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ALCOHOLS - ITS USE, ENERGY AND ECONOMICS - A BRAZILIAN OUTLOOK

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ABSTRACT

A survey is made of the state of the art of the production ethanol from sugarcane and other crops and the problems and constrains involved on its use as an automotive fuel. The inproved efficiency of modified internal conversion engines running on pure alcohol are discussed as well as pollution problems.

It is shown that these problems are not aggravated by the use of ethanol. The energy balance for the production of ethanol from sugarcane, cassava, sweet sorghum and wood - taking into account agricultural and industrial energy expenses - are compared in Brazil and in the United States. Costs of ethanol from different crops are avaluated and the conclusion reached that in present Brasilian conditions it is US$12.69/GJ when produced from sugarcane. Gasoline cost in Brazil is US$12.19/GJ ex-refinery. 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 breakeven point as compared with gasoline in Brazil.

ALCOHOLS - ITS USE, ENERGY AND ECONOMICS - A BRAZILIAN OUTLOOK

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1. INTRODUCTION

Any assessment of the energy needs of the world population by the year 2000 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; it's concentration level in the atmosphere is continually growing and will be a serious problem in the near future.(7)

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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 ecomical 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 sugar cane is being developed costs of alcohol have probably reached the breakeven 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 sugar cane in Brazil is approximately 0.2%. This number can be increased four fold as shown by the sugar cane 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.

Since wood is a very interesting feedstock, mainly because of it's extreme low agricultural energy requirements, all technologies capable of transforming this product in any liquid fuel should be utilized. In this paper we try to analyze it's use as a feedstock for ethanol production. The wood energy value is high and the price is low enough so that even before the quadruplication of oil prices by 1973 it was used largely for heating purposes, competing with oil, even in the United States.

2. FEEDSTOCKS

2A) Sugar Cane

Up until now the ethanol derived from sugar cane 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 sugar cane 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 sugar cane 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 l/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 (1000 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 classical process used to produce ethylic alcohol from sugar cane requires a unit with a flow chart shown in Fig. II.

Sugar cane is harvested and immediately transported to small size distilleries when compared with the oil refining complexes. The most common units in Brazil are able to produce 120,000 l/day and the largest ones, 1 million l/day. Sugar cane is received and washed to remove stones and soil dust; then, chopped and crushed in milling machines (very few plants use the diffuser so well accepted by the sugar beat processing industries in Europe). The milling process of sugar cane is performed by at least two sets of three stainless steel cylinders; the fiber is dampened again in water and goes through another milling operation. The extracted product, beer, is then diluted in water up to one part of sugar to ten parts of water.

The beer is kept refrigerated in large stainless steel containers through water cooling to avoid temperatures from going above 30-35°C, during the time required for efficient fermentation. (Generally twelve hours for economical reasons; a longer time span produces more alcohol, but since the efficiency of the yeast decreases significantly when a 7 or 8% per volume of alcohol is achieved, it then requires up to 36 hours to obtain alcohol in concentrations of 9 to 10%.)

The alcohol-water mixture undergoes distillation. A maximum of 95.5°GL can be obtained; the residual water is then removed by means of mixture with benzene and the alcohol is submitted to a new distillation (retification), where benzene is recovered and water free alcohol is obtained.

The almost 100°GL alcohol is then stored and large energy and monetary costs are required for it. Alcohol distilleries from sugar cane work only a fraction of the year (160-180 days) requiring the build-up of large stocks to supply the market all year around. These costs are included in our economical evaluations in section 6.

The flow sheet from Figure II shows that commercial processing plants have electricity and steam production stations, fed by the sugar cane bagasse, the fiber material which went through the milling machines. The bagasse, with a moisture content of 50% by weight, can be immediately burned to produce steam.(25) Up to now the most common units used super-heated steam under low pressure (21 atm), since the largest necessity of the plant is low quality energy required to heat the bottom of the distillation tower to ≃ 100°C. Any increase in pressure will decrease the amount of steam required to produce work (operation of crushing and milling machines, transportation belts, etc) but does not have any positive effect in the energy required for the distillation. Even working at modest pressures the autonomous plant (that is, the one designed for alcohol production only) does not use all the available bagasse as a fuel for boilers; 1/3 of the total amount is usually unused.(25)

The utilization of this excess bagasse as fuel for high pressure steam boilers capable of driving electrical generators, is under investigation.(26) The main drawback is the inability to produce electric power continuously. The sugar cane is harvested only during part of the year and the selling price of such intermittent power is very low. This is a typical situation in Brazil, where there is no shortage of electric energy; in other countries even an intermittent source of electricity can be very valuable if the harvesting season coincides with the low rainfall time. Another possible use of the bagasse requires the use of other crops (sweet sorghum or cassava) to extend the working season of the industrial plant. In this extended period the excess bagasse, stored from the sugar cane harvest season, would supply the energy requirements together with some wood. The stock keeping of bagasse is a normal practice of the paper industry in Brazil.

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 the same basic installation for the processing of sugar. The first autonomous distilleries, 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 sugar cane 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) 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 it's amount, as will be discussed in section 5, is not sufficient to supply all the energy required.

The use of corn as a feedstock for ethanol deserves a more detailed analysis; corn in the United States together with sugar cane in Brazil are being used in commercial application; the alcohol is supplied in the United States only through the Gasohol (a blend of 90% unleaded gasoline and 10% ethanol).

3. THE USE OF ETHANOL AS AN ALTERNATIVE FUEL

3A The Engine Efficiency

The use of ethanol or methanol as a substitute for gasoline was analyzed several times and determined to be an extremely bad option, since their energy content was considerably less than gasoline; 5100kcal/l for ethanol, 3800 kcal/l for methanol and 7300 kcal/l for gasoline. Nevertheless if we are willing to use these alternative fuels for an internal combustion engine it is incorrect to compare them with gasoline solely by means of the energy content. Other factors must be taken into account and they usually enhance the alcohols figure of merit.

Figure 3 shows that compression rates as high as 1:12 can be used with alcohols as a fuel; gasoline fueled engines do not go over 1:8 in countries where a high quality product does exist and can be as low as 1:6 in some developing countries like Brazil. A higher compression rate signifies higher thermal efficiency which can reach values as high as 40%(28) which is 50% better than what is usually achieved in an Otto engine fueled by gasoline (of course high compression rates also means higher friction loss and it is the general concensus that compression rates up to 1:16 or 1:18 used in conventional Diesel engines are the best we can have, as far as efficiency is concerned; nevertheless the Volkswagen Diesel car engine is designed to run with compression rates as high as 1:23).

The heat of vaporization for ethanol and methanol are much higher than the iso-octane (which will be used to simulate gasoline). They are 922 and 1167 kj/kg respectively and only 307.7 kj/kg for iso-octane. This higher value for the heat of vaporization yields differences of 3.4% in the heat of combustion of liquid and gaseous ethanol, 5% in the heat of combustion of methanol and only 0.7% in iso-octane, as shown in Table 4. The heat of combustion used to compare fuels is the lower one, when water produced from the reaction is in the gaseous form. Furthermore these values must be corrected for initial temperatures which vary according to the technique used to feed different fuels in the engine. This difference in the combustion heating can be recovered in at least three forms:

1) by utilization of the heat embodied in the exhaust gases; liquid ethanol has only 60% of the energy content of iso-octane and will require 5.72 times more heat to evaporate the amount of ethanol that will supply the same heat of combustion as iso-octane. Efficient use of the exhaust gases is more easily accessible in the case of ethanol than in iso-octane, yielding a better overall efficiency. The same is true for methanol(29).

2) performing an adiabatic evaporation of the fuel. In this condition the air-fuel mixture cools down and, from the practical point of view, a temperature of 0°C can be obtained (lower temperatures are impractical since air always has some amount of moisture that will freeze and impair the fuel feeding lines). The same technique when used in iso-octane, assuming the same percentage fraction of the heat of refrigeration used for ethanol, will cool

down the air iso-octane blend only 3°C. This decrease in temperature changes the energy density of the fuels, as shown in Table 5. Therefore, the use of an injection fuel system for liquid fuel will allow the use of an ethanol-air mix at 0°C that has 8.7% more energy density than the iso-octane air mix at 22°C (3.687 vs 3.413 MJ/m^3). This fact is also an advantage for methanol.(29) This is one of the main reasons for the use of ethanol or methanol as a fuel in racing cars; they yield more power for the same volume of the engine.

3) using catalysis to crack methanol at temperatures easily achievable with the exhaust gas of the automobile. By the cracking method, carbon monoxide and hydrogen can be obtained. This improves the energy economy by 18%.(30)

The excess weight produced by the extra volume of the fuel tank designed to carry alcohols, can be as much as 4% of the total car weight and consequently increases the fuel consumption by 2%.(31) This is definitely a drawback for ethanol utilization, but since there is an excess power produced (8.7%), this should allow a reduction in size and weight of the engine when compared with gasoline fueled motors; also the total amount of fuel required for the same road extension is less than what would be evaluated from the ratio of the heat content. A combination of these two factors should result in an improvement of 1% and 3% with compression ratios of 8.2 and 12, respectively.(32)

Modern automobiles use lean mixtures so that the amount of pollution is reduced and the efficiency is increased. The large fuel to air composition that we are allowed to use when operating an ethanol fueled car (see Fig. 3) yields a much easier flexibility for this fuel to handle leaner mixtures.

It is quite possible that an overall fuel economy of 2% will result.(33)

Table 6 compares all the advantages in efficiencies of an ethanol and gasoline engine.

As a final conclusion 1 liter of ethanol, with 5100 kcal of energy, has a performance index in an internal combustion engine equivalent to a gasoline of 6375 kcal/l, that is, its heat of combustion value has to be increased by 25% in order to make a comparison with gasoline. This means that the heat content of gasoline is $\frac{7800}{6375} = 1.22$ times the heat content of ethanol for the same volume. This corresponds with results obtained with a fleet of more than 2,000 cars in commercial operation in Brazil.(34)

3B) The pollution aspect

Very precise flame temperatures in an internal combustion engine can be evaluated only if we assume no gas dissociation. Because there is a significant dissociation in the temperature range of operation of these engines, a reasonable amount of energy is absorbed by these processes lowering the flame temperature evaluated under that simple condition. Iso-octane burning at a stoichiometric ratio should produce temperatures around 2440K and methanol only 2190K.(35) As a result of lower temperature, NO_x compounds, which are products of reactions mostly dependent of kinetics, (and then an exponential function of the temperature) will be produced in much smaller quantities.

Organic compound found in the engine exhaust are mainly unburned fuel and aldehydes. In order to identify the factors affecting these emissions several investigations were performed by General Motors(36) and Volkswagen(37) using methanol. The main conclusion is that if enough care is taken in the preparation of the fuel, the amount of unburned fuel emission can be reduced by 80 or 90%, bringing the emission level to almost the same value found for gasoline. The amount of aldehydes were also brought down almost an order of magnitude when compared with the standard intake system, reaching a level four times higher than that of gasoline.

Carbon monoxide emission depends primarily on the air-fuel ratio. In a lean fuel-air mixture its amount is much less than in a rich mixture as seen from Figure 4. They also depend strongly on the fuel preparation and correlate with the unburned fuel emission. So as the engine starts on cold days, when a rich fuel operation is required, the amount of CO can be higher than with gasoline and may require catalytic oxidation to perform with the U.S. standards.

Several advantages are indicated in favor of methanol or ethanol such as:

a) The elimination of lead emission: a significant pollution product from conventional gasoline; b) the reduction of carcinogenic and toxic properties of the aromatic compounds; c) the absence of particulate and sulfur compounds.

Extensive study is still required for a final comparison between pollution of alcohols and gasoline. Nevertheless, for a 10% blend as is being used in the U.S.A., very little change in the pollution pattern of pure gasoline should be expected since the accessible measurements never showed an increase in any pollutant larger than an order of magnitude when compared with gasoline, if appropriate care with the mixture preparation was taken. Unfortunately up until now a reliable measurement of the pollution pattern of 100% ethanol fueled cars in Brazil was not available.

4. 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 7 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.(38) 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 restriction 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.

Research performed in several models of Otto engines at Centro Tecnologico de Aeronautica em Sao Paulo(39) as early as 1976 showed that the 20% ethanol-gasoline blend would not indicate any significant decrease in the engine efficiency, nevertheless the heat value of ethanol was only 60% by weight of that from gasoline. Such an amount of alcohol would work as a gasoline booster improving gasoline octane. Presently there are several publications about tests performed by oil companies,(40) car manufacturers(41) and government offices of many countries,(42,43) assessing the performance of automobiles fueled by alcohol blends of 10 to 20%. The results are very controversial and the best we can learn is that if there is any change in performance it is at most a 2% value.

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.(44) The most common unit has a production capacity of 120,000 l/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 5. 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 are shown in Table 8.

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 6, 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 retrofiting 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;(45) 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. (41) Kits for the retrofiting of gasoline engines to run with a 100% ethanol fuel are already available.(46)

b) the ethanol consumption, per liter, is 20% higher than with gasoline, even after the compression ratio is increased; (41)

The reasons for the modifications listed in a) are the following: alcohol has an octane ratio $\frac{\text{RON* + MON**}}{2}$ of 98. This allows a higher compression ratio and better thermodynamic efficiency. The change in the carburator can be understood through the comparison of the reaction for oxidation of gasoline (iso-octane as an example) and ethanol, described in simplified form, respectively as

$$C_8H_{18} + 12.5\ O_2 \longrightarrow 8CO_2 + 9H_2O$$

and $$C_2H_5OH + 3\ O_2 \longrightarrow 2CO_2 + 3H_2O$$

and listed by molar and weight base in Table 9. As can be seen, the stoichiometric air to fuel ratio by weight is of the order of 9.12 for ethanol and 15.31 for gasoline. The auxiliary system for cold start uses a small gasoline tank or an electric heater with the purpose of producing alcohol vapor to fulfill the requirement to reach starting mixture. Table 10 shows the boiling temperature and vapor pressure for ethanol, iso-octane and gasoline. As can be seen, gasoline has a large range of products with different molecular weight and different boiling points. The compound with low molecular weights yields enough vapor pressure to permit prompt ignition even in a cold environment. Ethanol with a much lower vapor pressure than gasoline requires some additional process to achieve this same performance.

The goal set for 1985 will impose several difficulties for the oil refining industries if the production of Diesel oil and fuel oil will have 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

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*RON - Research Octane Number

**MON - Motor Octane Number

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, (see Table 11), demands that 46% of the oil be converted into gasoline. The average energy required for processing a barrel of crude oil is 740 MJ(47) distributed among several operations. (See Figure 6). 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 7 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 7a which clearly indicates that lead free gasoline requires a real consumption of 600kcal/10km over what is required for the production of the same octane gasoline with a lead content of 0.6g/1.

Figure 8 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 0.3g/1 of lead. From this figure and from Figure 7a) approximately 400kcal/10km could be saved (this number is obtained by extrapolation from data from Figure 7a);- in the case of minimum gas consumption with 0.4g/1 of lead, 11250kcal/10km is necessary and the minimum for a gas with 0.15g/1 of lead is 11650kcal/10km). Then a mixture with 9 liters of medium gasoline plus 1 liter of alcohol can yield an energy savings of 11,500kcal (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 2,000kcal as we will show in section 6. Therefore the real economy is 9500kcal; 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 7 and 8 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, as was stated in section 3A. 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(48,49) and engines have already run with blends as high as 70% ethanol.(50) 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.

5. THE ENERGY BALANCE FOR THE PRODUCTION OF ETHANOL

Several papers deal with the problem of assessing the amount of energy expended 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 sugar cane, cassava, sweet sorghum, corn and wood.

5-I Yields and Productivity

To carry an energy balance it is necessary to assess the ethanol and by-product yields from the feedstocks.

A) Sugar Cane

Sugar cane 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 12 shows typical composition of the most common species of sugar cane 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.

$$\begin{array}{ccc} C_6H_{12}O_6 & \longrightarrow & 2C_2H_5OH + 2CO_2 + \text{heat} \\ 180\text{g} & \longrightarrow & 92\text{g (64.3ml at } 15^{\circ}\text{C)} \end{array} \qquad \text{(A)}$$

$$\underset{\substack{\\ \\ 360\text{g}}}{C_{12}H_{22}O_{11} + H_2O} \longrightarrow \underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{fructose}}{C_6H_{12}O_6} \longrightarrow \underset{184\text{g}}{4C_2H_5OH} + 4CO_2 + \text{heat} \qquad \text{(B)}$$

A practical evaluation of the total amount of ethanol obtained must assume an extraction efficiency of 95% for the mono and dissacarides sugars from the crop and also a 95% efficiency in the fermentation process. This means that 1t of sugar cane, with an average composition shown in Table 12 yields 90 liters of ethanol. Using the typical productivity for commercial crops listed in Table 13 we arrive to 4700 liters of ethanol/ha-year.*

B) Cassava

This feedstock is being used in only one commercial plant for technical and economical reasons. The starch requires one more processing stage than sugar cane to yield ethanol; a preliminary hydrolysis is required. The technique used is enzimatic hydrolysis carried by two different enzymes: alfa-amilose and amilo-glycosidase. The former transforms starch in oligosacarides and the latter transforms this product into glucose. The theoretical efficiency is described in Eq. C

$$\underset{100\text{g}}{\text{Starch}} \longrightarrow \underset{130.7\text{g}}{\text{Glucose}} \longrightarrow \underset{84.1\text{ml at }15^{\circ}\text{C}}{\text{Ethanol}} \qquad \text{(C)}$$

since a) 85% of starch undergoes hydrolysis,

b) 95% yields dextrines which will produce glucose

c) 95% is the practical efficiency for alcohol fermentation, a more realistic yield is Eq. D:

$$\underset{100\text{g}}{\text{Starch}} \longrightarrow \underset{105.5\text{g}}{\text{Glucose}} \longrightarrow \underset{64.5\text{ml}}{\text{Ethanol}} \qquad \text{(D)}$$

From figures presented in Table 14 and equations A, B and D, 1t of roots yields 181 liters of ethanol, or 2260 liters/ha-year if we use the average productivity from Table 15.

C) Sweet Sorghum

This crop is not used in commercial applications in the country and all results presented in Table 16 were obtained from experimental crops. It is possible to transform 1t of stem in 78.5 liters and 1t of grain in 396 liters of ethanol, yielding an average production of 6106 liters/ha-year if two harvests per year are assumed, as shown by Table 16 and 17.

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*This figure is well above the average 3600 liters/ha-year commercially obtained in Brazilian distilleries. Inefficient sugar extraction and unavoidable losses associated with large scale production should be the reason for the lower figure.

D) Wood

The commercial use of wood as a feedstock for ethanol is presently very rare since several more stages are necessary than when using sugar cane. Cellulose, the largest component of wood is completely converted in glucose through hydrolysis, but the presence of other components (hemicellulose and lignin) pose some difficulty in the use of wood.

Several acid hydrolysis processes are available.(51) At present, only the Soviet Union has approximately 40 plants under operation for the production of protein for animal feeding and ethanol using the dilluted sulfuric acid process(52) (Scholher process). Brazil is now interested in commercial exploitation of wood as a source of ethanol and intends to put in operation a few units as big as 100,000 liters/day in the next two years.

Enzymatic hydrolysis still is under laboratory bench scale but some variations are already under consideration for commercial application in the U.S.A.(53)

The main product from acid hydrolysis is glucose. Since a fraction of the hemicellulose yields pentosanes as shown in Table 18, hardwood with a larger hemicellulose fraction than softwood, produces larger quantities of non-fermentable sugars which can be recovered for cattle feed. An economical evaluation of wood hydrolysis must assume that only glucose and manoses are fermentable sugars. We must also take into account that:

a) acid hydrolysis is able to convert 73%, by weight, these polysaccharides (54)

b) the amount of cellulose plus hemicellulose is on the average 70% by weight in wood

then 1 ODT of wood yields 233 liters of ethanol.

Large areas of Brazil have undergone reforestation in the last twenty years to supply feedstocks for the paper industry and reliable data for wood yields are available and displayed in Table 19. These figures yield 2750 and 3400 liters of ethanol/ha year for Eucalyptus and Pinus respectively.

E) Corn

It is not used in Brazil but in the U.S.A. is the most common feedstock for ethanol production which is the reason for it's inclusion in this paper.

As with cassava, the starch from corn must undergo hydrolysis before the fermentation process. Table 20 shows typical composition for corn grains. The crop residue, called stover, has a moisture content of 15% and is produced in large quantities.(55) Unfortunately, tillage practices require that 80% of this material be kept in the soil(55) and it's transportation to a processing plant would require extra energy, since the stover is not a by-product of the corn grain. This yields 1,170 t/ha of feedstock appropriate for boilers, with a heat content of 16GJ/t.

Table 21 lists typical productivity for corn grain in the U.S. and Brazil. Assuming that one bushel of corn yields 2.6 gallons of ethanol,(56) that figure translates in yields of 2100 and 970 l/ha year in both countries, respectively.

5-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.(47,57) More accurate evaluations can be made with the utilization of input-output matrix already available for the Brazilian economy.(58) Labor energy is systematically neglected in the energy evaluation following the prescription of some energy schools.(59) However, even in a developing country like Brazil, the human expenses in agricultural production is never larger than 5% and it's 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 sugar cane. Using the productivity in alcohol/ha-year listed in Section 5-I, 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 21. The expenses account for soil preparation, plantation, harvesting and transportation of the feedstocks up to a distance of 20km from the farm.

5-III Industrial Expenses

The conversion of biomass in ethanol is made by several techniques as was discussed in Section 5-I. 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 sugar cane 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 sugar cane flow sheet evaluation, as shown in Figure 2. The input-output Brazilian matrix(58) was used to assess energy built-in in capital goods, operation, maintenance and fuel. Table 22 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 are almost due to the fuel required. Fuel is such a large part of the total expenses that is 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 23 quotes fuel costs for the biomass under analysis.

A comparison drawn between Tables 3 and 23 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 nobel fuels (oil, natural gas and electricity) in the ethanol processing. This is the main reason for the success of sugar cane 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. From Table 12, the amount of dried fiber is 110kg per t of harvested biomass. In practical application, fibers with 50% moisture content (which means a heat value of 1800kcal/kg) are used as boiler feed. Each kg of bagasse produces 2.4kg of steam which yields 5.9kg of steam/liter of ethanol. This amount of steam is more than enough for the industrial processing. Any excess of bagasse is undesirable since an extra cost will have to be added for the return of biomass to the farm.

The present day efficiency of the steam system in Brazil is quite modest as can be noticed when compared with the U.S.(60) The consumption of steam is the same, but in Brazil there is no drying of the sillage, since it is pumped back to the soil as a fertilizer. Sillage drying is responsible for 1/3 of the total energy cost. Many improvements can be added to the plant, if better distillation techniques already available will be introduced in industrial plants and a market for unused bagasse is developed.

Other feedstocks like cassava and corn do not compete with sugar cane 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 23 shows the amount of energy required as being much higher than for sugar cane. Plants in operation in Russia require 25kg of steam and turn-key Switzerland plants require 13kg of steam.(61) 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%). Figure 9 displays how the wood production would be split for both applications.

It is obvious now that this technique of soil partition can be used for any other crop. This improves the energy balance for cassava and corn. Also shown in Fig. 9 is how a hectare has to be divided to accomodate cassave and wood, and corn and wood in such a way that the processing plant will be self-sufficient. Table 24 lists the amount of ethanol produced from several crops using a self-sufficient hectare and the total energy required from external sources for the agricultural and industrial phase. It is important to stress that all numbers for the industrial processing of cassava, corn, and wood are less reliable than the one for sugar cane, nevertheless it is clear that the agricultural expenses are now the major fraction of expenses for all crops but wood, where the costs for operation, maintenance and capital goods are very similar to the agricultural costs. The last column of Table 24 shows the energy costs/liter of ethanol, which have to be compared with results available for the oil industry. In the U.S.A., the extraction and refining of high quality gasoline is very near 2000kcal/1.(57,62)

5-IV The Situation in the United States

The energy balance must always be analyzed for each country. So, results found in Brazil can not be easily extrapolated for other countries and as we intend to show are not good for developed countries.

Table 21 presents agricultural expenses for some crops in Brazil and the U.S. As a general trend, the yield is larger in the developed country, but the amount of energy required is much higher in such a way that the energy expenses per t of biomass is smaller in the developing country. This is a natural behavior of the technological improvement, since more powerful tractors are available, mechanized harvesting is a common practice and large amounts of fertilizer are used to improve the yield.

The analysis for corn shows that even under the self hectare practice, and the assumption that expenses for operation, maintenance and capital good in the industry are neglected (which is a good approximation as discussed in Section 5), the amount of energy required for the production of 1 liter of ethanol in the U.S. is 4.58Mcal and only 1.88Mcal for Brazil. To emphasize this issue, Figure 10 shows a comparison between the amount of oil required to produce alcohol in Brazil and the U.S.

6. THE ECONOMICAL PROBLEM

The evaluation of the production of ethanol will be made for only two feedstocks: sugar-cane and wood; even so we reclaim calculations to be more precise for sugar cane which is being used extensively in Brazil.

Sugar Cane

The evaluation is more realistic for the southeastern part of the country where data is available for the evaluation of the 1976/77 harvest.(21) The size of the investments and of the agricultural yield are presented in Fig. 11 for a hectare of soil exploited in a 4 year span. Table 25 presents the costs for sugar cane 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's producers (Zanini S.A.): 10^7 dollars for a processing plant of 120,000 l/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 26. Operation costs represent \$2.20/GJ.(21)

As was shown in section 5-I, one hectare produces 226/GJ year of biomass (assuming 18GJ/ODT)and yields 4700 liters of ethanol or 99GJ. 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 2.3GJ of feedstock. The cost for sugar cane is \$3.04/GJ(adding some value to the soil 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 27.

Wood

Figure 12 presents the magnitude of fixed investments required for typical Eucalyptus plantation carried in the state of Sao Paulo. Assuming the same interest rate as for sugar cane (6%) we arrive to 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 soil 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 28 for an interest rate of 6% per year. As in the case of sugar cane, 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. 62 which is good for the American market.

As shown in Fig. 13, it is necessary to start with 1.12GJ of oil to produce 1 GJ of gasoline. Furthermore, .12GJ 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(63) which means that gasoline is produced at a cost of $10.50/GJ assuming $35/barrel for the 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 8. 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. 5. 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

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*Diesel is generally 10% less expensive than gasoline ex-refinery and fuel oil 33% as expensive.

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 to 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 breakeven point as compared with gasoline in Brazil.

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REFERENCES

1. U.S. Energy Outlook, National Petroleum Council, Washington, D.C., 1971.

2. "Estimated Growth of Civilian Nuclear Power", - WASH-1055, U.S. Atomic Energy Commission, Washington, D.C., 1965.

3. Rose, D.J., "Energy Policy in the U.S.", Scientific American 230, pp. 20-29, 1973.

4. Vauge, C., "Le Choix Solaire, Une Energie qui Entre dans la Vie Quotidienne", CNRS/Tchou, 1979.

5. Antal, M.J., "Thermochemical Conversion of Biomass: The Scientific Aspects", Report to the Office of Technology Assessment of the Congress of the United States, 1979.

6. Staff-Republican Conference, U.S. Senate, "Alcohol: The Renewable Fuel from our Nations Resource, A Technical and Economic Report on the Use of Alcohol as a Motor Fuel", October, 1977.

7. Woodwell, G.M., "The Carbon Dioxide Question", Scientific American 238, pp. 34-43, 1978.

8. Nash, A.W. and Howes, D.A., "Principles of Motor Fuel Preparation and Applications", Vol. I, 2nd Edition, John Wiley and Sons, N.Y., pp. 461-561, 1938.

9. The Report of the Alcohol Fuels Policy Review", U.S. Department of Energy, DOE/PE-0012, p. 33, June 1979.

10. Utilization of Wood and Other Biomass for Small Scale Electric Power Generation, C.E.A., Contract #77-58, p. 104, 1977.

11. Berkowitz, N., "Coal Gasification - "A State-of-the-Art" Review", Information Series 64, Alberta Research, Edmonton, Alberta, p. 13, 1973.

12. Da Silva, J.G. - comunicacao privada, 1979.

13. Murata, D. and Gibson, W. Hawaiian Planter's Record 59, pp. 51-57, 1967. Hawaiian Sugar Planter's Association, Experiment Station, Sugar Technology Department, 1974.

14. Alexander, A.G., "Sugar and Energy Attributes of the Genus Saccharum". Symposium on Alternate Uses of Sugarcane for Development. Caribe Hilton Hotel, San Juan, March 26-27, 1979. Alexander, A.G. et al. "Production of Sugarcane and Tropical Grasses as a Renewable Energy Source". First and second Quarterly Reports 1979-80 to the U.S. Department of Energy, Agricultural Experimental Station, University of Puerto Rico, Rio Piedras, Puerto Rico, p. 12, 1980.

15. Inojosa, A.E. de A. Cooperativa Fluminense dos Productores de Acucar, Rio de Janeiro, R.J., Brasil - comunicacao privada, 1979.

16. Ladisch, M.R. and Dyck, K., Science 205, pp. 898-900, (1979).

17. Miller, B., Friedman, H.L. and Meiser Jr., C.H., Textile Research Journal, 50, pp. 10-16, (1980).

18. "Fuel From Farms - A Guide to Small Scale Ethanol Production" - Solar Energy Information Data Bank and Solar Energy Research Institute, Contract #EG-77-C-01-4042, p. 57, February, 1980.

19. Pino and Longo, W. "Bio Energy '80 World Congress and Exposition", Programs and Systems Seminar, Major Systems, Alcohols-Brazil, Atlanta, Georgia, April 21-24, 1980.

20. Instituto de Acucar e Alcool do Brasil - Informacao privada.

21. Poole, A. e Moreira, J.R., "Energy Problems in Brazil with a Closer Look at the Ethanol - Methanol Problem", Internal Report, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, S.P., C.P. 20516, Brazil, 1979.

22. "Energy Alternatives - A Comparative Analysis" - The Science and Public Policy Program, University of Oklahoma, Norman, Oklahoma, pp. 2-41 and 2-42, May 1975.

23. This figure is quoted in 1980 dollar value. A scale-up factor of .7 was used and inflation correction applied to the figure quoted by Hokanson, A.E., and Rowell, R.M., "Methanol from Wood Waste: A Technical and Economic Study", General Technical Report FPL12, U.S. Forest Service, 1977.

24. Browning, E. "Toxicity and Metabolism of Industrial Solvents", Elsevier Publishing Company, p. 324, 1965.

25. Da Silva, J.G. et al, Science 201, pp. 903-907, 1978.

26. Moreira, J.R., Serra, G.E. and Goldemberg, J. Ciencia e Cultura 30, p. 822, 1978.

27. Lipinsky, E.S. e Kresovich, S. "Sorghum as Energy Crops", Biomass Sources Seminars, Energy Crops, Agriculture Seminar, Bio Energy '80, The Georgia World Congress Center, Atlanta, Georgia, April 21-24, 1980.

28. Stumpf, U.E. "Aspectos Tecnicos de Motores a Alcool" 29 Reuniao Anual da Sociedade Brasileira para o Progresso da Ciencia, Sao Paulo, 1977.

29. Hagen, D.L. "Methanol Its Synthesis, Use as a Fuel, Economics and Hazards", Master thesis to the Graduate School of the University of Minnesota, pp. 4-7, December 1976.

30. Purohit, G. and Houseman, J. "Methanol Decomposition Bottoming Cycle for IC Engines," Soc. Auto. Eng. Paper No. 790427, 1979.

31. Hagen, D.L. "Methanol as a Fuel: A Review with Bibliography", Soc. Auto. Eng., Paper No. 770792, 1977.

32. Hagen, D.L. "Methanol Its Synthesis, Use as a Fuel, Economics and Hazards", Master thesis to the Graduate School of the University of Minnesota, pp. 2-30, December 1976.

33. Koenig, A., Lee, W. and Bernhardt, W., "Technical and Economical Aspects of Methanol as an Automotive Fuel" Soc. Auto. Eng., Paper No. 760545, 1976.

34. "Performance da Frota de Veiculos a Alcool da Telesp" Companhia de Telecomunicacoes do Estado de Sao Paulo, Sao Paulo, S.P. Brazil, January, 1980.

35. Hagen, D.L. "Methanol Its Synthesis, Use as a Fuel, Economics and Hazards", Master thesis to the Graduate School of the University of Minnesota, Appendix II-1, December, 1976.

36. Hilden, D.L. and Parks, F.B. "A Single Cylinder Engine Study of Methanol-Emphasis on Organic Emissions" Soc. Auto. Eng. Paper No. 760378, 1976.

37. Wempo, L. e Winfried, G. "Engine Performance and Exhaust Emission Characteristics of Spark-Ignition Engines Burning Methanol and Methanol-Gasoline Mixtures", Am. Inst. Ch. Eng. 90th Meeting, Boston, Paper #31d, September 9, 1975.

38. Conselho Nacional de Petrōleo, private communication, 1978.

39. Stumpf, U.E. "Ethanol: Combustivel e Materia Prima" Semana da Tecnologia Industrial - Ministerio da Industria e Comercio, Secretaria da Tecnologia Industrial, Rio de Janeiro, 1976.

40. Most, W.J. e Longwell, J.P., "Single-Cylinder Engine Evaluation of Methanol-Improved Energy Economy and Reduced NO_x," Soc. Auto. Eng., Paper No. 750119, February, 1975.

41. Pischinjer, N.P., "Experiences with the Utilization of Ethanol/Gasoline Blends and Pure Ethanol in Brazilian Passenger Cars", Volkswagen do Brasil-3rd International Symposium on Alcohol Fuels Technology in Asilomar, May 28-31, 1979.

42. Lawrence, R., "Gasohol Test Program" EPA TAEB Report 79-4A, December, 1978.

43. Richardson, D., "Exhaust Emissions and Fuel Economy for Automobiles Using Alcohol/Gasoline Blends Under High Altitude Conditions", EPA TAEB Report 79-1, October, 1978.

44. These figures were supplied by the Official Brazilian Delegation in "Bio Energy'80 world Congress and Exposition", Atlanta, Georgia, April 21-24, 1980.

45. "A Participating Protocol Agreement for the Brazilian Alcohol Program" - Brasilia, September, 1979. Published in New York Times, December 28, 1979.

46. "Conversao de Motores para Alcool". Published by COFAP, Cia Fabricadora de Pecas, Santo Andre, Sao Paulo, Brazil.

47. Haynes, V.D., "Energy Use in Petroleum Refineries" Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37830, ORNL/TM-5433, p. 37 , September, 1976.

48. Hirako, Y. e Ohta, M., "Effect of Lean Pre-Mixture on the Combustion in Diesel Engines," Bulletin of Japan Society of Mechanical Engineers, 16, 1750, 1973.

49. Bro, K. e Pedersen, P.S., "Alternative Diesel Engine Fuel: An Experimental Investigation of Methanol, Ethanol, Methane and Ammonia in a D.I. Diesel Engine with Pilot Injection", Soc. Auto. Eng., SAE - Paper No. 770794, 1977.

50. Bracco, F.V., Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, N.J., 08544, comunicacao privada.

51. Bliss, C. e Blake, D.D., "Sivicultural Biomass Farms - Volume V, Conversion Process and Costs" - Mitre Technical Report #7347, Contract No. ERDA-E(49-18), 2081, Appendix B, May 1977.

52. idem, page 32.

53. Pye, E.K. e Humphrey, A.E. "Production of Liquid Fuels From Cellulosic Biomass", Fuels from Biomass Conference, Solar Energy Research Institute, Golden, Colorado, June, 1979.

54. Serra, G.E., Goldemberg, J., Moreira, J.R. e DeCarvalho, C.M., "Estudo Energetico de Alternativas Brasileiras para Producao de Energia Renovavel", XV Convencao Union Pan Americana Desenvolvimento e Investigacao UPADI, Santiago, Chile, 1-7 October, 1978.

55. Starr, P.J., Finn-Carlson, D.W. e Nachtshein, C.J., Energy Sources, 3(1978) 353-373.

56. "Fuel From Farms-A Guide to Small Scale Ethanol Production"-Solar Energy Information Data Bank and Solar Research Institute, Contract #ED-77-C-01-4042, Appendix D, February 1980.

57. Bullard, C.W., Penner, P.S. e Pilati, D.A., Resources and Energy 1, (1978) 267-313.

58. Vanin, V., Moreira, J.R. e Goldemberg, J. "Relatorio sobre a Obtencao dos Coeficientes de Energia" - Relatorio Intermo, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, S.P., C.P. 20516, Brasil, 1980.

59. Bullard, C.W., Penner, P.S. e Pilati, D.A. "Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis". Center for Advanced Computation. University of Illinois, Urbana-Champaign, 1976.

60. Birkett, H.S. and Polack, J.A., Sugar J. 40, 9 (1978).

61. Goldemberg, J. "Relatorio da Missao Tecnica Empresarial do IBDF a Uniao Sovietica e Suica" - Instituto Brasileiro de Desenvolvimento Florestal, Brasilia, Brasil, 1979.

62. "Net Energy Analysis: An Energy Balance Study of Fossil Fuel Resources", Editor-Bruce Polich. Colorado Energy Research Institute, P.O. Box 366, Golden, Colorado 80410, pg. II-38, April 1976.

63. Reinstein, R., Energy Regulatory Administration, U.S. Department of Energy, Washington, D.C., private communication, 1979.

64. Brown, R.I. "Wood Consumption in Brazil" - Relatorio Interno, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, S.P., C.P. 20516, Brasil, February, 1980.

65. Serra, G.E., Moreira, J.R., Goldemberg, J., Heezem, A.M., "Avaliacao da Energia Investida na Fase Agricola de Algumas Culturas". Relatorio Final a Secretaria de Tecnologia Industrial, Ministerio da Industria e Comercio, Brasilia, D.F., Brasil, September, 1979.

66. Moreira, J.R., Vanin, V.R. e Goldember, J. "Energy Balance for the Production of Ethyl and Methyl Alcohol". Workshop on Fermentation Alcohol for Use as Fuel and Chemical Feedstock in Developing Countries, Vienna, Austria, March 26-30, 1979. Preprint IFUSP/P-165, Instituto de Fisica da Universidade de Sao Paulo, S.P., C.P. 20516, Brasil, 1979.

67. Hagen, D.L. "Methanol-Its Synthesis, Use as a Fuel, Economics and Hazards". Master thesis, Graduate School of the University of Minnesota, pp. II-6, December, 1976.

68. Gallant, R.W., "Physical Properties of Hydrocarbons", Vol. 1, Gulf Publishing Company, Houston, Texas.

69. Goldemberg, J. e Moreira, J.R., "Alcohol From Plant Products- A Brazilian Alternative to the Energy Shortage" - Preprint IFUSP/P-126, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, S.P., C.P. 20516, Brasil.

70. Araujo, N. de Q. et al., "Hidrolise Enzimatica da Mandioca", Informacoes do Instituto Nacional de Tecnologia, 9, pp. 42-52, 1978.

71. Pimentel, D., "Algricultural Production: Resource Needs and Limitation". Transaction of the 40th North American Wildlife and Natural Resources Conference, Wildlife Management Institute, Washington, D.C., 1975.

72. V. Cervinka et. al., Energy Requirements for Agriculture in California, California Department of Food and Agriculture, University of California, Davis, California, 1974.

73. S.R. Aldrich et. al., <u>Modern Corn Production</u>, ASL Publication, Champaign, Illinois, May, 1975.

74. W. A. Scheller, "Net Energy Analysis of Ethanol Production", 169th American Chemical Society Meeting, Philadelphia, Pennsylvania, 1975.

75. G.H. Heichel, "Agricultural Production and Energy Resources", American Scientist, 64 January/February, 1976.

76. Hoffman, K.C. etal, "Reference Material System: A source for Renewable Materials System Assessment," NRC, National Academy of Science, Washington, DC, 1976.

77. Chamber, R.S., Herendern, R.A., Joyce, J.J. and Penner, P.S., Science 206 , 789, 1979.

78. Da Silva , J.G., Serra, G.E., Moreira, J.R. and Gonçalves, J.C., "Balanço energetico Cultural da Produção de Alcool Etilico da Cana de Açucar, Mandioca e Sorgo Sacarino - Fase Agricola e Industrial", Brasil Açucareiro , December, 1976.

79. Little, I.M.D. and Mirrlees, J.A., "Project Appraisal and Planning for Developing Countries," Basic Book, New York, 1974.

80. Cook, E., Scientific American 224, pp. 135-144, 1971.

81. Moreira, J.R. e Goldemberg, J. "Alcohol-Considerações Economicas". Relatório Interno, Instituto de Física da Universidade de São Paulo, São Paulo, S.P. C.P. 20516, Brasil, 1978.

82. Haynes, V.O. "Energy Use in Petroleum Refineries", OaK Ridge National Laboratory, OaK Ridge, Tennesse, 37830, ORNL/TM-5433, p. 17, September, 1976.

83. Dartnell, P.B., "Minimising Crude Oil Usage by Optimising Engines and Gasoline", the Associated Octel Company Limited, March, 1976.

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. 64; 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

Energetic Expenses \ Crop	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. 65 and 66

TABLE 4[†]

HEAT OF COMBUSTION ΔH_c AT 25°C FOR GASOLINE AND ETHANOL

Ethanol C_2H_5OH	Liquid Fuel (MJ/Kg)	Gaseous Fuel (MJ/Kg)
Higher (H_2O liquid)	29.70	30.62
Lower (H_2O gas)	26.68	27.60
Methanol CH_2OH		
Higher (H_2O liquid)	22.66	23.85
Lower (H_2O gas)	19.92	21.10
Iso-octane* C_8H_{18}		
Higher (H_2O liquid)	47.85	48.18
Lower (H_2O gas)	44.38	44.71

*Iso-octane is used as the standard hydrocarbon to compare fuel properties

†From 56 and 67

TABLE 5[†]

ENERGY DENSITY OF THE FUEL CHARGE

Gaseous Oxidant	Liquid Fuel		Gaseous Fuel	
	Volume (m^3/kg mol of fuel)	Energy Density (MJ/m^3)	Volume (m^3/kg mol of fuel)	Energy Density (MJ/m^3)
T = 25°C				
Ethanol + Air	356.93	3.433	381.39	3.328
Iso-octane + Air	1487.30	3.407	1511.61	3.378
T = 0°C				
Ethanol + Air			349.39	3.687
T = 22°C				
Iso-octane + Air			1496.38	3.413

Assuming:

1) Air with 50% humidity

2) Air as an ideal gas at 25°C; ideal volume = 22.464 liter/mol at 25°C and 1 atmosphere

3) Ethanol density $\rho(25^{\circ}C) = 0.789 g/cm^3$

4) Iso-octane density $\rho(25^{\circ}C) = 0.687 g/cm^3$

5) Vol of C_2H_5OH (as a liquid) = $.0669 m^3$/kg mol

6) Vol of C_8H_{18} (as a liquid) = $.166 m^3$/kg mol

[†] From Refs. 56, 67 and 68.

TABLE 6[†]

COMPARISON OF ETHANOL AND GASOLINE EFFICIENCIES

	Compression Ratio 8.2	Compression Ratio 12
1) Compression Ratio	0	+ 16
2) Increase in Efficiency due to fuel injection	+ 8	+ 8
3) Surplus of Power	+ 1	+ 3
4) Surplus of Fuel Weight	- 2	- 2
5) Use of Lean Mixture	+ 2	+ 2
TOTAL	+ 9%	+ 25%

[†] Adapted from Ref. 32

TABLE 7[†]

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. 69

TABLE 8[†]

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 9

STOICHIOMETRIC RELATIONS FOR OXIDATION

Fuel →	Ethanol				Isooctane			
Oxydent →	O_2		Air[*]		O_2		Air[*]	
	(moles)	(kg)	(moles)	(kg)	(moles)	(kg)	(moles)	(kg)
Fuel	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Oxydent	3.0	2.087	14.591	9.122	12.50	3.50	60.7	15.31

[*] Assuming air with 50% humidity, 76.66% N_2, 20.56% O_2, 1.83% H_2O, 0.92% A 0.03% CO_2; equivalent molecular weight of air = 28.76 g; molecular weight of O_2 = 32 g; molecular weight = 46.10 g; molecular weight of isooctane = 114.20 g.

TABLE 10[†]

BOILING TEMPERATURE AND VAPOR PRESSURE OF SOME FUELS

	Molecular Weight (g)	Boiling Temp. (°C)	Vapor Pressure[*] (kPa)
Isooctane	114.2	99.3	15.5
Regular Gasoline (summer)	98	32-186	70
Regular Gasoline (winter)	"	"	90
Ethanol	46.1	78.3	15.2

[*] 37.8 °C

[†] From Refs. 56 & 68.

TABLE 11[†]

PERCENT YIELDS OF REFINED PETROLEUM PRODUCTS FROM CRUDE OIL IN THE UNITED STATES

	1967	1969	1971	1973
Gasoline	44.0	44.8	46.2	45.2
Jet Fuel	7.5	8.2	7.4	6.8
Liquified Gas	3.1	2.9	2.9	2.8
Kerosene	2.7	2.6	2.1	1.7
Distillate Fuel Oil	22.3	21.7	22.0	22.5
Residual Fuel Oil	7.7	6.8	6.6	7.7
Petrochemical products	2.4	2.5	2.7	2.9
Naftas	0.8	0.7	0.7	0.7
Lubricant & Wax	2.0	1.9	1.8	1.7
Coke & Asphalt	6.0	6.1	6.4	6.5
Others	4.5	4.7	4.4	4.5
Deficit	- 2.9	- 3.1	- 3.4	- 3.6
	100.0	100.0	100.0	100.0

[†] From Ref. 47

TABLE 12[†]

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. 54

TABLE 13

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. 54

* Average

TABLE 14[†]

TYPICAL COMPOSITION OF BRAZILIAN CASSAVA

Stem Components	% of stem by weight
a) total extractive material	0.2
b) Ash	0.9
c) Fiber	23.0
d) Moisture	75.9

Root Components	% of root by weight				
a) Total Fermentable Sugar	26.1			27.5*	
a-1) Starch (as % of glucose)		21.6			25*
a-2) Total amount of mono and disaccharides (as % of glucose)		3.4			3.5*
a-2.1) Disaccharides (sucrose)			2.2		
a-2.2) Monosaccharides (glucose)			1.2		
a-3) Pentosanes		1.1			
b) Fiber	1.4				
c) Moisture	68.2				
d) Others	4.3				

*Average of commercial crops

[†] From Ref. 70

TABLE 15
YIELD OF COMMERCIAL CASSAVA CROPS IN BRAZIL[†]

	Cycle (Months)	Production (t/ha)	Yields (t/ha/year)	(t/ha/month)
Roots	18-22	20-30	10-15	1.11-1.67
Average	20	25	12.5	1.25
Stem	13-20	13-20	7.5-10	0.72-1.11
Average		16.5	8.75	0.83

[†] From Ref. 54

TABLE 16
AVERAGE COMPOSITION OF SWEET SORGHUM[†]

Stem Components	% of Stem By Weight
Sucrose	9.0 - 12.0
Reducing Sugars	1.0 - 4.0
Total Fermentable Sugars (as % of glucose)	12.0 - 16.5
Fiber	14.0 - 17.0
Moisture	84.0 - 75.5
Grain Components	
Starch	55 - 65
Total Fermentable Sugars (as % of glucose)	1 - 2
Moisture	12 - 15

[†] From Ref. 54

TABLE 17†

YIELD OF SWEET SORGHUM (2 CROPS PER YEAR)

	Cycle (month)	Production (t/ha)		Yields	
		Plant	Ratoon	(t/ha/yr)	(t/ha/month)
Stem	4 - 5*	30 - 35	15 - 25	45 - 60	3.75 - 5.0
Grain		2 - 4	15 - 25	3.5-6.5	0.29 - 0.54

*For each harvest

† Adapted from Ref. 26 and 54.

TABLE 18[†]

TYPICAL COMPOSITION OF WOOD

Components	Eucalyptus (% by weight)			Pinus (% by weight)		
1) Cellulose	50			50		
2) Hemicellulose	20			15		
A) Hexosanes		2.5			9.6	
a) Mananes			1.3			7.0
b) Galactanes			1.2			2.6
B) Pentosanes		17.5			5.4	
a) Xylanes			16.8			3.9
b) Arabanes			0.7			1.5
3) Lignin	25			30		
4) Others	5			5		

[†] From Ref. 54

TABLE 19[†]

TYPICAL YIELDS OF COMMERCIAL WOOD FARMS IN BRAZIL

Production	Eucalyptus	Pinus
(m^3/ha)	430	655
(ODT/ha)	250	365
(ODT/ha/year)	11.8	14.6
cycle (years)	21	25

[†] From Ref. 54

TABLE 20

TYPICAL COMPOSITION OF CORN GRAIN[†]

Components	% By Weight
Starch	72.2
Protein	8.9
Total Amount of Mono- and Disaccharides (as % of glucose)	1.8
Moisture	13.8
Ash	1.4
Others	1.9

[†] From Ref. 56

TABLE 21

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. 75
2) From ref. 76
3) Average value from ref. 72, 73, 74 e 75
4) From ref. 77; includes only energy for harvesting
5) From ref. 54

TABLE 22[†]

ENERGY REQUIRED FOR THE INDUSTRIAL CONVERSION OF SUGAR CANE TO ETHANOL -- TYPICAL BRAZILIAN DISTILLERY

Industrial Expenses	Energy $\left(\frac{10^9\ \text{kcal}}{\text{year}}\right)$
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. 66

TABLE 23[†]

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	25 - 13
Pinus	

[†] From Refs. 25, 61

[*] This figure is evaluated for the Brazilian technology. In the United States, much more energy is required (see Ref. 76) since stillage is dried to be used as cattle feed.

YIELDS OF ETHANOL AND TOTAL ENERGETICS EXPENSES FOR SEVERAL CROPS EXPLOITED UNDER THE ASSUMPTION OF SELF-SUFFICIENT HECTARE

Crop	$Y_{ethanol}$ (l/ha)	Land Fraction Used for Eucalyptus (%)	Total Energy Req'd. in the Agricultural Phase Crop + Eucalyptus (Meal/ha/yr.)	Industrial Energy Req'd. for Other Uses Than Fuel (Meal/ha/yr.)	E Energy Total (Meal/ha/yr.)	E/Y ($\frac{kcal}{l}$)
Sugar Cane	4700	0	3796 + 0	2204[1]	6000	1280
Cassava	1790	21	1920 + 116	840[2]	2876	1605
Sweet Sorghum	6106	0	7316 + 0	2890[1]	10206	1675
Corn	883	10	1756 + 55	415[3]	2226	2560
Eucalyptus	1700	39.5	333 + 218	799[4]	1340	790

1) From Ref. 66, all energy expenses are included, except the fuel used in the industrial processing.

2) An evaluation of all the capital costs for an industrial plant using cassava as a feedstock to ethanol is not available; the single unit already in operation in Brazil was assembled to perform technological investigation in parallel with the industrial operation; so it is overengineered. The use of cassava for ethanol products requires one more step than sugar cane, since it is necessary to perform the starch hyrolysis. The extraction of the beer is much simpler, since large milling cylinders are not necessary. The milling cylinders are responsible, in a sugar cane processing plant, by 10% of the total energy invested in capital goods; so it seems quite reasonable to assume that the energy saved in the mills would be used in the hydrolysis machinery -- the total energy "built-in" in the factory is taken the same as for the sugar cane based distillery. Fuel requirements are 6.5 kg of steam per liter of ethanol.

3) Data are not available for an assessment of the economical and/or energy evaluation of an ethanol distillery using corn as a feedstock, in Brazil. The flow chart of the plant has to be very similar to a unit that uses cassava; so, accordingly with comment 2), we assume the energy costs equivalent to the sugar cane distillery.

4) Typical cost for an ethanol plant that uses wood as a feedstock and acid hyrolysis technique is 2.5 times bigger than for sugar cane. This number is not very reliable, since it is the quotation for the first few units to be built in Brazil. Little experience is available presently to guarantee the construction of energy efficient units and it is not even clear if there will be a continuous market for this kind of technology in the future. Nevertheless, the unit can operate over 330 days per year, which results in a capital cost in liters/year very similar to the sugar cane plant. Because of the poor data available, we decided to use the same capital cost/l/year of the sugar cane; that is 470 kcal/ℓ

TABLE 25[†]

ECONOMICAL EXPENSES FOR THE SUGAR CANE CROP

1. $\overline{E}$ (average energy value of biomass) I		226 GJ/year
2. $I_a\overline{CRF}_a$ (clearing & purchasing land levelized annual revenue) II	x = 12% (VII)	\$272/year
	x = 6% (VII)	\$135/year
	x = 3.5% (VII)	\$82/year
3. $I_b\overline{CRF}_b$ (purchased equipment levelized annual revenue) III	x = 12%	\$105/year
	x = 6%	\$88/year
	x = 3.6%	\$79/year
4. $I_c\overline{CRF}_c$ (investment in planting levelized annual revenue) IV	x = 12%	\$217/year
	x = 6%	\$166/year
	x= 3.6%	\$147/year
5. $\overline{f}_{OM}$ (operating and maintenance costs) V	x = 12%	\$300/year
	x = 6%	\$298/year
	x = 3.6%	\$297/year
6. $\overline{R} = I_a\overline{CRF}_a + I_b\overline{CRF}_b + I_c\overline{CRF}_c + \overline{f}_{OM}$ (total levelized annual revenue requirement)	x = 12%	\$834/year
	x = 6%	\$687/year
	x = 3.6%	\$605/year
7. $\overline{C}$ ($\overline{R}/\overline{E}$)	x = 12%	\$3.95/GJ
	x = 6%	\$3.04/GJ
	x = 3.6%	\$2.67/GJ
8. $\overline{R}$ (excluding land purchase) VI	x = 12%	\$630/year
	x = 6%	\$565/year
	x = 3.6%	\$531/year
9. $\overline{C}$ (excluding land purchase)	x = 12%	\$2.78/GJ
	x = 6%	\$2.50/GJ
	x = 3.6%	\$2.38/GJ

[†] From Ref. 21

I) Defined as $\overline{E} = \sum_{i=1}^{M} E_i$

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. 78 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 (79) 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 26[†]

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 27[†]

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 28[†]

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

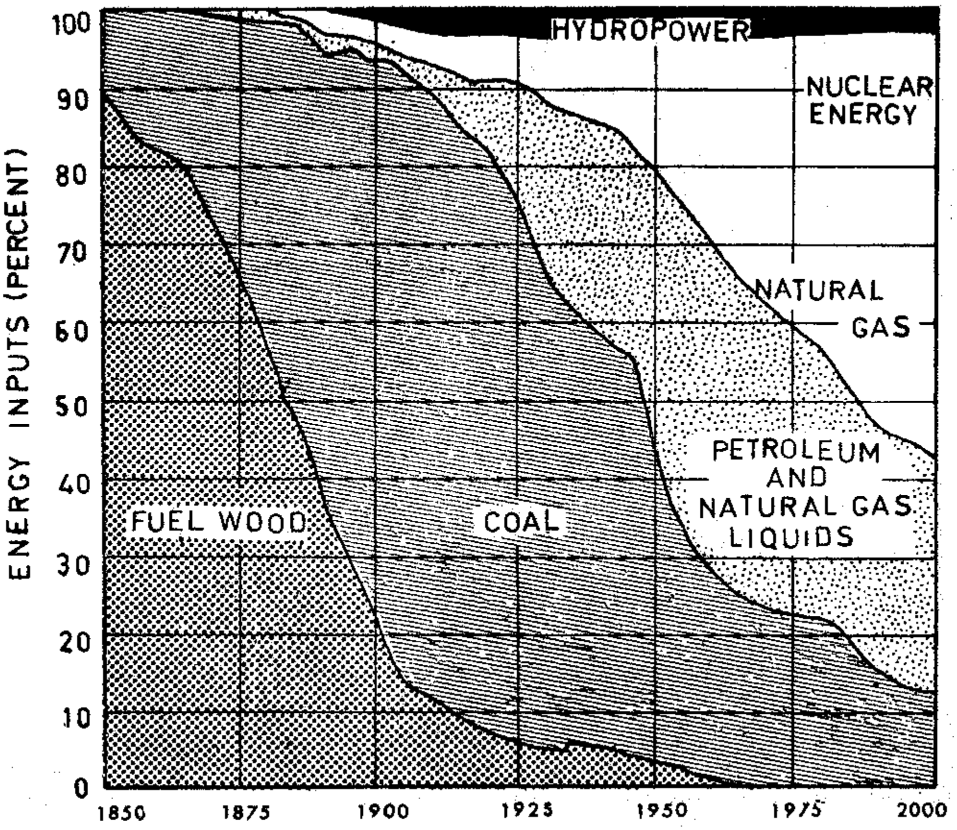
[†] Update to 1980 dollar value from data presented in Ref. 21. Assuming that the large devaluation of Brazilian money occurred in December 1979 (30%) was enough to offset the dollar inflation in 1978 and 79.

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*



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*From ref. 80

Figure 2

BLOCK DIAGRAM - ETHANOL DISTILLERY

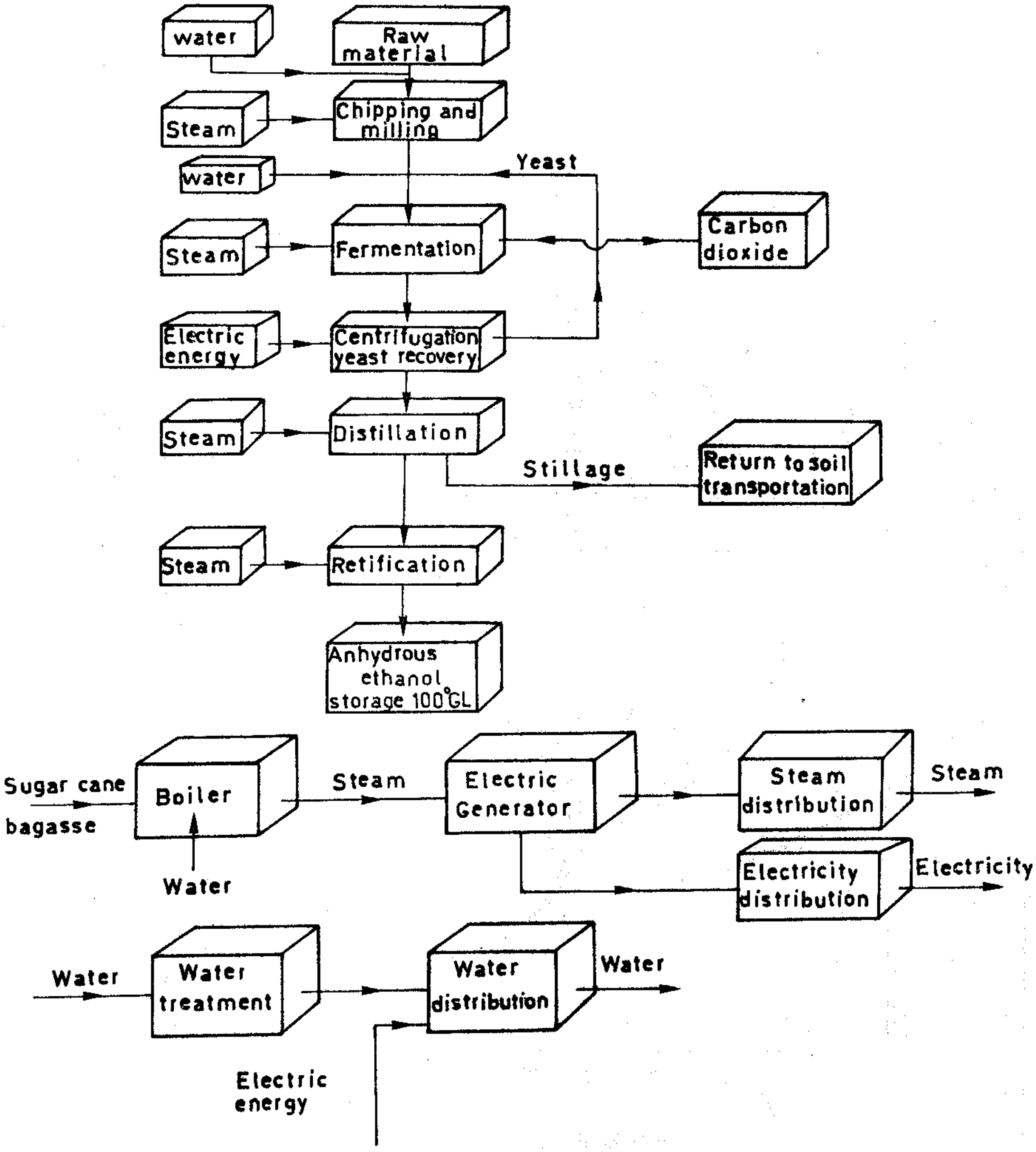
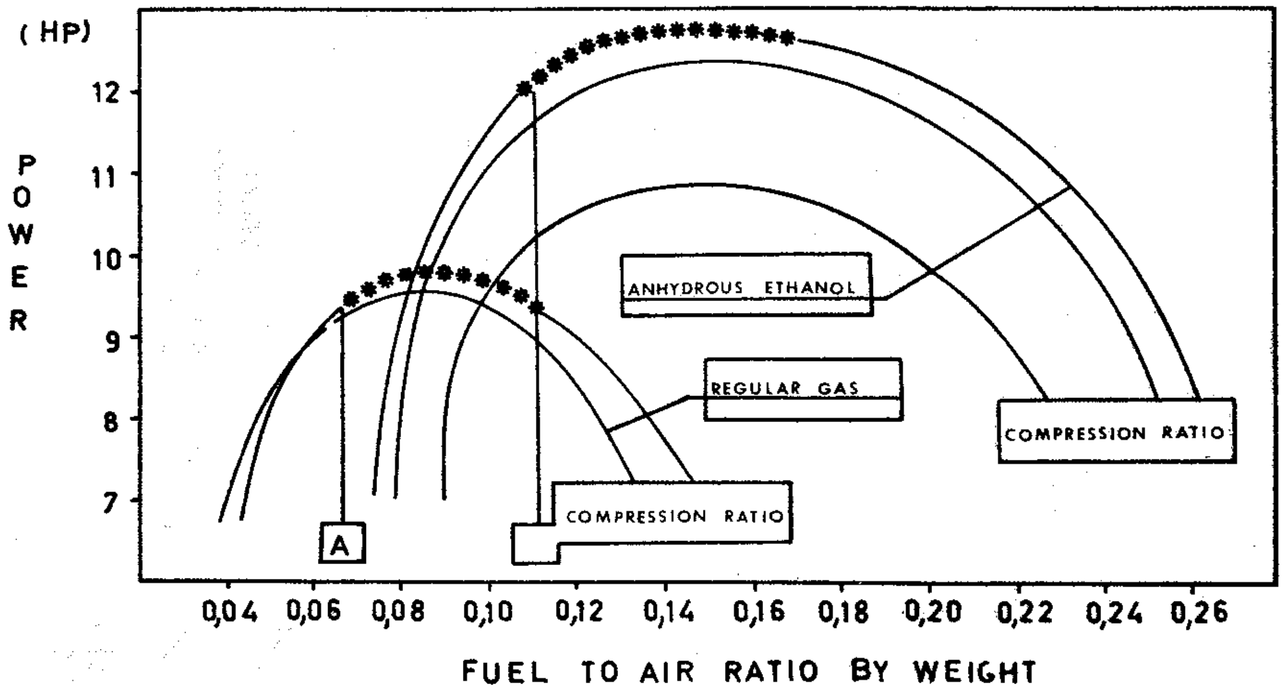


Figure 3

COMPARASION OF REGULAR GASOLINE AND ANHYDROUS ETHANOL

ENGINE POWER VERSUS FUEL TO AIR RATIO



**** Knocking region

A - Stoichiometric mixture for gas

B - Stoichiometric mixture for ethanol

FIGURE 4

EMISSIONS vs FUEL AIR EQUIVALENCE RATIO

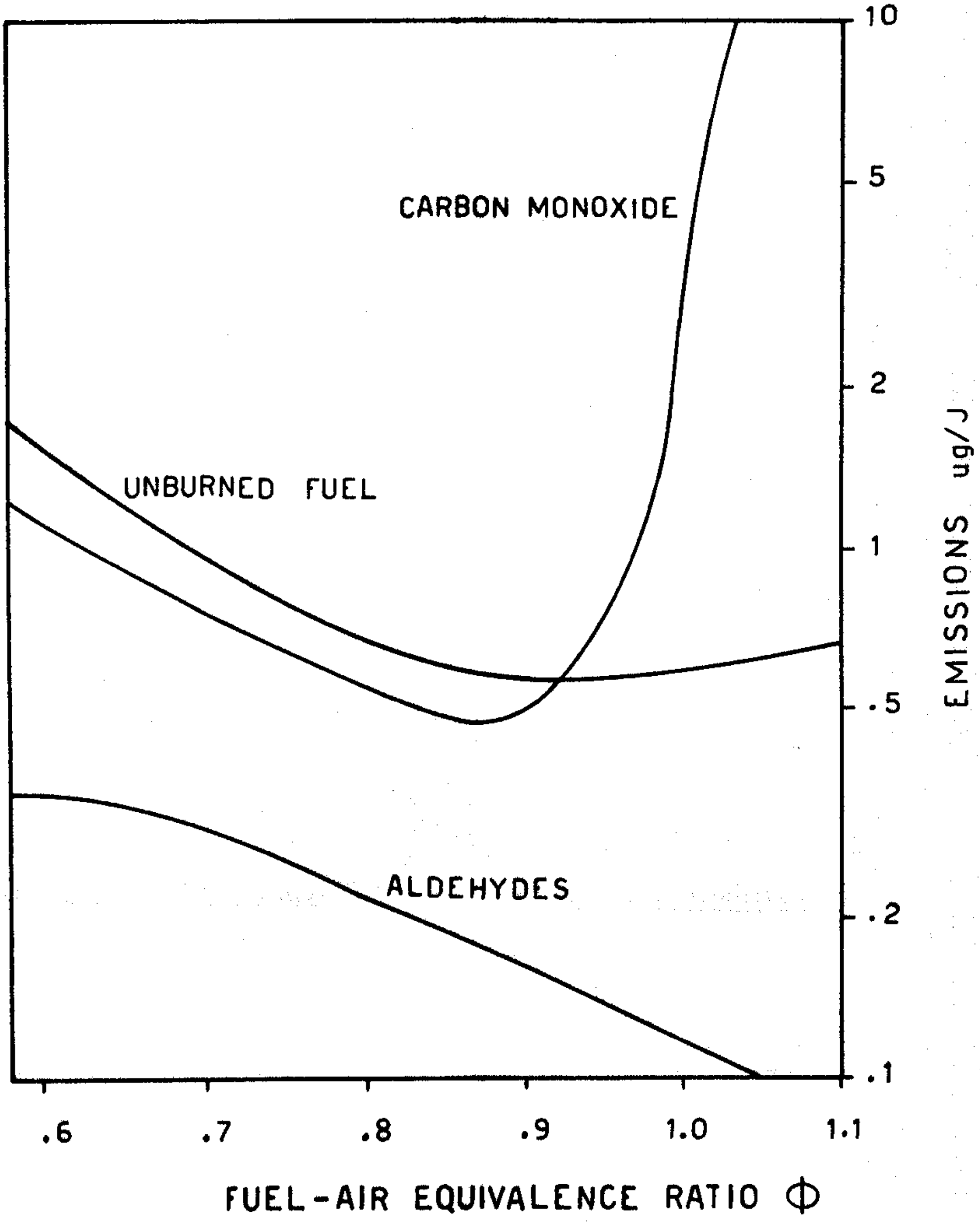
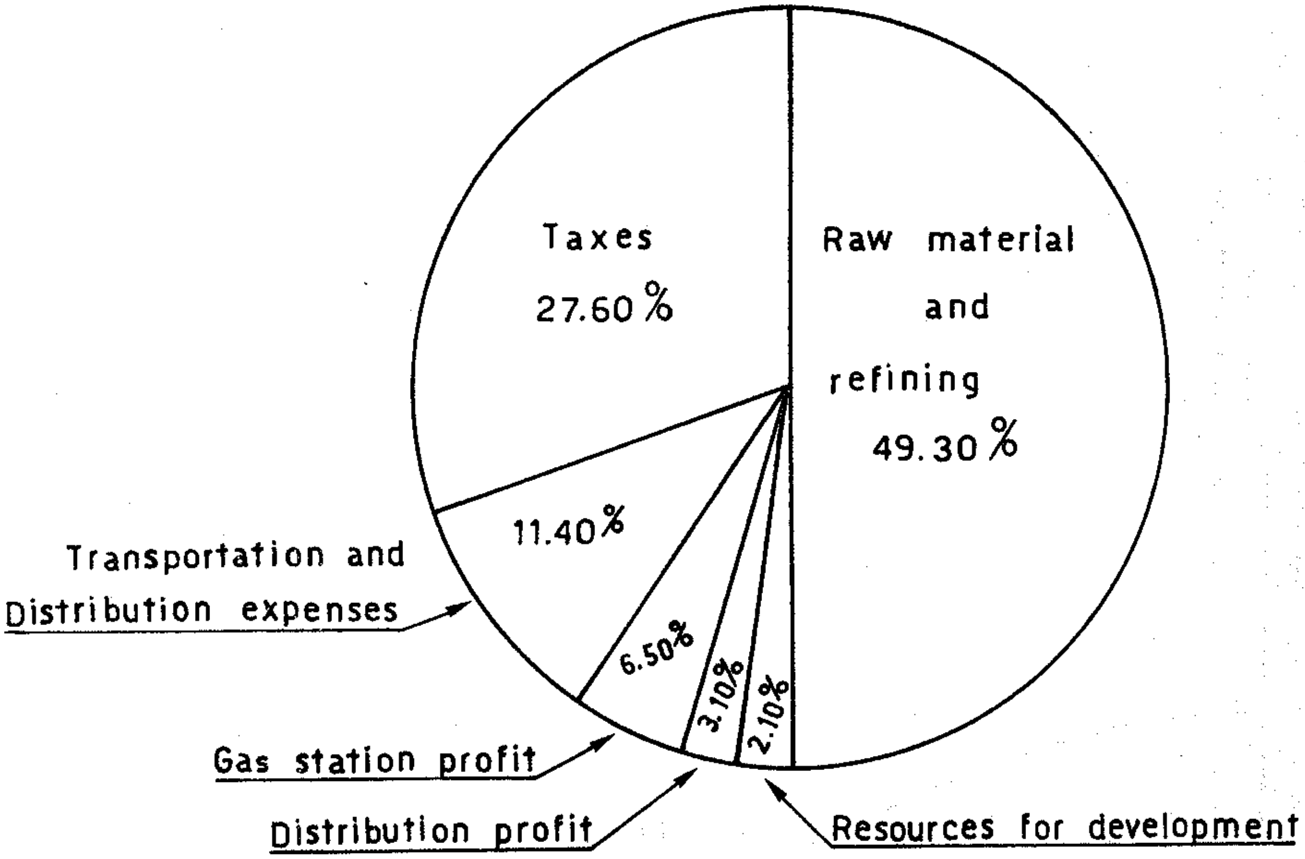


Figure 5

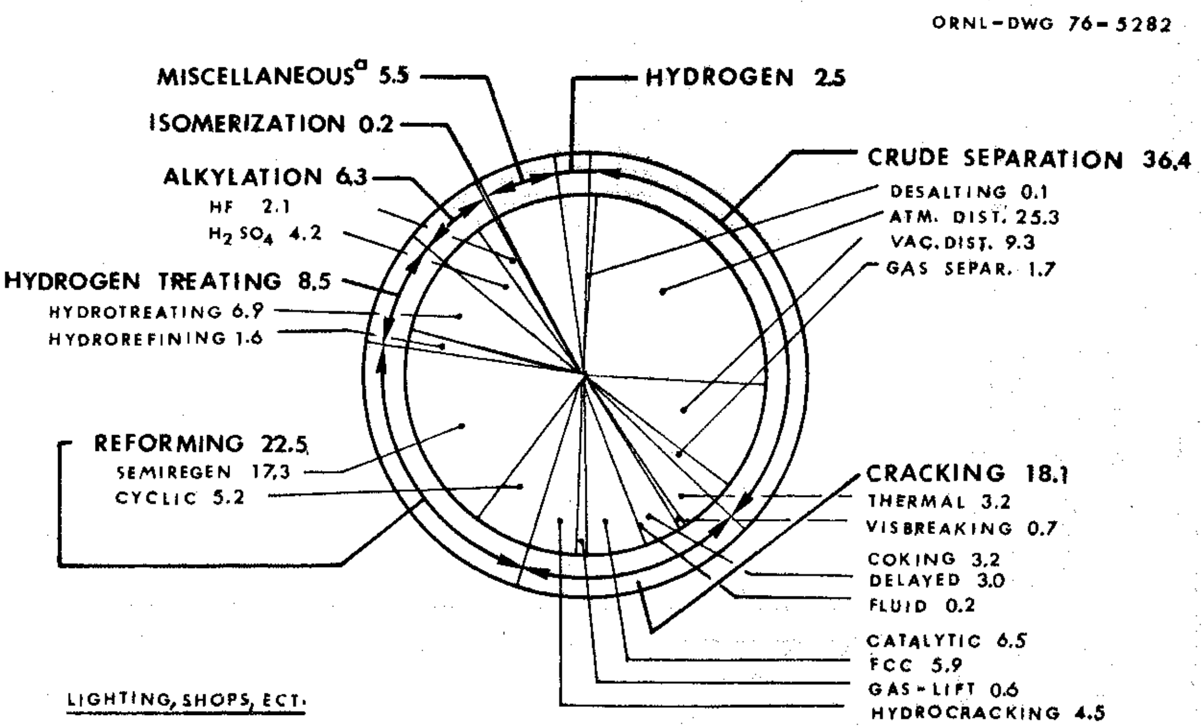
PRICE STRUTURE OF GASOLINE IN BRAZIL [†]



[†] From ref. 81

Figure 6

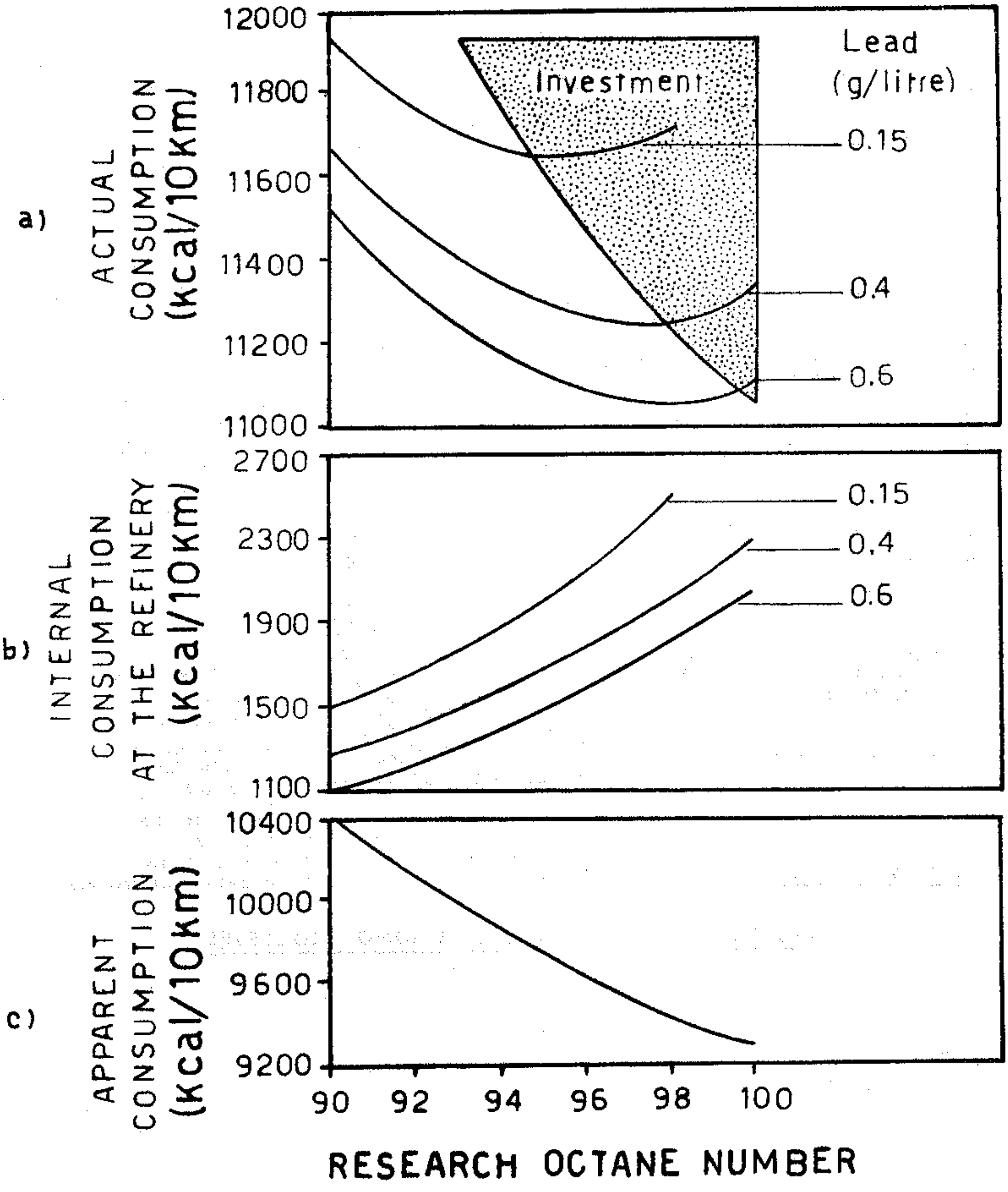
ENERGY EXPENDITURES IN THE DIFFERENT PHASES OF OIL PROCESSING[†]



(a) ENERGY DISTRIBUTION AMONG PROCESSES

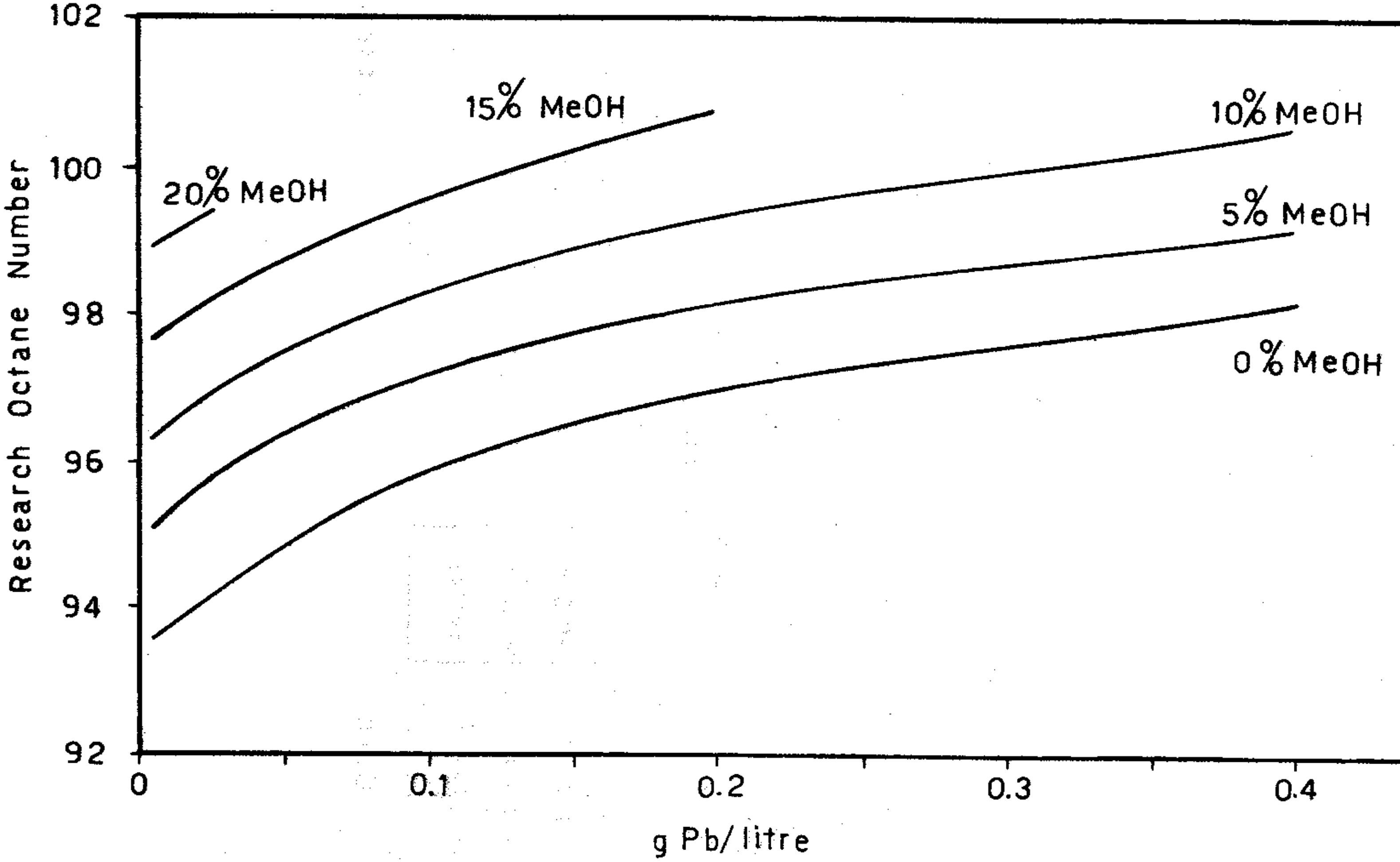
[†] From ref. 82

FIGURE 7 - VARIATION IN APPARENT AND ACTUAL CONSUMPTION WITH OCTANE NUMBER †



† From ref. 83

FIGURE 8 - METHANOL IN OLEFINIC GASOLINE - RON RESPONSE WITH TEL †



† From ref. 83

Figure 9

LAND DISTRIBUTION FOR THE EXPLOITATION OF SOME CROPS UNDER THE ASSUMPTION OF SELF-SUFFICIENT HECTARE

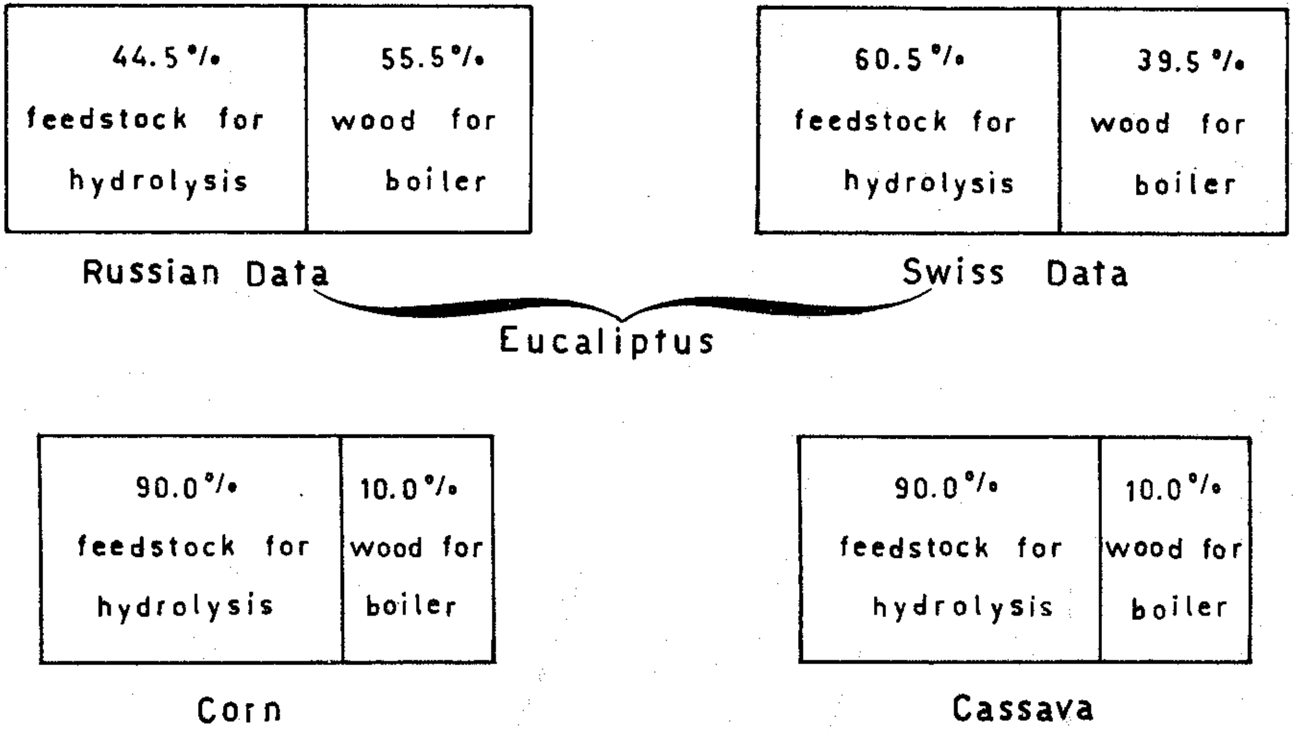


Figure 10

ENERGY EXPENDITURES FOR ETHANOL DERIVED FROM CORN IN UNITED STATE AND BRAZIL

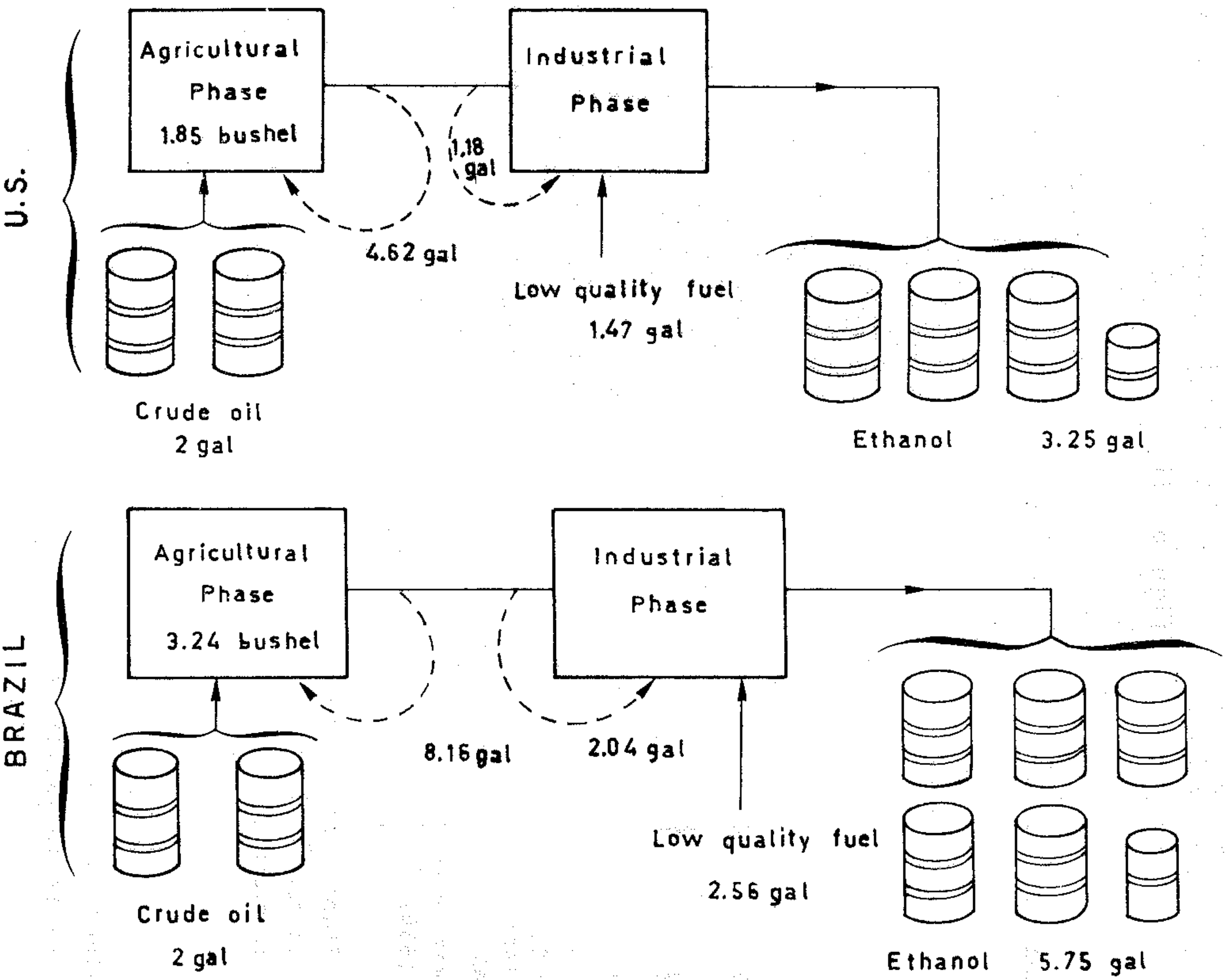
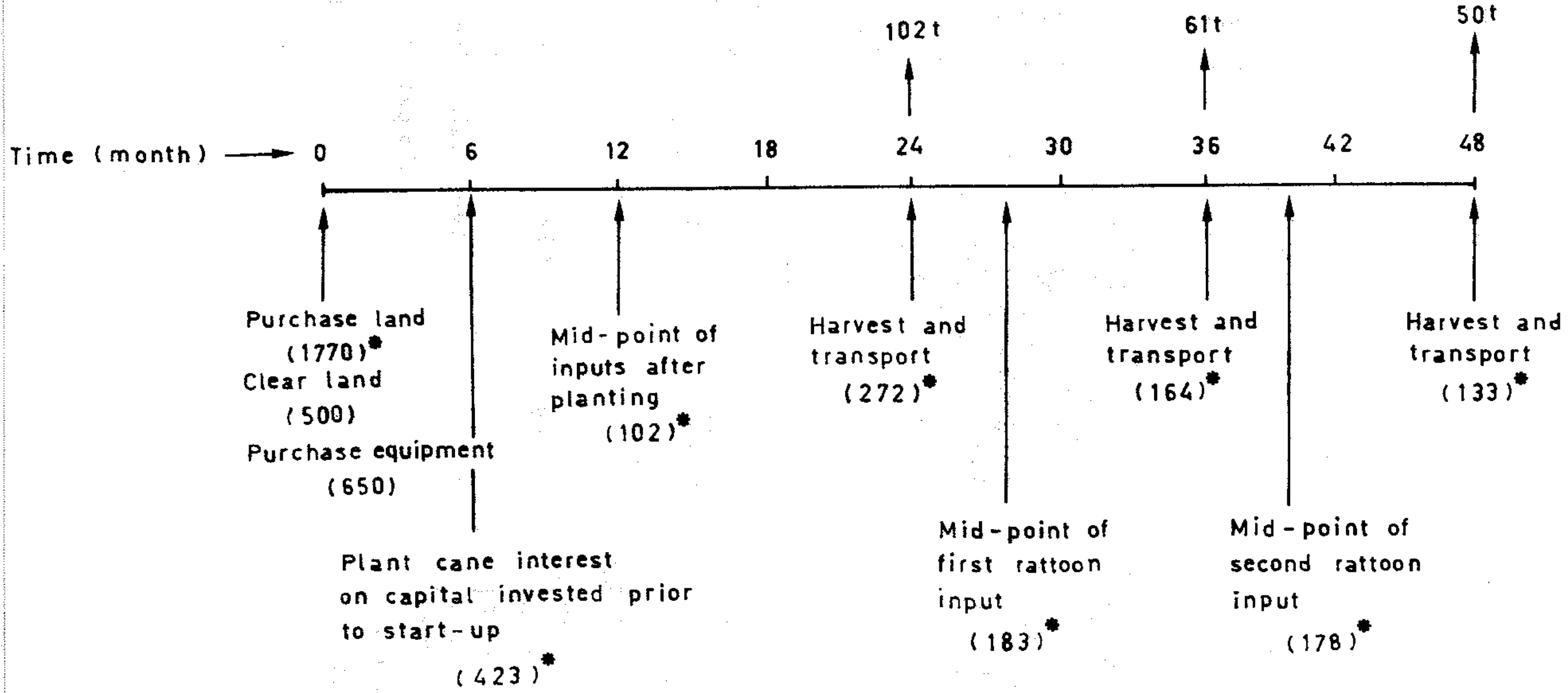


Figure 11

TIMING AND MAGNITUDE OF COST AND OUTPUTS OVER FOUR YEAR SUGAR CANE CYCLE IN SOUTHEAST OF BRAZIL



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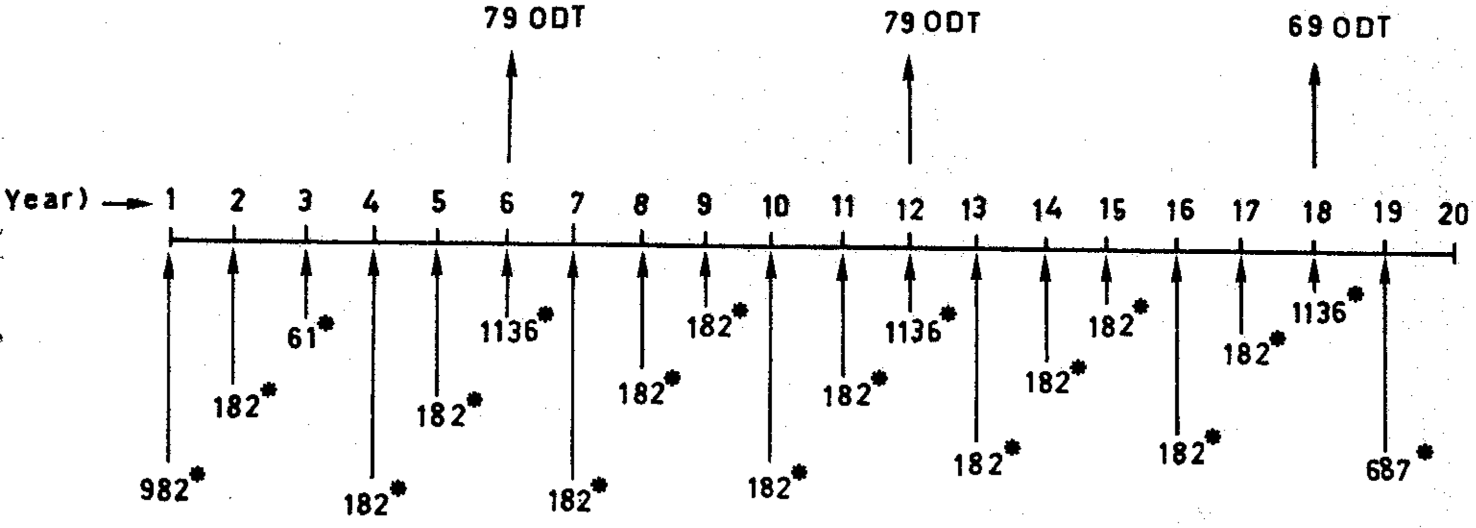
*Update to 1980 dollar value from data presented in Ref.21. Assuming that the large devaluation of Brazilian money occurred in December 1979 (30%) was enough to offset the dollar inflation in 1978 and 79.

Figure 12

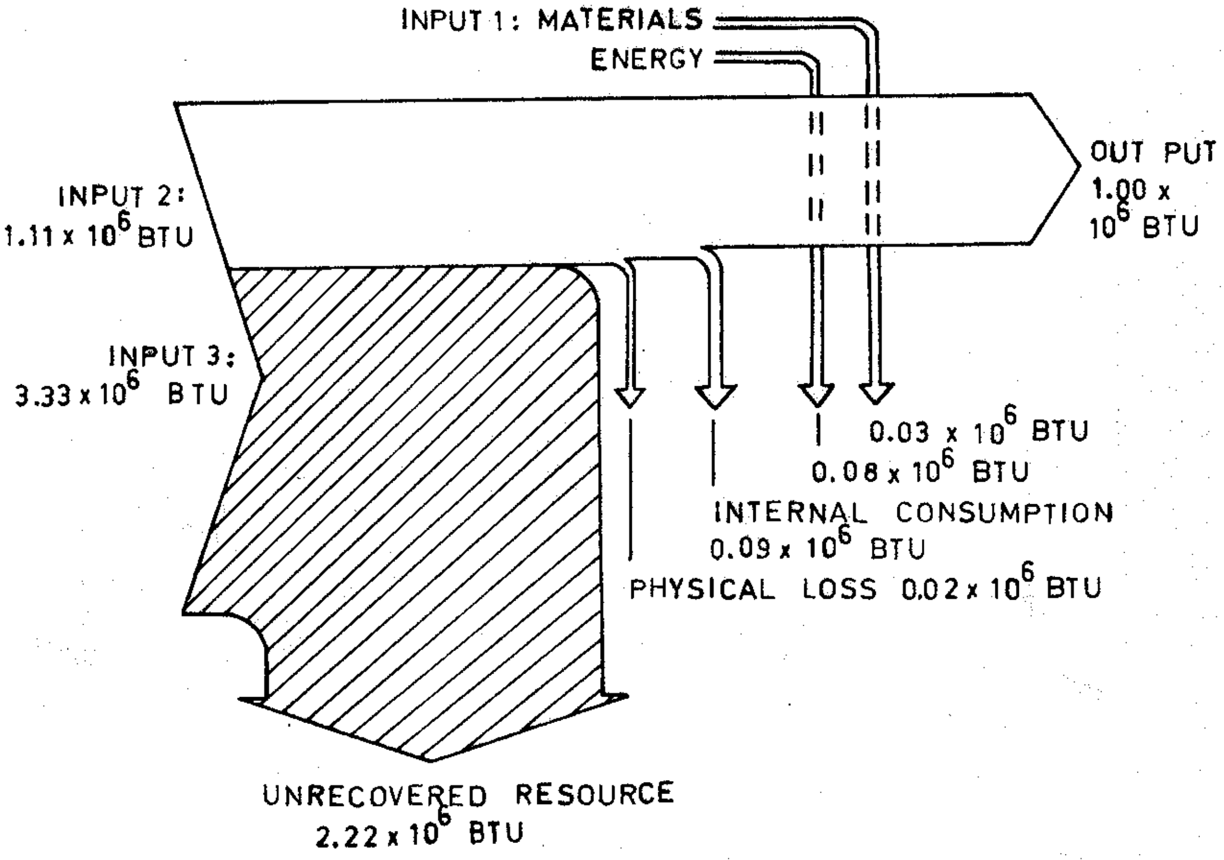
COST AND TIMING DISTRIBUTION OF INPUTS AND OUTPUTS IN AN EUCALIPTUS WOOD FARM IN BRAZIL



* 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 13

ENERGY COSTS FOR THE PRODUCTION OF GASOLINE [†]



[†] From ref. 62