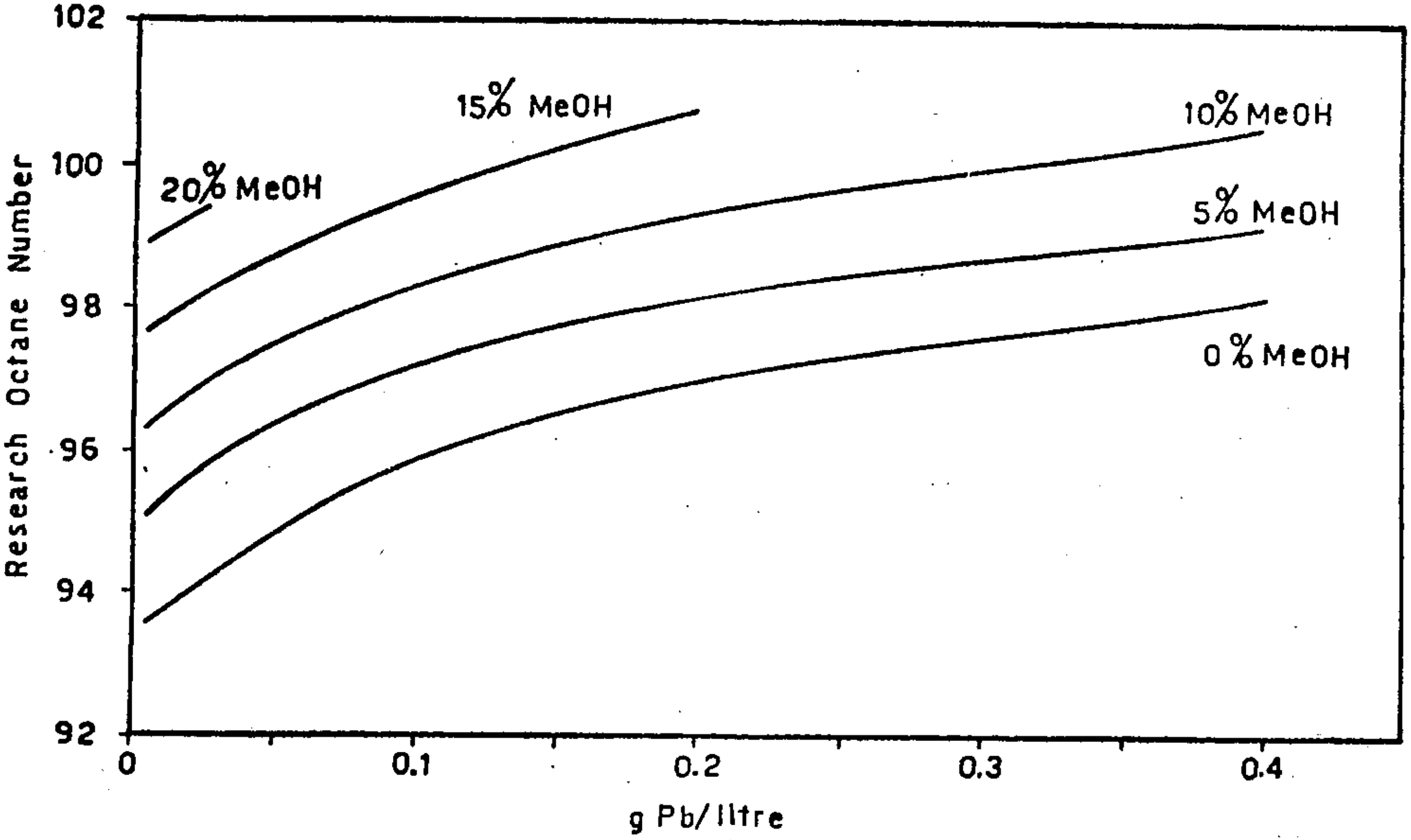
[+] From ref. 52

FIGURE 4 -VARIATION IN APPARENT AND ACTUAL CONSUMPTION WITH OCTANE NUMBER †



† From ref. 53

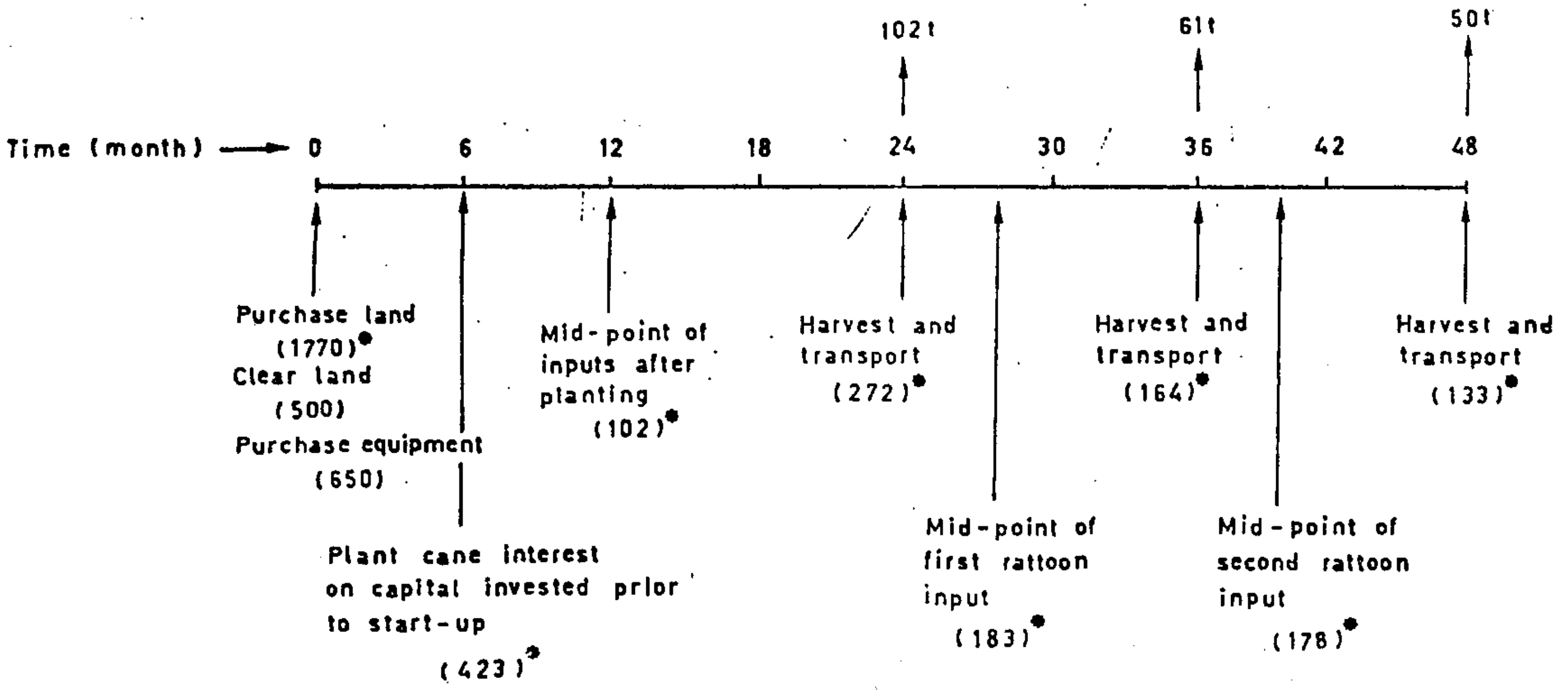
FIGURE 5 - METHANOL IN OLEFINIC GASOLINE - RON RESPONSE WITH · TEL †



† From ref. 53

Figure 6

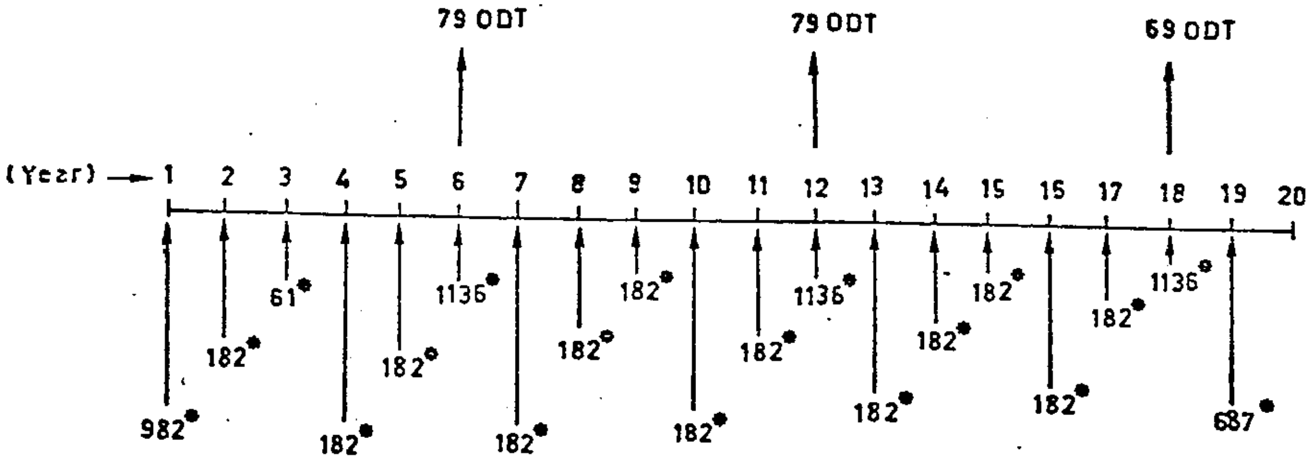
TIMING AND MAGNITUDE OF COST AND OUTPUTS OVER FOUR YEAR SUGAR CANE CYCLE IN SOUTHEAST OF BRAZIL



*Update to 1980 dollar value from data presented in Ref.21. Assuming that the large devaluation of Brazilian money occurred in December 1979 (30%) was enough to offset the dollar inflation in 1978 and 79.

Figure 7

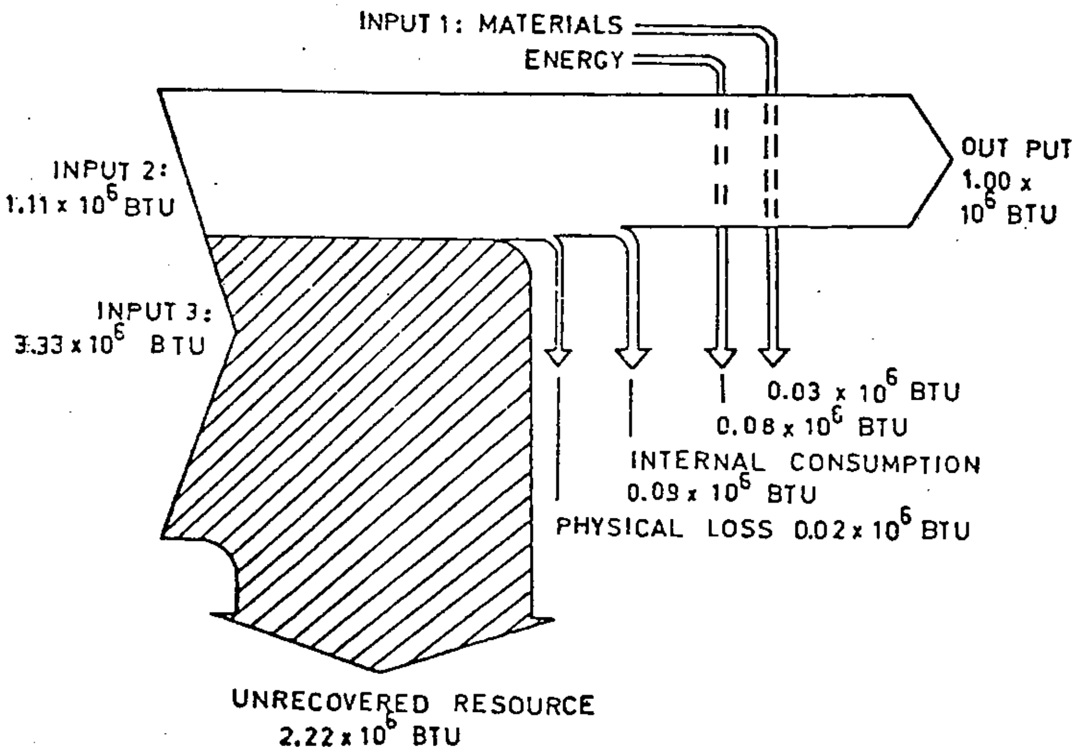
COST AND TIMING DISTRIBUTION OF INPUTS AND OUTPUTS IN AN EUCALIPTUS WOOD FARM IN BRAZIL



* Update to 1980 dollar value from data presented in Ref.21. Assuming that the large devaluation of Brazilian money occurred in December 1979 (30%) was enough to offset the dollar inflation in 1978 and 79.

FIGURE 8

ENERGY COSTS FOR THE PRODUCTION OF GASOLINE †



† From ref. 41

GASOHOL OUTLOOK FOR U.S. SUGAR AND GRAIN CROPS

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

BATTELLE COLUMBUS LABORATORIES
Columbus, Ohio

GASOHOL OUTLOOK FOR U.S. SUGAR AND GRAIN CROPS

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GASOHOL OUTLOOK FOR U.S. SUGAR AND GRAIN CROPS

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ABSTRACT

THE FACTORS influencing alcohol production from sugar crops and grain include the need for fuel alcohol, the resource base, process options, economics, subsidies and markets. The analysis of these factors provides insight into where alcohol is coming from and where it is going. We conclude that most U.S. fuel alcohol in the early 1980s will be made from grain, specifically corn and milo. Sugar crops are too expensive for fuel alcohol. Fuel alcohol production will grow to about 2 billion gallons by mid-decade. Further expansion will depend upon the availability of petroleum and the development of ethanol from cellulose technologies.

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GASOHOL OUTLOOK FOR U.S. SUGAR AND GRAIN CROPS

NEED

IN 1973 and early 1974, the OPEC oil prices increased dramatically. The average OPEC sales price in 1973 was \$3.39/bbl, which increased to an average of \$11.28/bbl in 1974. Further price rises occurred throughout the decade, but were largest in 1979 and 1980. In September, 1980, the average OPEC sales price was \$31.59/bbl, and spot gasoline prices in New York and Rotterdam have recently been \$40 and \$44/bbl, respectively. Furthermore, the oil producing nations have indicated a desire to exert more control over world oil production and prices, although to date OPEC has not fully used its potential monopoly power.

The increasing prices of petroleum in world markets and the realization that the consuming countries were at the mercy of the exporting nations prompted a search for alternative fuels which could reduce petroleum imports. In the United States, 1979 energy consumption was 80 quadrillion Btu, of which 18.4 quadrillion Btu were imported. Of these imports, 16.9 quadrillion Btu were crude oil and refined petroleum products. This is equivalent to net petroleum imports of 7.9 million barrels per day in 1979.

Alcohol fuels, both ethanol and methanol, provide an alternative source of energy which has the potential to somewhat reduce the importation of liquid petroleum fuels. To date, most of the emphasis has been on ethanol made from grains and sugar crops. The government estimates that between 80 and 100 million gallons of fuel-grade ethanol are currently being produced annually in the United States. Furthermore, we believe there are about 600 plants with capacities ranging from slightly over 1 million gallons to over 100 million gallons in various stages of planning. In one state, we have recently identified planned alcohol ventures totalling 530 million gallons ethanol capacity per year. These planned alcohol ventures use both grain and sugar as raw materials. However, it seems unlikely that more than a fraction of these ventures will become reality.

The Department of Energy has set goals for alcohol production of 920 million gallons per year by the end of 1982, and 1.8 billion gallons per year by the end of 1985.

RESOURCE BASE

Ethanol can be made from a wide variety of crops containing either sugar or starch. These crops include sugarcane, sugarbeets, corn, milo, wheat, and potatoes.

Sugar Crops. Throughout most of the United States sugar crops are not currently available for alcohol production. U.S. sugarcane is grown only in Hawaii, Texas, Louisiana, Florida, and Puerto Rico. In addition, sugarbeets are grown in many northern states, but production has been declining. Beet sugar is usually more expensive to produce than cane sugar. All U.S. sugar production now goes to food uses. At present, and probable future, world sugar prices, it is unlikely that current sugar crops will be used for alcohol production in the United States. Recent prices for selected alcohol feedstocks are shown in Table 1.

A major advantage of sugar crops is the high alcohol yield per acre of cultivated land. As can be seen in Table 2, much more alcohol can be produced from an acre of sugarcane than from an acre of grain.

All sugar crops have a major disadvantage compared to starch crops for alcohol manufacture. Sugar crops or dilute sugar solutions obtained from them cannot be stored without microbial degradation. Therefore, they must be either concentrated to high-test molasses (an expensive operation) or the alcohol plant must be operated only during the harvesting season. This latter approach increases capital charges and increases the price of alcohol. This is discussed in a later section.

Grains and Tubers. The two grains most likely to be used for alcohol manufacture are corn and milo (grain sorghum). Other grains like wheat, oats, rice, and barley are suitable, but they are much more expensive.

Potatoes and other starch tubers are also suitable for alcohol. Food-quality potatoes are too expensive for alcohol manufacture, but adequate quantities of low value cull potatoes are available at some locations in the northern United States. We believe that only a small fraction of U.S. alcohol production will be made from potatoes or other starchy tubers.

Most U.S. alcohol production in this decade will be made from corn and possibly milo. At a yield of 2.6 gallons per bushel, each million gallons of alcohol requires 385,000 bushels of grain. To reach the 2 billion gallon level, we shall need to commit 770 million bushels of grain. This is ten percent of the record 1979 corn crop (7.76 billion bushels) and about 12 percent of the estimated 1980 crop of 6.53 billion bushels. The 2 billion gallons ethanol would replace about 1.3 billion gallons gasoline or 1.2 percent of gasoline consumption. This assumes that mileage is proportional to the energy content of the fuel, which GM has demonstrated in the new cars with automatic carburetor adjustment.

There is probably adequate land available to produce additional grain for alcohol feedstock. Each billion gallons ethanol requires 3.5 to 4 million acres of crop land. Recently there were 14.8 million acres in the soil bank and another 24 million acres in pasture land which could be converted to crop land with limited risk of soil erosion. Finally, the byproduct animal feed from alcohol plants would displace some soybeans. For each billion gallons of alcohol made from corn, about 2 million acres of soybeans could be taken out of production.

Future Feedstocks. Several feedstocks which are not now available in commercial quantities have been suggested for alcohol manufacture. These include sweet sorghum, fodder beets, Jerusalem artichokes, and cattails. All of these potential feedstocks require research in crop management and possibly genetic improvements.

Sweet sorghum has about the same processing characteristics as sugarcane. Unlike sugarcane, however, sweet sorghum can be grown in much of the United States. It has the potential to provide high yields–the equivalent of about 350-500 gallons per acre. At the present time, sweet sorghum is not widely grown. It is unlikely to make any significant contribution to alcohol production before the end of the decade.

Fodder beets contain both sugar and starch. They are said to have higher yields of fermentable carbohydrates per acre than sugar beets. In addition, they have better storage characteristics and are easier to grow than sugar beets. However, they are subject to diseases and pest damage. More research remains to be done before fodder beets are commercialized.

Jerusalem artichokes have shown potential as an alternative sugar crop for fermentation. They can be grown in the northern United States and do not require high fertilization. Processes to convert the fructose polymer (inulin) to fermentable sugars have not passed the laboratory stage. The true potential has not yet been fully evaluated.

Cattails have been recently suggested as a source of easily grown starch for fermentation. Cattails can be grown on low quality land in much of the United States. The research on cattails is in its early stages, and we do not believe that cattails will become a promising feedstock for widespread alcohol manufacture.

PROCESS OPTIONS

The technologies for the manufacture of ethyl alcohol from grain and sugar crops have evolved primarily from the beverage industry. Several modifications and improvements have been made to convert from beverage alcohol technology to modern fuel-alcohol technology. One of the major changes has been in the alcohol recovery system. Whereas in beverage manufacture the removal of trace impurities which affect the flavor is important, the fusel oils are generally blended into fuel-grade alcohol. Furthermore, most of the existing beverage alcohol plants were built in the mid-twentieth century when fuel cost was not an important criteria. The modern alcohol plant designs have much more energy efficient distillation systems. Furthermore, several organizations are continuing research on the recovery of fuel-grade alcohol from fermentation beers, and the energy requirements to make anhydrous alcohol may be further reduced in the near future.

Traditionally, when ethanol is made from sugarcane there has been an excess of bagasse which is used to fuel the alcohol plant. Therefore, energy efficiency has been less of a concern in sugar-based plants. As fuel prices rise, however, alternative uses are being found for bagasse as a fuel. The CEER Energy Cane Concept is an example of this. Consequently, we would expect to see the adoption of more energy efficient technologies in the future.

The current commercial technologies for manufacture of alcohol from grain employ either dry or wet milling technologies. The corn wet milling plants are more expensive to build, but the higher capital cost is offset by higher byproduct credits. The byproducts from wet milling alcohol plants are corn oil, gluten feed, and gluten meal worth about $0.65 per gallon alcohol produced at today's prices. This compares with byproduct distillers dark grains and solubles worth about $0.39 per gallon.

Byproduct carbon dioxide is obtained from all alcohol fermentations. The carbon dioxide is marketable only in a few special cases.

New technologies which will manufacture ethanol from lignocellulosic materials like wood or agricultural residues are currently under development. These technologies are still in the research stages. Nevertheless, many observers believe that cellulosic materials will displace grains as a major alcohol feedstock by the end of the decade.

New processes are currently being developed for the manufacture of alcohol from starch and sugar feedstocks. Some of these new technologies are reported to significantly reduce the capital investment required. These new technologies have not yet been translated into commercial realities, however.

In addition to the commercial alcohol plants, some projections include numerous small, farm-scale alcohol plants contributing to alcohol supply. One DOE report projects 2200 small plants (under 1 million gallons per year) producing 660 million gallons fuel alcohol by 1985.* This estimate seems overly optimistic. In the first place, most on-farm stills are much smaller than this 300,000 gallon per year average. In the second place, although there is much interest in alcohol, few farmers are spending money as yet. Most farmers seem more interested in raising grain prices than in making alcohol. They would probably prefer to stay out of the alcohol business unless that was the only way to obtain higher prices. Although many farm-size stills will be built, we do not anticipate that they will provide a large fraction of the nation's fuel alcohol.

ECONOMICS

The most economic feedstocks for ethanol manufacture using current technology are corn and milo. Like most agricultural commodities, corn prices can fluctuate over a wide range. During the past decade, Chicago corn prices have ranged from a low of about $1.20/bushel in 1970 and 1972 to a high of about $3.40/bushel in 1980. Local prices in the corn belt and elsewhere can vary considerably from the quoted Chicago prices. With corn at $2.80/bushel and dried distillers grain at $132/ton, the net feedstock cost is about $0.62/gallon and the net manufacturing cost in a commercial-scale plant is about $1.60/gallon. The manufacturing cost, including profit, will vary with a specific plant design and location, but generally we believe that the total cost is in this range.

The manufacture of alcohol from sugarcane is very sensitive to the sugar value and to the

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* Draft copy, A Guide to Commercial Scale Ethanol Production and Financing (October, 1980).

growing season. One of the technical disadvantages of using sugar crops is the inability to store them for extended periods. If sugarcane were valued at $25/ton, then the feedstock cost per gallon of alcohol would be about $1.60/gallon. With a 180-day growing season, the total manufacturing cost of ethanol from sugarcane would be about $3/gallon in a new plant. With sugar at its current high price, the manufacture of fuel alcohol from sugar would appear generally uneconomic. Furthermore, the land available for sugarcane production in the United States is quite limited.

There is some possibility that sweet sorghum, which is very similar to sugarcane in its processing characteristics, may be grown throughout much of the United States. Sweet sorghum is not a widely grown crop at present, however. While we believe that sweet sorghum may be an economic crop to grow for the manufacture of fuel alcohol, it will be at least mid-decade before this can be confirmed. The relatively short harvesting season (about 90 days) for sweet sorghum will adversely affect the manufacturing costs unless an economic storage system is devised.

The manufacture of ethanol from cellulosic residues is still in the research and development stages. We have examined several processes for the manufacture of ethanol from cellulose. The most economic of these appears to have manufacturing costs of about $1.28/gallon with a cellulosic feedstock like corn stover at $30/dry ton. Although it is difficult to speculate on the final cost of such advanced technologies by the time they are ready for commercialization, they do appear to be promising.

The manufacturing cost of various alcohol fuels is compared in Table 3. These costs generally do not compare favorably with gasoline at $1/gallon. The recent gasoline prices on the Rotterdam spot market were between $38 and $46/barrel, or $0.90 to $1.10/gallon. With present economics, it appears that alcohol may need some form of subsidy to be competitive.

It is somewhat misleading to directly compare the price of alcohol with the price of gasoline. There are two other factors which need to be considered. The first of these is that the ethanol contains only 2/3 the heating value per gallon as does gasoline. The second is that ethanol has a high blending octane and may in fact have more value as an octane improver than as a gasoline. The value of ethanol as an octane improver depends upon the quality of the raw gasoline and the options available to the blender. Some recent estimates have indicated that the octane improvement value ranges from $0.10 to $0.30/gallon ethanol.

INCENTIVES

In order to promote the use of alcohol fuels, the government has devised a number of incentives. The largest incentive is the reduction of the excise taxes on gasoline alcohol blends. For gasohol, or blends containing 10 percent alcohol, the federal excise tax of 4¢/gallon is waived. This is equivalent to a subsidy of 40¢/gallon of alcohol. The various state excise tax reductions vary from 1¢ in Connecticut to 10¢ in Iowa. The Iowa exemption of 10¢ is only an effective exemption of about 6.4¢ because a 3 percent sales tax is imposed on fuels which are exempt from the state road use tax. The greatest state subsidy occurs in the State of Arkansas, which has a 9.5¢/gallon tax exemption for gasohol. In total, 24 states have tax exemptions for gasohol, and most of these are in the 4-5¢/gallon range. Many of the state tax exemptions have either a decreasing tax exemption or an expiration date. Furthermore, the gasohol tax exemption is restricted in many states to alcohol produced from crops grown within the state, or blended within the state. The states which have state tax exemptions are illustrated in Figure 1. Other incentives for alcohol production include a ten percent investment tax credit on equipment used in alcohol manufacture, which is in addition to the normal ten percent investment tax credit, and various property sales and/or income tax incentives provided by the states. Finally, there are a number of federal loan and guarantee programs available for alcohol plants.

The state and federal excise tax exemptions are by far the largest incentives and subsidies for alcohol manufacture. When the excise tax incentives are considered, the economics of alcohol from grain appear competitive with gasoline.

MARKET ACCEPTANCE

Consumers appear to have accepted gasohol. In 1979, about 50 million gallons of ethanol were blended with gasoline and sold through about 2,000 retail outlets. Major alcohol producers appear to have difficulty keeping up with demand and have announced several plant expansions.

Most gasohol sales have been in the corn belt where there appears to be deep support for fuel made from farm products. The long standing state subsidies also help. Not surprisingly, there appears to be a correlation between the subsidies and the sale and manufacture of fuel alcohol.

Consumers have been willing to pay a premium for gasohol over unleaded regular. Perhaps this is due to the higher octane of current gasohol, perhaps due to a patriotic urge to reduce petroleum imports.

Recently, gasoline retailers' and wholesalers' interest in gasohol has waned. This is partly because of a temporary gasoline surplus which is widening the cost differential between gasoline and gasohol, partly to the special attention needed to keep water from gasohol, and partly because many petroleum companies are developing unleaded premium grades of gasoline.

We believe that dealer interest in gasohol will increase in times of tight supply. Also, dealers and jobbers would be more interested in gasohol if they were given a slice of the subsidy pie.

OUTLOOK FOR ALCOHOL FUELS

To summarize, alcohol fuels are growing rapidly. Last year, production was about 50 million gallons. If announced capacity is built, capacity will exceed 900 million gallons in 1983. Alcohol capacity will probably be about 2 billion gallons by mid-decade.

Beyond mid-decade the outlook is not clear. The economics of alcohol from sugar crops are very unfavorable. Alcohol from grain is competitive with petroleum only if subsidized. Grain alcohol may be competitive with alternative fuels, however. Grain, particularly corn and milo, will be the preferred feedstock for alcohol in the early 1980s.

The cost of subsidization is high, and the subsidies currently reduce road maintenance budgets. Furthermore, the creation of a significant fuel alcohol industry will increase grain and meat prices. Unless there is a petroleum shortage in the first half of the decade, we expect public support for alcohol fuels from grain to diminish. The growth of fuel alcohol plants will slow. Attention will be turned from alcohol fuels by fermentation to higher value chemical products.

The reduction in public support for alcohol from grain and sugar crops will provide an opportunity in the latter part of the decade for alcohol from lignocellulose. Whether or not alcohol fuels continue to grow depends in large measure on the success of current research and development on lignocellulosic technologies. For example, the sugar crops (sugarcane and sweet sorghum) have considerable potential as ethanol resources if technology to convert lignocellulose contained in the stalks to ethanol achieves commercialization.

ALCOHOL RESEARCH AND DEVELOPMENT OUTLOOK FOR PUERTO RICO

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

Caribe Hilton Hotel, San Juan, Puerto Rico
November 24 and 25, 1980

Contributed By

THE UPR AGRICULTURAL EXPERIMENT STATION
Rum Pilot Plant, Río Piedras

ALCOHOL RESEARCH AND DEVELOPMENT OUTLOOK FOR PUERTO RICO

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ALCOHOL RESEARCH AND DEVELOPMENT OUTLOOK FOR PUERTO RICO

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ABSTRACT

ALCOHOL research in Puerto Rico is directed primarily to the needs of the Puerto Rican Rum Industry. Most of this research is conducted at the Rum Pilot Plant of the Agricultural Experiment Station.

The research program discussed places special emphasis at present and in the immediate future on raw material and the fermentation process in search for efficient processes which will minimize the effects of scarcity of raw material, energy costs and pollution control.

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ALCOHOL RESEARCH AND DEVELOPMENT OUTLOOK FOR PUERTO RICO

INTRODUCTION

IN PUERTO RICO, the major part of the research on alcohol is conducted at the Rum Pilot Plant, which is a department of the Agricultural Experiment Station of the University of Puerto Rico. The Rum Pilot Plant was created by the Legislature in 1948 and its main purpose is to provide scientific support to the Puerto Rican Rum Industry. It's main objective, therefore, is to assist local rum manufacturers in obtaining and maintaining high quality rum. The Plant is equipped with semi-industiral fermentation and distillation facilities, as well as chemical and bacteriological laboratories and an aging warehouse. It is staffed with experienced chemists and bacteriologists and has several engineers under part-time contracts.

Up to 12 years ago the rum industry in Puerto Rico was in fairly good shape. The market was good, with a strong increasing trend. Raw material was relatively cheap and abundant and, with the exception of union struggles now and then, the rum manufacturers had no great worries.

Then, beginning in 1968, a series of events began to occur which have affected the industry to a point where the future does not look as bright as before. The three major events were:

(a) The Environmental Protection Agency's ruling in 1968 that the industry had to comply with the Clean Waters Act. After more than a decade of briefings, studies, administrative hearings, etc., the major rum industries are now involved in design and construction of treatment facilities to meet EPA's efficient standardssby 1983.

(b) Petroleum prices began increasing in 1973 and have continued to increase causing such a drastic effect on this energy intensive industry that it has become the major consideration in any projections, expansions, or future plans.

(c) The decrease in local sugar production has resulted in a decrease in the production of blackstrap molasses, a by-product of sugar manufacture which is the raw material for the production of rum. This has led to a greater dependency on imported molasses.

These three events have been responsible for changes in the technological viewpoints of the rum manufacturers in areas where a few years ago they were hesitant or unwilling to introduce changes. Specific areas of interest are raw materials and the fermentation process. The changes contemplated in these areas to minimize the effects of scarcity of raw material, energy costs, and pollution control, create an increasing number of interesting research problems which must be solved in a relatively short time. One of the objectives of the Rum Pilot Plant for the present year is to develop a modern fermentation process for the manufacture of high quality rums with emphasis on the optimum utilization of raw materials, efficient usage, and conservation of energy. To undertake these studies it is necessary to set up the pilot scale facilities to operate as flexibly as possible, and this is now being done.

RAW MATERIAL

Blackstrap molasses, the main by-product obtained from sugar manufacture, is the only raw material used in Puerto Rico for rum manufacture. The availability and quality of this material has been decreasing since 1969, forcing the rum producers to obtain molasses from other rum producing countries[1/] (1). The available molasses varies in composition with respect to fermentable sugars and undesirable solids such as minerals and gums, depending on the country of origin. The adverse effects of low quality molasses are many, ranging from inhibition of yeast, blocking centrifuge nozzles, scaling in the beer column, and contributing greatly to the pollutant character of the stillage. Two alternatives are being considered by the rum industry to compensate for the scarcity and the low quality of the molasses. One is pretreatment of blackstrap molasses to remove undesirable solids prior to fermentation. An objection to pretreatment is the loss of sugar during the process. Usually, the process involves heat treatment and clarification to destroy bacteria and remove certain volatiles in the raw material that can inhibit fermentation. In the Almotherm pretreatment process which will be employed in our studies, suspended solids are removed together with much of the soluble calcium salts. By counter-current washing, minimal loss of sugars can be achieved.

As will be seen later, the present tendency in the rum industry is to increase alcohol productivity and lower operational costs. To attain this goal, yeast recycling is being considered by the rum manufacturers. If this is the case it is almost mandatory to pretreat the blackstrap molasses in order to obtain a clean yeast cream. Additional benefits to be expected by combining pretreatment with yeast recycling are: (a) Reduced scaling in distillation units (beer column); and

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[1/] It is estimated that the industry will need 59 million gallons of molasses in 1980. The local mills will produce only 8 million gallons.

(b) the quality of the stillage from the beer column will be such that part of it could be used to dilute incoming molasses, thus providing savings in process water and acid and reducing the volume of stillage to be treated, and thus the stillage treatment costs.

The other alternative being considered is the use of high test molasses in the fermentation process.

High test molasses is defined as clarified sugarcane syrup, partially inverted to avoid crystallization, and evaporated to 85° Brix. Its composition is different from that of blackstrap molasses as can be seen in Table 1.

Based on experimental work conducted at the Rum Pilot Plant (2), in which various procedures for inversion of sucrose in sugarcane juice were studied, preliminary tests on a larger scale (1000 gallon batch) were conducted at Guánica Sugar Mill by Rum Pilot Plant personnel. The tests were carried out by Chemists Eduardo Rosado and Mario Ramírez with the collaboration of Bacteriologist Nivia Murphy. Tests on this scale are important as more reliable data in optimum conditions, costs, and energy requirements can be obtained.

Three thousand gallons of high-test molasses were produced in these experiments in which the enzymatic inversion method was employed. The inversion time averaged 10 hours and the tests showed that this operation could be carried out parallel to the sugar refining process. Part of the material produced was fermented and distilled and is being aged with adequate controls and analysis to characterize the final product. However, there are many economical and technological aspects to be evaluated before any commitment can be attained regarding the coversion of a significant portion of the sugarcane harvest for high-test molasses instead of sugar and blackstrap molasses. To this effect, the Puerto Rican Rum Producers Association, at the request of the Economic Development Administration, has submitted a statement defining their position and concern on the molasses crisis and recommending a program to evaluate the economical and agricultural aspects which will guarantee the amount and quality of raw material needed by the rum industry without depending on exterior sources.

The important point is that circumstances have made the rum manufacturer interested in other sources of raw material. If high-test molasses, or sugarcane juice, are not suitable substances then perhaps a whole new approach such as the Ex-Ferm process should be closely examined.

FERMENTATION PROCESS

The impact of the three major events mentioned earlier has been reflected in the increasing cost of producing alcohol by fermentation. This has awakened interest in areas where changes can be introduced in the process without adversely affecting quality, yet would result in cost reductions. A great part of the research effort at the Rum Pilot Plant at present and in the immediate future will be the development of efficient fermentation processes which will be evaluated under different conditions.

These include:

(a) Pre-treated blackstrap molasses as raw material

(b) High-test molasses as raw material

(c) Both materials to be evaluated with and without yeast recycling.

The initial phase which is now underway involves setting up flexible pilot scale facilities to conduct studies on batch, incremental, or continuous fermentation, with or without pretreatment of raw material, and with or without yeast recycling. With this approach it should be possible to determine the ideal conditions and best substrate for producing rum at the lowest possible cost.

The advantages of combining pre-treatment and yeast recycling were mentioned in the previous section. The importance of yeast recycling lies in the fact that in addition to building up a high yeast concentration, and, as a result, shortening the fermentation time, higher alcohol yields are obtained. This is due to the presence of more fermentable sugars in the mash being converted to alcohol, instead of being used to grow yeast cells, as is the case in conventional fermentation systems.

By means of centrifugal separators designed specifically for yeast recovery, and by acid-washing of the yeast before re-use, it is possible to maintain a vigorous mass of yeast cells in the system. An extremely high yeast concentration tends to suppress bacterial or fungal growth, thus reducing undesirable by-products of fermentation from these micro-organisms and enhancing the alcohol yield. Other methods for preserving the yeast cream that will be studied include use of antibacterial agents, flotation process, refrigeration, and drying.

Yeast recycling will be studied with special reference to the continuous fermentation process, although the flexibility of the installations will permit re-use of yeast in either batch or incremental fermentation processes.

The optimal procedure selected for incremental and continuous fermentation will be based on response to controlled fermentation variables, and conservation of energy. Variables include yeast concentration, nutrient formulation, pretreatment of the mash, mash formulation, pH, temperature control, and alcohol yield and quality. The impact on energy savings will be assessed in all experiments. Re-use of water and stillage will be evaluated as a source of heat and diluting liquor.

FERMENTATION OF DISTILLERY WASTES

Although the rum manufacturers are already involved in definite plans for treatment of distillery wastes, research in this area will continue at the Rum Pilot Plant. Stillage produced from the various experiments using different raw materials and techniques will be characterized. Data on the composition of distillery wastes obtained from the fermentation of high-test molasses indicate that the BOD content is approximately 50% of that of stillage obtained from the fermentation of blackstrap molasses. Based on this value, treatment costs should be much lower for stillage from high-test molasses than from blackstrap molasses. Complete analyses of these two wastes will be published in the near future by Chemist Mario Ramírez.

Studies on fermentation of distillery wastes for the production of fodder yeast will continue.

OTHER STUDIES

1. New Yeast Strains

The strong demand for higher fermentation rates and higher alcohol productivity has intensified research on development of yeast strains compatible with high alcohol concentrations and temperatures. Although the Rum Pilot Plant will not be directly involved in developing these strains, the yeast development program will continue and as these new strains become available from different sources they will be added to the yeast collection. They will be evaluated first on a laboratory scale and then on a pilot plant scale.

2. Dense Cell Culture

In addition to yeast recycling as a means for building up yeast cell concentrations, other methods have been mentioned in the literature (3). Some of these are:

- (a) The tower fermenter, using a flocculating yeast
- (b) Packed tower with immobilized cells
- (c) Membrane-dialysis
- (d) Hollow-fiber fermenter technique
- (e) Rotor fermenter

As more information becomes available the most promising of these techniques will be evaluated and compared with the yeast recycle approach.

3. Ex-Ferm Process

A new approach to the production of alcohol by fermentation is being studied by C. Rolz and his associates at the Central American Research Institute for Industry in Guatamala (4). Basically, this process, called Ex-Ferm, combines extraction and fermentation of sucrose directly from sugarcane pieces in one operation. Research has been conducted on laboratory scale (2 liters) in vertical reactors and in horizontal tubular packed bed fermenters with different yeast strains and different sizes of cane particles. This process will be evaluated at the Rum Pilot Plant on the laboratory and pilot-plant levels and the results will be made available to the rum industry.

4. Alcohol For Energy

Research at the Rum Pilot Plant will not involve production of alcohol for energy purposes, such as gasohol. This is being investigated from all aspects in many research laboratories in various countries. However, the Rum Pilot Plant is in a position to collaborate with other investigators in this field, especially with regard to fermentation and distillation of by-products.

CONCLUSION

The research program in which the Rum Pilot Plant is involved, as mentioned previously, is aimed at obtaining solutions to problems which may affect the Rum Industry. High priority is given to the problem of raw material, and to fermentation techniques which may result in higher alcohol productivity and lower costs.

ACKNOWLEDGEMENTS

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Table 1

COMPOSITION OF HIGH-TEST MOLASSES (INVERTED) AND BLACKSTRAP MOLASSES

Parameter	% Composition, For —	
	High-Test	Blackstrap
Specific Gravity (°Brix)	80—86	86.0
pH	5.0—5.7	5.6
Total Sugars, As Invert	74—79	57.0
Invert Sugar	50—65	20.0
Sucrose	12—26	37.0
Soluble Solids, Non-Sugar	6.0—7.5	29.0
Ash	2.2—3.0	9.6

ENVIRONMENTAL IMPLICATIONS OF BIOMASS AND OTHER ALTERNATIVE FUELS USAGE IN PUERTO RICO

Presented To The Symposium

FUELS AND FEEDSTOCKS FROM TROPICAL BIOMASS

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Terrestrial Ecology Division, Río Piedras, P. R.

ENVIRONMENTAL IMPLICATIONS OF BIOMASS AND OTHER ALTERNATIVE FUELS USAGE IN PUERTO RICO

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ENVIRONMENTAL IMPLICATIONS OF BIOMASS AND OTHER ALTERNATIVE FUELS USAGE IN PUERTO RICO

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ABSTRACT

THE SMALL size and relative isolation of Puerto Rico necessitates responsible management of existing environmental resources. Here, as on similar islands, natural ecosystems are extremely susceptible to disturbance. As Puerto Rico develops its energy alternatives for the future, adequate consideration must be given to the environmental impacts of development so that valuable and irreplacable resources are not lost.

In the immediate future, coal is likely to be used to reduce Puerto Rico's dependence on oil for electrical power generation. However, several unique attributes favor the development of a variety of renewable energy resources. Abundant sunshine, nearly constant trade winds, suitable climate for year-long crop production, and proximity to deep ocean waters can all be used to provide energy for Puerto Rico. Preliminary studies have not detected any unresolvable technical problems, but the ecological implications for large scale implementation must be closely scrutinized.

Environmental assessment is necessary in order to make intelligent decisions concerning both the technology to be used and the location of energy producing facilities. Many schemes have been developed for classifying impacts. Some current categories are briefly discussed. By evaluating impacts, the environmental scientist is making value judgements based on available information. For this reason, it is important to maintain a broad perspective on the problems of energy development in Puerto Rico and elsewhere.

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ENVIRONMENTAL IMPLICATIONS OF BIOMASS AND OTHER ALTERNATIVE FUELS USAGE IN PUERTO RICO

INTRODUCTION

PUERTO RICO possesses a unique combination of environmental characteristics which directly influence the types of future energy resources which can and should be used. Because Puerto Rico lacks fossil energy reserves, it must depend on distant sources of these fuels. Although worldwide reserves have not yet reached critical low levels (5, 7), eventual depletion of these fuel resources is an absolute certainty. On the brighter side, intensive and nearly constant sunshine, almost constant trade winds, suitable climate for year-round cropping, and the proximity to deep ocean (required for OTEC facilities) place Puerto Rico in an advantageous position to exploit a number of energy alternatives (9).

The small size and relative isolation of Puerto Rico necessitates responsible management of existing environmental resources. Natural ecosystems on islands are extremely susceptible to environmental degradation (18), and much of the damage is irreversible because of the unique assemblages of plant and animal species on each island (6, 23). Limiting our concept of environment to natural systems might be convenient in some situations, but can obscure the interrelationship among all relevant factors. I will therefore use the word "environment" as defined in Webster's New Collegiate Dictionary:

> "The complex of climatic, edaphic, and biotic factors that act upon an organism or an ecological community and ultimately determine its form and survival."

Within this definition, man is included as part of the biotic community, but the socioeconomic and human health aspects will not be evaluated as topics separate from other biological components. A quantitative evaluation of all possible energy alternatives is not presently possible or appropriate. Therefore my objectives are:

- To describe some of the potential environmental consequences of developing alternative energy sources in Puerto Rico.
- To present methods which can be used to classify these impacts.
- To identify important areas where additional information is needed in order to adequately assess environmental impacts.

ENVIRONMENTAL IMPACTS

Puerto Rico's heavy dependence on fossil fuels is likely to continue for some time, but rising costs and dwindling world reserves have created a mounting need for the development of renewable energy sources (13). The National Academy of Sciences has evaluated six renewable energy sources potentially contributing to Puerto Rico's energy needs (9). Their study revealed that there are no easy or low-cost solutions, and concluded that a variety of domestic resources can substantially contribute to decreasing Puerto Rico's need for imported fossil fuels (Table 1). The impact of using these renewable resources plus coal, currently proposed as a partial substitute for imported oil, are the alternatives which have the greatest chance for immediate development and therefore need immediate evaluation.

1. Biomass

Only a century ago biomass in the form of wood was the primary fuel used in the United States (5). Biomass can provide fuel directly in the form of fiber and indirectly as alcohol. Wood or cane fiber can be processed for use in electrical generation facilities to supplement fossil fuel combustion, and ethanol can be used as a fuel supplement for gasoline powered vehicles. Economic and technical arguments for the immediate development of these resources are persuasive. No new technology is required, development could be integrated with solar drying and modern agricultural methods to optimize resource use, the year-long growing season in Puerto Rico is favorable for maximum productivity, fuel costs are competitive, and the molasses byproduct (in the case of sugar crops) could be sold to further reduce fuel production costs.

Like other forms of energy there are both negative and positive aspects to its use. Two significant potential problems associated with biomass production are (a) erosion, which depletes soil fertility and affects air quality, water quality, and adjacent ecological communities, and (b) land use, which can adversely impact important ecotypes and wildlife habitat (20). The use of insecticides and fertilizers poses additional threats to the environment. Among the beneficial results of using biomass instead of fossil fuels for energy production is the reduction in air pollutants, particularly SO_2 and NO_x emissions (1, 19). I hasten to add, however, that NO air pollution is a more desirable environmental goal.

There is a clear need for additional information on the environmental impact of biomass, including its production, transportation, and use as a fuel. There is a concomitant need for studies of the effects of large scale development of this process in an island environment. What is the optimum area which could be committed to biomass production without adversely affecting other components of the environment? It is likely that there is no precise answer, given our present methods of cost/benefit analysis, but some estimates should be obtained before large scale development is begun.

Current information indicates that 50,000 acres of energy plantation would be required to maintain a 300 MW modern coal/oil biomass boiler operating at 80% capacity. Proper management could reduce the area needed to 15,000 acres (Alexander, personal communication). In order to account for a substantial percentage of the Island's energy requirements, many square miles would need to be converted to energy plantations. On an island the size of Puerto Rico (approximately 3,400 square miles), most of which is covered with mountains or karst and with a population of over three million people, land use quickly becomes an important consideration.

Conversion of large areas of land to energy crops is a very real danger to natural ecosystems. The consequences would be felt the strongest in flat lowland areas (3, 15). Because many of these areas are already highly disturbed, additional modification of these lands might have insignificant adverse environmental impact.

Another source of biomass is the large volume of water hyacinths which covers lakes, ditches and other slow moving bodies of water in Puerto Rico. Studies conducted by the Terrestrial Ecology Division of the Center for Energy and Environment Research have shown that this weedy species can be used as a biofilter to improve the water quality of sewage treatment facilities and produce biomass fuel for bioconversion (21, 22).

2. Solar Energy

In a broad sense, many forms of energy (fossil fuels, hydroelectric, wind, etc.) are different manifestations of solar energy. Even the energy in biomass is solar energy fixed in organic materials by the process of photosynthesis. For purposes of this report, only photovoltaic, residential solar water heating, and wind will be evaluated as solar technologies. These solar technologies do not differ from other energy sources in that they produce both positive and negative environmental effects. Preliminary environmental evaluation conducted by the Solar Research Institute of the U.S. Department of Energy has not identified any unresolvable technological problems (e.g. CO_2 emissions) or large scale hazards (e.g. possibility of catastrophic accidents) which would hamper development (16).

Photovoltaic electricity generation would produce relatively few impacts when compared to other energy sources. The direct impacts would be chiefly in the commitment of large land areas for the collection of diffuse solar radiation and water quality effects caused by the discharge of working, storage, and heat-transfer fluids (12).

The residential and industrial use of solar hot water heaters would produce insignificant environmental impacts since these devices could be placed on buildings to avoid disturbance of land areas. Even optimistic projections for their use would have only a slight impact on the overall energy needs of the Island, however (9).

A preliminary appraisal indicates that a small percentage of Puerto Rico's power could be generated by wind by the year 2000 (9). Although some land would be required for windmill installation, the chief environmental problem seems to be noise and vibrations of the wind machines which can affect both the human and wildlife inhabitants in the vicinity of these devices (16).

3. Hydroelectric Power

Most of Puerto Rico's rainfall occurs at high elevations, but the small area of land and short rivers involved limit the possibilities for hydroelectric generation (9). Environmental costs are very high when compared to returns in power generation. Large areas of land, much of which is habitat for unique and endemic species, would be affected. Normal flow patterns would be interrupted, and the movement of minerals and organisms impeded. The reservoirs produced could provide some benefits, but these would probably be insignificant compared to the habitats lost and ecosystems disturbed by their creation.

4. Ocean Thermal Energy Conversion

The proximity of Puerto Rico's power grid to cold deep ocean water makes it a prime location for an OTEC facility. Both the technical feasibility and environmental impacts of such an installation are largely unknown. An operating OTEC system consumes large volumes of cold, nutrient-rich water and dumps them into warmer surface water. There will undoubtedly be a significant impact on the marine biota, but whether the net impact is negative or positive and whether it is significant or insignificant have not yet been determined.

5. Coal

A considerable body of data is available on the environmental impacts of burning coal to provide energy. The most noteworthy direct negative impact is air pollution. High ash content and SO_2 emissions (10, 17) have polluted major industrial areas throughout the world and have caused considerable damage. The environmental impact of coal combustion on Puerto Rico proper is likely to be minor because of proposed plant locations and existing Commonwealth and Federal air quality standards. The impact on the downwind marine environment, including air-breathing forms such as whales and sea turtles, is unknown but potentially significant.

The use of coal as a fuel for electrical power generation will require the construction of a protected ocean port facility and will increase the ship traffic in that region. Both of these actions may harm the marine environment. Other plant-related facilities will include ash disposal sites and transmission line rights-of-way which should produce only minor environmental disturbances.

CLASSIFICATION OF IMPACTS

The major impacts of various energy alternatives have been mentioned, but an overall evaluation has not been provided. Such a task is beyond the scope of this report, but some suggestions as to how to classify impacts might be helpful at this point. Both the technology and location of the alternative energy installation need evaluation, and size requirements are important.

Some of the commonly encountered categories for judging impacts are listed below:

- Positive/negative
- Long term/short term
- Reversible/irreversible
- Primary/secondary (direct/indirect)
- Avoidable (can be mitigated)/unavoidable
- Significant/insignificant
- Acceptable/unacceptable

Air pollution and land use commitment can readily be designated as negative environmental impacts, but the size and location must be known before any evaluation can be made of their significance. A project may be unacceptable because of the technology employed (e.g. nuclear power) or the location of the installation (e.g. critical habitat of an endangered species).

It is apparent at this point that we are making value judgements and trying to predict the future on the basis of past experience and exploratory calculations. But as Schumacher (11) has remarked, "...all predictions are unreliable, particularly those about the future."

CONCLUSIONS

On the basis of existing assessments, biomass shows the greatest promise of any renewable resource for meeting the energy needs of Puerto Rico in the near future. Potential environmental impacts have been identified and need to be critically evaluated.

Coal will be used as one alternative to oil in order to supply electrical power to Puerto Rico in the near future. The environmental impacts of coal combustion are generally negative, but additional work may be needed to determine their exact nature and overall significance.

Puerto Rico's unique environmental attributes favor the development of renewable energy sources which are now in the developmental stages. Among these are wind, photovoltaic, and ocean thermal energy conversion. Once these technologies have been tested and their environmental impacts assessed, the Island will have additional options for attaining some level of energy self-sufficiency.

ENVIRONMENTAL PERSPECTIVE

Scientists and engineers tend to view the world as a composite of more or less isolated systems. For instance, as an ecologist I find it convenient to study the rain forest ecosystem as an entity separate from adjacent agricultural land. A broader perspective is needed, however, in order to understand world mineral cycles of which the rain forest is only a segment. The interrelatedness of ecological systems and of all environmental components is difficult to ignore. As the naturalist John Muir observed more than half a century ago, "When we try to pick out anything by itself, we find it hitched to everything else in the universe" (8). It is likewise necessary to maintain a broad perspective when evaluating the environmental implications of energy development.

The most urgent problem of our time, however, is not energy, but rather world population (2). This is particularly evident in Puerto Rico. Although the per capita demand for energy has increased greatly in the last few decades, population growth has also risen sharply. Two symptoms of this condition are (a) intensive farming for food production and (b) the frenzied exploitation of non-renewable resources, including fossil fuels. By confining ourselves to evaluating only direct impacts of energy development we will be treating the symptom rather than attempting to cure the disease.

Biological populations, both plant and animal, are controlled by limiting factors such as disease, food supplies, and living space (4, 14). Man's populations are partially limited by available energy, but it is important to realize that there are others. I would therefore ask that we all take a broader and longer look at the environmental implications of energy development; otherwise truly relevant solutions will not be achieved in Puerto Rico or elsewhere in the world.

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Table 1.- Potential Contributions of Renewable Energy Sources to Puerto Rico's Electricity Needs [1/]

	Percent Contribution For Year —				
	1977	1990		2000	
Source		Optimistic Projection	Planning Expectation	Optimistic Projection	Planning Expectation
Biomass-derived Electricity	0.0	10.4	3.2	30.0	9.9
Residential Solar Water Heating	0.0	1.0	0.6	2.0	1.1
Hydroelectric	0.7	1.0	0.6	1.0	0.6
Wind	0.0	0.8	0.2	1.8	0.5
Photovoltaic	0.0	0.0	0.0	0.1	0.0
Ocean Thermal Energy Conversion	0.0	0.5	0.0	1.3	0.6

[1/] Taken from the National Academy of Science's Report on Energy in Puerto Rico's Future (9).