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U.S. Department of Energy
Office of Alcohol Fuels

November 1980

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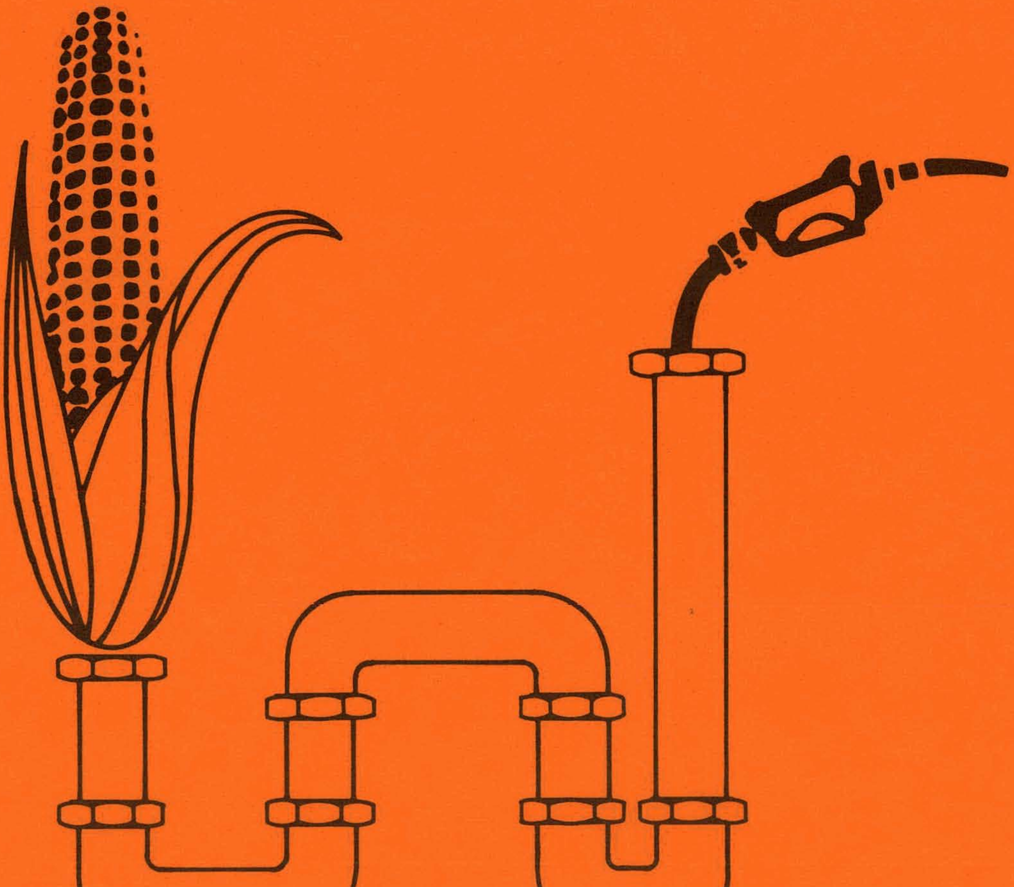
MASTER

Draft

Internal Combustion Engines for Alcohol Motor Fuels

A Compilation of Background Technical Information



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November 1980

U.S. Department of Energy
Office of Alcohol Fuels
Washington, D.C. 20585

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ACKNOWLEDGEMENT AND STATEMENT OF PURPOSE

This compilation is a draft training manual, containing technical background information on internal combustion engines and alcohol motor fuel technologies. Many of the articles in this manual have been reproduced from existing literature on the subject who's sources are acknowledged in the bibliography. The permission these publishers for the use of their materials is appreciated. In some cases, assurance of the publishers' approval was in process when this book was being prepared.

The compilation is a refined, balanced crosssection of available literature. It is presented here in three separate parts, each covering a specific discipline of emerging formulated alcohol motor fuels technology. Because this publication is intended only for the disemination of information, the publisher does not solicit critical reviews of its contents. However, readers are encouraged to submit new material for review and possible addition to this manual.

Alcohol Fuels Technology
U.S. Department of Energy
Office of Alcohol Fuels
Washington, D.C. 20585

> Enough has been said to give an idea of the capabilities and values of this new form of fuel, at least, and as far as the United States is concerned.
>
> With its advent not only will American genius perfect the machinery for its use, but the American farmer is given a new market for his crops.
>
> Distilleries, big and little, are likely to be set up all over the country, and the time is not far distant when the farmer will be able to carry his corn to the distillery, and either return with the money in his pocket or with fuel for farm engines, machinery, and perchance his automobile.
>
> F.B. WRIGHT
> "Distillation of Alcohol
> from Farm Products"
> New York-London 1907

FOREWORD

At the beginning of this century, gasoline was nothing more than a by-product of the production of kerosene for lamps. The kerosene market was then destroyed by Edison's invention of the electric light bulb. The oil industry, seeking new markets, began refining vast quantities of petroleum into gasoline for use in internal combustion vehicles. This gasoline was so plentiful and cheap that it became the standard motor fuel.

From that time, internal combustion engines have been optimized for petroleum based liquid fuels and the early primitive forms of gasoline have been considerably improved through refining formulation. Because of the continued abundance of fossil resources; notwithstanding F.B. Wright's optomistic prediction for alcohol; little or no consideration has been given to liquid and gaseous fuels derived from biomass.

Today, the fear of pollution, coupled with the growing scarcity of petroleum and the concomitant desire for fuel efficiency, have turned our attention to other, older sources of fuel, especially those derived from renewable resources.

Alcohol fuels will become precursors of several energy oriented economic, political, and sociological changes in America. They will help set the pace and tone for other renewable energy systems to be developed in the future. The emphasis of the work is alcohol, but it also includes other fuels, solids, liquids, and gases that can be made through the refining of biomass. Gasohol, alcohol, and biomass fuels are the ABCs of an energy system of major proportions that is about to dawn.

We cannot, however, rely merely on hope while we further study the alcohol/biomass fuels issue. Whatever the reasons, we have already missed the chance to address the subject of biomass fuels in a "proper and polite" scientific and academic manner. We must undertake now, a major educational effort to establish the understanding necessary to effectively gain the contributions available from biomass.

Richard F. Blaser
1980

TO THE READER

The success of the internal combustion engine has been an amazing phenomenon, and the unabated demand for more and more engines to fulfill the growing need for power for our constantly developing society, has shaped the dynamics of their technology and nurtured their achievements. However, the need to compromise the time-bounded chemical equilibrium of the real combustion process with the thermodynamic assumptions of the addition event of heat of their power cycles, has been the principal source of operative setbacks.

It is well known that the power cycle of operative engines must accommodate to the requirements of the real process of combustion. However, by doing this the engines are far away from the theoretical thermodynamic assumptions. It is a fact that up to the present time all designs have been intended to accommodated to the natural combustion process. However, most of the achievements and improvements in engine designs (new geometrics, improved materials, better fuels, helping additives, auxiliary hardware, etc.) are cosmetic and have not solved the real distortion problem of the combustion process of those engines.

Moreover, in modern engines, the unavoidable thermodynamic constraints, of the addition of heat event, are degenerative to the always critical equilibrium of the chemistry of the combustion. We must recognize that the formulated fossil fuels of today have exhausted their capabilities to control pollution and increase efficiency. For more than twenty years, engine design changes such as modifications in compression ratio, timing, and exhaust gas manipulation, restricted formulations (unleaded gas) and add-on equipment (catalyzers, electronic ignition, and computerized fuel supply), have attempted to remedy the problem but they have actually deteriorated the primary function of the internal combustion engine -- the transformation of chemical energy into mechanical torque with the maximum of efficiency. In any comparison of fossil and biomass fuels we must consider the total cost in money and energy of these inadequate remedies. We must, therefore, consider the ability of biofuels to avoid these negative remedies in order to meet pollution standards and improve combustion efficiencies.

In any evaluation of a formulated biofuel we must consider the combined system -- fuel and the conversion of fuel into torque.

The entire system, the contribution of the fuel feedstock, the conversion and refining of the fuel, and the engine using this fuel, must be considered in order to determine the capability an engine to meet its functional expectations.

In most of my professional career, I have advocated that the answers to the pollution, efficiency and performance problems inherent in contemporary internal combustion engines rest within the creative use of modern science and technology. We must refine the over one hundred year old theoretical assumptions of the heat engines thermodynamic power cycles. We must also re-address the cycles addition of heat events to allowing the use of energy flux theory for its evaluation. We must recall that heat was considered matter in the early days of engine development.

To the best of my ability this work has been based on unbiased information. This should avoid irrelevant controversy about its contribution to the consolidation of the scientific foundation of formulated alcohol motor fuels technology.

Only a limited sample of information was included in this compilation despite the overwhelming quality and quantity available from highly qualified sources. This sample represents a crossection of the relavent facts necessary for a correct preliminary evaluation of the state-of-the-art of biofuels technology. The reader is encouraged to read other texts and to consult other sources to expand his knowledge of this emerging technology.

Richard Blaser
July 1980

SUMMARY OF CONTENTS

PART ONE

- Compilation of Facts from the State of the Art on Internal Combustion Engines Fuels; Their Characteristics and Requisites
- Overview of Fuel Sources, Fuels Technology and Future Projections for Availability and Alternatives

PART TWO

- Compilation of Facts from the State of the Art on Alcohol Chemistry and in Alcohol Identification, Production, and Use
- Ethanol as "Spirit" and as Fuel
- Overview of Modern Evaluation of Alcohols as Motor Fuels
- Characteristics of Alcohol Fuels and Expectations

PART THREE

- Compilation of Cross References on the State of the Art on Handling and Combustion of Fuels in Internal Combustion Engines and Presentation of Basic Evaluations of Events Leading to the Use of Alcohols as Motor Fuels
- Overview of Today's Advanced Applications of Alcohols as Motor Fuels
- The Formulation of Alcohol Fuels for the Engines and the Modification of the Engine and Fuel Handling Hardware for Using the Alcohol Fuels
- Introduction to Multifuel Engines Concept, Today's Approaches, Their Practical Results and Expectations

BIBLIOGRAPHY

B-2 "Alcohol Fuels." Hearings before the U.S. House of Representatives Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, Washington, D.C.: July 11, 12, and 13, 1978. U.S. Government Printing Office.

A-12 "Alcohols - A Technical Assessment of Their Application as Fuels." Publication 4261 Washington, D.C.: American Petroleum Institute, 1976. pp.27-53.

A-6 "Automotive Fuels-Outlook for the Future." Bidwell Joseph, Warren, Michigan: General Motors Research Laboratories, 1978. GMR-2733. pp. 625-681.

A-11 "Alcohol Fuels." Special Hearing of the U.S. Senate Committee on Appropriations. Washington, D.C.: January 31, 1978. U.S. Government Printing Office. Stock Number 052-070-04679-1.

"Alcohol as an Alternative Fuel." Kirik, Mart p. 622-624.

"Elements of Diesel Engineering. Adams, Orville, New York, New York: Norman W. Hanley Pubishing Company, 1936.

A-4 Excerpt from Chapter VI, pp. 159-177

U.S. Department of Energy. "Proceedings: International Symposium on Alcohol Fuel Technology-Methanol and Ethanol." July, 1978. Available from National Technical Information Service. Stock No. CONF-771175, July, 1978. Stock No. 052-070-04679-1

A-7 "Methanol in Motor Gasoline--Impact on Oil Refining" by E.H. Spencer, pp. 658-668, A.F. Senate 7-2(1) thru 7-2(7)

A-8 "Gasoline-Methanol Fuels; Blending Optimisation with Respect to Manufacturing Economics and Engine Performance" by R.W. Hooks, K.H. Reders, and A.A. Reglizky, 7-1(1) thru 7-1(9)

C-2 "Utilization of Methanol as an Automative Fuel--A Report from IIEC-2, The Inter-Industry Emission Control Program" by R.E. Baker, et. al. pp. 220-236, AF Senate (also pp. 688-706, 2-7(1) thru 2-7(8), and pp. 413-420, AF House)

C-3 "Development of Methanol and Petrol Carburation Systems in the Netherlands" by J. Vander Weide and M.W.A. Ramschess, 6-1(1) thru 6-1(10)

C-4 "Problems in the Application of Ethanol as Fuel for Utility Vehicles" by W. Bandel, 2-3(1) thru 2-3(22)

C-5 "Possibilities for Cost-Effective Use of Alcohol Fuels in Otto Engine-Powered Vehicles, by Dr. Ing Winfried Berhardt, 1-5(1) thru 1-5(13)

C-6 "Factors that Improve the Performance of an Ethanol-Diesel Oil Dual Fuel Engine" by N.R. Panchapikesan, K.V. Gopalakridinan, and B.S. Murthy, 2-2(1) thru 2-2(8)

Combustion Engines. Fraas, Arthur P., New York, New York: McGraw-Hill Book Company, 1948

A-2 Excerpt from Chapter VIII, pp. 214-215

C-1 "Methanol: An Automative Fuel in Our Future?" Search, Vol. 12 No. 1, Jan-Feb 1977, GM Research Laboratories

High Speed Diesel Engines. Judge, Arthur W. Fifth Edition, New York, New York: D. Van Nostrand Company, 1957

A-5 Excerpt from Chapter XIX, pp. 549-559.

Internal Combustion Engines. Maleev, V.L. New York, New York. McGraw-Hill Book Company, 1933

A-1 Excerpt from Chapter IX, pp. 86-89

B-1 Excerpt from Chapter I, p. 1-24

B-4 "Seminar on Automobile Fuel Efficiency - Volume II, Proceedings," Meader, Marion W. McLean, Virginia: The Mitre Corporation, 1978. Report No. M. 78-96.

Internal Combustion Engines and Air Pollution, Obert, Edward F., New York, New York: Intext/Harper and Row, Publishers, 1973.

A-3 Excerpt from Chapter VIII, pp. 222-287

B-1 Excerpt from Chapter I, pp. 1-24

B-2 Excerpt from Chapter XI, pp. 382-409

B-3 Excerpt from Chapter XII, pp. 427-429.

Distillation of Alcohol and De-Naturing, F.B. Wright, New York, New York: Spon and Chamberlain, 1907.

B-1 Organic Chemistry, Morrison and Boyd, Boston, 1959.

PART ONE

TABLE OF CONTENTS

CHAPTER 1
FUELS FOR INTERNAL COMBUSTION ENGINES PAGE

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* Denotes source document - see Bibliography

PART ONE - continued

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PART ONE

Compilation of Facts from the State-of-the-Art on Internal Combustion Engine Fuels; Their Characteristics and Requisites.

Overview of Fuel Sources, Fuels Technology and Future Projections for Availability and Alternatives.

CHAPTER I

FUELS FOR INTERNAL COMBUSTION ENGINES

Fuel Types and Sources

Introduction

Fuels used in internal-combustion engines come from all three groups—gaseous, liquid, and solid.

Composition — In all fuels the two basic combustible elements are carbon and hydrogen, encountered either separately or in combinations called hydrocarbons. At atmospheric temperature and pressure some of the hydrocarbons are gases, while some are liquids. The general chemical formula for all hydrocarbons is C_nH_m. The three main series of hydrocarbons are paraffins, C_nH_{2n+2}, naphthenes, C_nH_{2n}, both called also aliphatics, and aromatics, C_nH_{2n-6}. In different combinations n varies from 1 to 12 and m from 2 to 26.

A fourth group consists of methyl, CH_4O, ethyl, C_2H_6O, and butyl, C_4H_9OH, alcohols. These are not true hydrocarbons, since each contains oxygen in the molecule.

Gaseous fuels mostly used at present are natural gas, coke-oven gas, blast-furnace gas, and producer gas.

Liquid fuels can be divided into two main groups: liquids which are vaporized and handled similarly to gas fuels—gasoline and alcohol are the main ones in this group and sometimes kerosene—and liquids which are injected into the combustion space—fuel oils, so-called Diesel fuel oils, sometimes also kerosene or coal oil and gas oil.

Solid Fuels — are coal, chiefly anthracite and coke, up to lately used only indirectly, in gas producers. Recently the problem of using coal directly seems to have been brought nearer to a practical solution in engines burning pulverized coal, and very similar to compression-ignition oil engines.[1]

Gaseous Fuels — Natural gas is found in many parts of the United States. By extensive pipe lines it is made available many hundreds and in some cases even a thousand miles away from the wells from which it is obtained.

Natural gas obtained from oil wells is called casing-head gas and is usually treated for the recovery of gasoline, after which, called dry gas, it is delivered into the pipe-line systems to be used as fuel.

The analysis of natural gas varies considerably with the location. The limiting values for each component can be seen from Table 5, which also gives specific gravity and heat values of different natural gases found in the United States. An additional column gives data referred to an imaginary average gas.

---

[1] Power, vol. 68, July 24, 1928, p. 136; November 6, 1928, p. 746.

Coke-oven gas is obtained as a by-product when making coke and its analysis depends upon the coal used and also upon the method of operating the oven. Table 5 shows that its heat value per cubic foot is only about one-half that of natural gas, but it requires about half the air for combustion and the heat value of the actual air-gas mixture is practically the same as when natural gas is used.

Blast-furnace gas is a by-product of melting iron ore. Its analysis varies considerably with the fuel used and the method of operating the blast furnace. Actual and average data given in Table 5 show that the heat value of the gas-air mixture is only slightly less than that of the first two fuels.

Part of the gas is used for preheating the air necessary to operate the blast furnace itself and the blowing engines. The rest, about one-fourth of the total amount, can be used as engine fuel for power production. For use in gas engines the blast-furnace gas must be thoroughly cleaned as it contains from 1 to 1-1/2 gr of dust per cubic foot. This dust acts as a grinding compound on the cylinders and pistons. The above mentioned dust content may be better appreciated if it is stated that the gas necessary to operate a 1,000-bhp engine yields from 14 to 21 lb of dust per hour.

The cleaning of the gas is usually done in two or three steps. Part of the dust is removed by allowing it to settle out in stationary dry-dust catchers. In the second stage wet scrubbers and wet revolving washing machines are used and after that the gas sometimes is led through sawdust scrubbers. Proper cleaning can reduce the dust content to about 0.0054 gr/cu ft. A dust content of 0.01 gr/cu ft is usually considered satisfactory, meaning a cleaning efficiency of 99 to 99.5 percent. This leaves, in the case of a 1,000-hp engine running 24 hours a day, from 600 to 1,200 lb of dust carried into the cylinders per year.

Producer gas as fuel for gas engines is not used in the United States as much as it was expected some 15 years ago. The causes of this are improvements in other prime movers, particularly in the mechanical-injection oil engines which are simpler and more economical in operation.

Producer-gas analysis varies with the fuel used, anthracite, coke, bituminous coal, wood, and dampness of air which influences the hydrogen content. Resembling blast-furnace gas in general, it has a fairly low heat value. However, it needs a smaller air excess than the richer gases, and therefore the heat value of the actual air-gas mixture and available power per cubic foot of piston displacement is only about 15 percent smaller than with the richer gases.

Engines running on blast-furnace and producer gases can be operated with higher compression without danger of preignition. This raises their thermal efficiency and makes the power available per cubic foot of mixture only slightly less than that from a natural-gas or coke-oven-gas mixture.

TABLE 5.—DATA ON COMPOUND GASEOUS FUELS

Composition	Natural gas		Coke-oven gas		Blast-furnace gas		Producer gas	
	Limits	Average	Limits	Average	Limits	Average	Limits	Average
Hydrogen, H_2, per cent vol	0–26	......	48–57	50	2– 5	3.5	10–20	15
Methane, CH_4, per cent vol	32–99	84	27–36	31	0.2– 1.6	0.5	0– 4	2
Ethylene, C_2H_4, per cent vol	....	......	2– 4	3	....	......	0– 0.5	
Ethane, C_2H_6, per cent vol	0–67	15						
Other hydrocarbons, per cent vol	0– 2	......	0– 1	......	....	......	0– 1	
Carbon monoxide, CO, per cent vol	0– 3	......	3– 6	5	25–28	27	20–29	24
Carbon dioxide, CO_2, per cent vol	0–26	......	1– 3	2	6–13	11	4– 8	5
Oxygen, O_2, per cent vol	0– 2	......	0–12	1	0– 2	......	0.2– 2	1
Nitrogen, N_2, per cent vol	0–38	1	2–13	8	56–63	58	50–58	53
Specific density (air = 1)	0.57– 0.89	0.62	0.35– 0.40	0.39	0.80– 1.02	1.00	0.80– 0.90	0.84
Heat value, low, Btu/cu ft	760–1350	988	400–500	475	90–110	100	110–170	135
Theoretical air, cu ft/cu ft	....	10.5	....	4.7	....	0.78	....	1.12
Actual air, cu ft/cu ft	....	13.5	....	6.0	....	0.94	....	1.4
Ratio actual/theoretical	....	1.28	....	1.28	....	1.21	....	1.25
Heat value of mixture, Btu/cu ft	....	68	....	68	....	52	....	56

Liquid Fuels — The reasons for the most universal use of petroleum as a fuel in the internal-combustion engine field soon become evident if all potential sources of fuels are examined and the fuel costs and characteristics are compared. Table 13 presents data on representative fuels, including their approximate cost (not including taxes) if purchased in quantities of about 50 gal or the most nearly equivalent standard unit of measure for that fuel. The prices of these fuels, of course, vary considerably from one section of the country to another, as well as with the price structure as a whole. Note the favorable position of gasoline with respect to the other fuels, keeping in mind that gasoline is a highly refined product that can be used to much better advantage in a small, light power plant than a fuel such as coal. Not only does it have a higher heating value and a negligible ash content, but it is a liquid. Liquids are much easier to handle in transferring the fuel from one storage tank to another, and they can be delivered from the tank to the engine more easily and metered far more accurately with relatively inexpensive apparatus than would be possible with a solid fuel.

An examination of Table 13 discloses that all the liquids which appear economically attractive as fuels come from coal, petroleum, or natural gas. Such fuels as alcohol, acetone, or lard oil derived from vegetable or animal matter are characterized by a high cost.

TABLE 13. HEATING VALUE AND COST OF SOME POTENTIAL FUELS (IN 1947)
Liquid fuels

Fuel	Density, lb/gal	Lower heating value		Fuel cost, cents/gal	Heat cost, cents/1000 Btu
		Btu/gal	Btu/lb		
Gasoline, 100-octane aviation	6.0	114,000	19,000	24	0.210
Gasoline, premium automobile	6.0	114,000	19,000	13.0	0.114
Gasoline, regular automobile	6.0	114,000	19,000	11.0	0.096
Kerosene	6.59	123,000	18,650	10.3	0.084
No. 1 fuel oil (distillate)	6.91	128,000	18,500	9.3	0.073
No. 2 fuel oil (distillate)	7.07	130,000	18,400	9.3	0.072
No. 3 fuel oil (distillate)	7.30	134,000	18,300	8.8	0.066
No. 4 fuel oil (distillate)	7.48	136,000	18,150	8.5	0.062
No. 5 fuel oil (bunker B)	7.78	140,000	18,000	7.7	0.055
No. 6 fuel oil (bunker C)	8.04	144,000	17,900	7.0	0.048
Arkansaw crude	7.24	132,000	18,250	3.0	0.023
Benzol	7.34	126,000	17,200	21	0.166
Wood alcohol	6.62	56,000	8,400	36	0.642
Grain alcohol	6.58	76,000	11,600	72	0.948
Acetone	6.61	79,400	12,000	55	0.693
Lard oil	7.63	130,000	17,100	110	0.847

Sources and Expectations

The origin and subsequent evolution of petroleum in liquid and gaseous forms are not definitely known. However, petroleum is generally found in certain rock formations that, thousands of years ago, were the floors of oceans. It is believed that marine organic material on the sea bottom was enfolded by rock layers and subjected to high pressures. Here the organic matter under temperatures of 150° to 300°F was cracked over a period of 1-2 million years* to a lower molecular weight bituminous material. The heavy oils or tar sands first formed contained few light hydrocarbons but with the passage of time underwent progressive evolution. Thus crude oils found in the oldest rock formations contain the light hydrocarbons; the younger rock formations contain heavier oils with little or no light portions, and with appreciable amounts of nitrogen and oxygen-containing compounds. By what method the oxygen was eliminated is unknown. It has been premised that bacterial action might have been responsible; another theory presupposes continuous exposure through the ages to slight radioactivity from neighboring rock formations.

Essentially the same sequence of processes was undergone by coal except that here the original organic material appears to have been land vegetation. Quite possibly, however, oil might be a distillate from the same vegetation and the oil was able to migrate through porous rock to another location.

Today, crude petroleum is found accumulated in porous rocks or sands or limestones and covered with an impervious rock cap. These underground rock traps also contain large amounts of natural gas and salt water. The salt water is believed to have been retained in the pores of the rocks from the time when the organic matter was first deposited. Tar sand deposits are also found that consist of common sand bonded together by a viscous tar of petroleum origin. With the presence of slate, an oil shale may be formed. The oil shales are hard rock formations that contain veins or strata of an organic matter called Kerogen which analyzes about 40 percent hydrocarbons and 60 percent compounds of nitrogen, sulphur, and oxygen.

Upheavals of the land may expose the buried oil. A natural refining or weathering takes place and the oil is converted into asphalt—the name given to a heavy, black, tarlike substance of uncertain chemical structure but with a relatively small amount of hydrogen.

Geological evidence indicates that about 11 million square miles of the earth's surface, which were once under water, probably contain oil. Most oil originated in the shallow waters of landlocked seas because such waters would contain abundant organic material which would be buried through the years by sediment deposits from the surrounding land.

Petroleum is also formed without the necessity of a burial ground. Smith* concluded that small amounts of hydrocarbons are continually being evolved from chemical action on the remains of aquatic organisms in both fresh and salt waters.

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*Oil has been found in rocks that date back 500,000,000 years and coal in rocks of age 250,000,000 years. However, quite possibly the oil could have migrated to the older formations. (The "oldest coal in the world" is found in upper Michigan and is believed to date back 500,000,000 years.)

There are four great oil regions, each near a landlocked sea: the Eastern Mediterranean Basin, the Caribbean Basin, the Far East Basin, and the North Polar Basin. Such regions are, today, the great oil-producing basins of the world and, most probably, the source of oil for tomorrow. The richest source lies at the eastern end of the Mediterranean Sea—the cradle of mankind—and includes the lands which surround the Caspian Sea, the Red Sea, the Black Sea, and the Persian gulf: Iran (Persia), Iraq (Mesopotamia), Southwestern Russia, Arabia, Rumania. Here man's earliest civilizations built temples around the "eternal fires" (fed by gas escaping from the ground) and became fire worshippers. Asphalt was used as a mortar for stone or brick houses, as a floor for the Hanging Gardens of Babylon, and as roads for the chariots of Nebuchadnezzar. The Caribbean Basin includes the gulf states of the United States, Mexico, Venezuela, Colombia and Central America. Much of South America is unexplored for oil. The Far East Basin lies between Asia and Australia spanning the islands of the East Indies—here the oil resources can only be surmised. Many thousands of years ago, the North Polar Basin was a warm sea, tropical plants and marine life abounded—conditions believed to be essential for the genesis of oil.

Offshore, the lands of the earth are underwater plains or continental shelves. The shelf descends slowly for miles to depths of hundreds of feet before descending sharply (continental slope) to meet the continental rise of the ocean's floor. Beneath the shelf (and slope) are large sources of oil and gas. Offshore drilling is underway all over the world. (See Table 8-1.)

TABLE 8-1

CRUDE PETROLEUM OIL AND NATURAL GAS RESOURCES (1972)†

Regions and Countries (with 1972 oil production)	Production	Proved and Probable Resources		Est. Economic Resource
	Oil (10^9 bbl)	Oil (10^9 bbl)	Gas (10^{12} scf)	Oil (10^9 bbl)
Persian Gulf‡ (medium to high sulfur) Saudi Arabia 2.0; Iran 1.8; Kuwait 1.0; Iraq 0.55; Abu Dhabi 0.36, Others 0.56	6.27	380	345	2,000
Other Middle East Israel, Jordan, Lebanon, Syria, Turkey	0.11	8	1	100
Africa‡ (low sulfur) Libya 0.82, Nigeria 0.66; Algeria 0.39	2.07	106	190	500
United States (low sulfur)	3.48	45	273	500
Alaska	—	10	32	200
Russia (and bloc)	2.87	75	640	500
Caribbean (high sulfur) (Venezuela‡ 1.2, Others 0.25	1.45	30	60	400
Canada	0.55	10	55	600
Indonesia‡ (low sulfur)	0.38	10	6	600
South America	0.28	13	24	400
Asia-Pacific Australia 0.11, Malaysia 0.10	0.29	5	100	600
China	0.19	20	21	500
Western Europe	0.11	10	180	200
North Sea	—	40	110	400
World Total (including countries not shown)	18.5	720	1,880	8,000

†Data mainly from *The Oil and Gas Journal*. Estimated Total Resource includes off-shore.

‡Members of the OPEC (Organization of Petroleum Exporting Countries). Sulfur Low 0.05%, High > 2%

* * * * *

Oil shale in the Green River Formation of Colorado, Utah and Wyoming, is estimated at 750 billion bbl of probable reserves—the world's single largest hydrocarbon deposit.* The oil-shale strata are 50 to 1,400 ft in thickness, and an average yield of 25 gal shale oil per ton of rock is believed feasible. Shale oil is obtained by destructive pyrolysis of the crushed shale at atmospheric pressure and 900°F. The first full-scale commercial oil-shale plant in the United States (1967) is located in western Colorado. It is believed that the shale oil from this plant can be delivered in Los Angeles for $4.50/bbl by 1975 versus the 1972 price of $4.00/bbl for crude oil of comparable quality. Thus the only competition would be that from foreign oil (and here the price is increasing sharply, Table 8-5).

Average yields from refining shale oil would be 15-17 percent gasoline, 30-32 percent kerosene, 18-26 percent gas oil, 15-18 percent light lube oils, and 10-12 percent of heavy oils and paraffin wax.

Oil or tar sands in the Athabasca field in northern Alberta, Canada, are estimated to contain 300-600 billion bbl of recoverable oil, or 10-20 times the proved reserves of the United States. Tar sands are also found throughout the United States, principally in Utah, California, Alabama, Kentucky, and Oklahoma. The oil can be obtained by distillation or by solvent treating after strip mining (although most of the sands lie far below the surface and in-place processes need to be invented). The first full-scale plant (Edmonton, Canada) began operating in 1967 with capacity of 45,000 bbl/day of light crude oil (not good for lube fractions).

Natural gas, primarily methane, is found throughout the United States, either associated with crude oil or in a separate natural reservoir within the earth. [In the 1930's, before the advent of pipelines, one billion cubic feet of gas per day was flared (burned) in the Panhandle district alone. At least the same amount is undoubtedly being wasted today from fields such as those in the Middle East or in South America.] A few plants have been built to produce gasoline and fuel oil by synthesis of natural gas.

Coal is our most abundant fuel and the total resource in the United States has been estimated in trillions of tons—a more conservative economic figure is shown in Table 8-2. Considerable research is underway on methods that in the future will produce either gasoline or gas from coal: gasoline for our automobiles, and gas for our pipelines.

TABLE 8-2

FUEL RESOURCES OF THE UNITED STATES

Fuel	Production 1972	Energy Content	Estimated Total Economic Resources†		
			Units Shown	Q, 10^{18} Btu	Equivalent 10^9 bbl Crude Oil‡
Crude oil (conventional)	$3.48(10^9)$ bbl	$5.8(10^6)$ Btu/bbl	$250(10^9)$ bbl	1.5	250
Coal§	$551(10^6)$ ton	$24(10^6)$ Btu/ton	$1,000(10^9)$ ton	24	3,000
Natural gas¶	$23.9(10^{12})$ ft³	1,000 Btu/ft³	$1,700(10^{12})$ ft³	1.7	143
Shale oil	—	$9(10^6)$ Btu/ton	$1,300(10^9)$ ton	12	1,000
Tar sand	—	$5(10^6)$ Btu/ton	$100(10^9)$ ton	0.5	42

† Not including Alaska or offshore.

‡ If converted into "a crude oil" by modern methods, ½ ton coal + H_2 = 1.3 ton shale oil = 12,000 ft³ natural gas = 2.4 tons tar sand = 1 bbl synthetic crude oil (1 bbl = 42 gal)

§ About 15% lignite (North Dakota and Rocky Mountain Region)

¶ Proved and probable resource = $262(10^{12})$ ft³

* * * * *

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*Not including Alaska or offshore.

* * * * *

Crude Petroleum

Crude oil is a mixture of an almost infinite number of hydrocarbon compounds, ranging from light gases of simple chemical structure to heavy tarlike liquids and waxes of complex chemical structure. The oil as it comes from the ground also contains various amounts of sulphur, oxygen, nitrogen, sand, and water. Although the ultimate constituents are relatively fixed, the percentage of carbon varying generally from 83 to 87 percent, and that of hydrogen from 11 to 14 percent. The many compounds of the crude belong primarily to the paraffin, naphthene, and aromatic families along with a considerable amount of asphaltic material of unknown chemical structure. The general formulas for the families are shown in Table 8-3 along with the structures or arrangements of the molecules.

TABLE 8-3
PRIMARY FAMILIES OF HYDROCARBONS IN CRUDE OIL

Family		Formula	Structure
Paraffin (alkanes)		C_nH_{2n+2}	Chain
Naphthene		C_nH_{2n}	Ring
Aromatic	benzene	C_nH_{2n-6}	Ring
	naphthalene	C_nH_{2n-12}	

However, the mixture of oil cannot be entirely divided into these separate families because many of the individual oil molecules may be made up of molecules from several families. Thus a ring nucleus may be joined to a chain compound and, also, several rings, of either the same or of different families, may be jointed together to form a single molecule. Because of this complexity, the components and properties of the erude oil and products will exhibit extreme differences.

The crude oil is often classified by the relative amounts of paraffin wax and asphalt residues in the oil: paraffin-base, mixed-based, and asphalt-base oils. The paraffin-base oils, such as the Pennsylvania crude, contain relatively large amounts of paraffin wax and little or no asphalt; the asphalt-base oils of the west coast have the opposite characteristics. The mixed-base crudes contain both paraffin wax and asphalt. This classification, although widely used, is faulty in that the remainder of the components of the crude may not necessarily follow the pattern dictated by the base or residual part of the oil. It has been estimated that 30 to 40 percent of the Pennsylvania crude oil is paraffinic while 30 percent of all crudes, on the average, is composed of naphthenic compounds. Gasoline, however, almost invariably contains a high percentage of paraffinic compounds (Table 8-4).

TABLE 8-4
AVERAGE PERCENTAGES OF HYDROCARBON FAMILIES OBTAINED FROM VARIOUS REFINING PROCESSES AND AS BLENDED IN GASOLINE
(percent, average, for United States)

Family	Gasoline†		Processes					
	Premium	Regular	Straight-Run	Thermally Cracked	Catalytically Cracked	Hydro-cracked	Catalytically Reformed	Alkylate
Aromatic	25	20	5	25	25	24	45	0
Paraffins	58	59	70	35	25	35	50	100
Naphthenes			24	15	10	40	5	0
Olefins	17	21	>1	25	40	1	1	0

†U.S. survey by Ethyl Corp., 1960

Division of Crude Oil into Petroleum Products

It is entirely possible, but not economically feasible, to convert almost completely the crude petroleum into gasoline and diesel fuel. However, since a demand exists for many products other than gasoline, the cost of refining equipment, as well as the market price of the products, dictate the division of the crude oil into various components of widespread utility. In Fig. 8-2 are illustrated the fundamental steps in dividing the crude into several components.

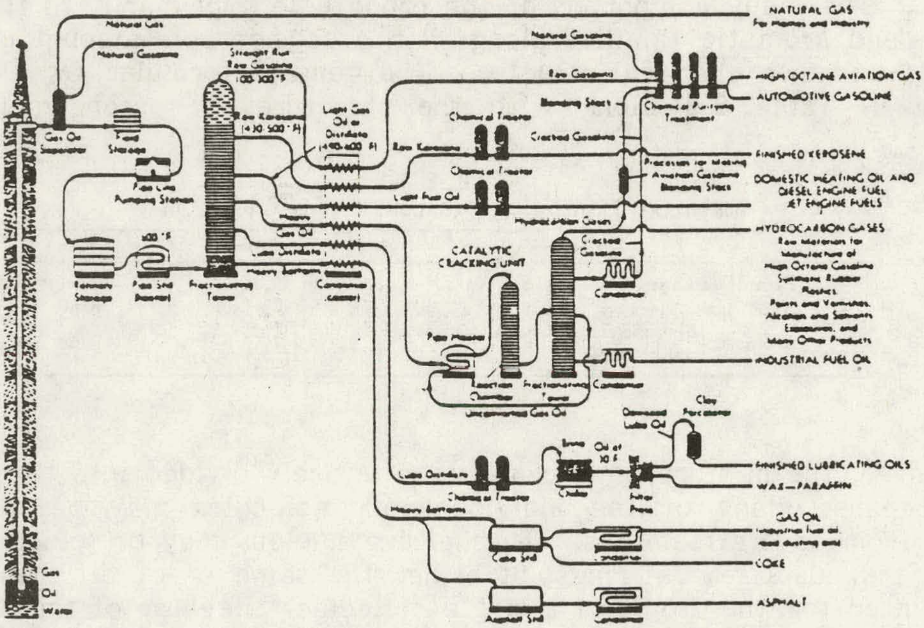


FIG 8-2. Simplified refinery flow chart. (Courtesy of American Petroleum Institute.)

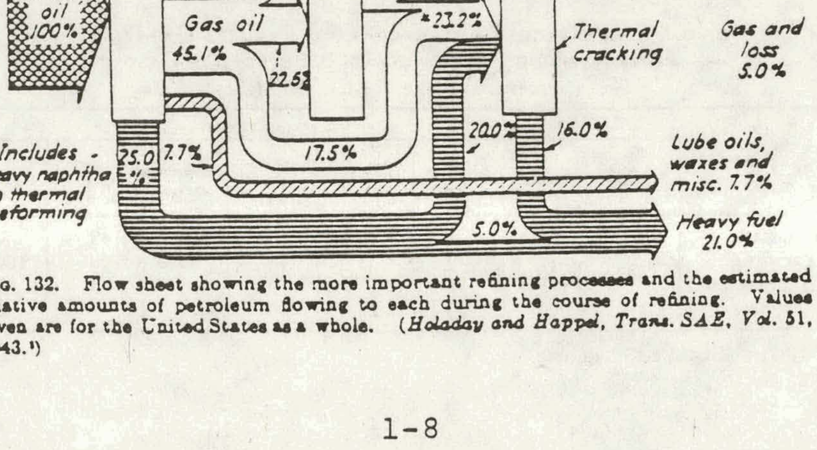


FIG. 132. Flow sheet showing the more important refining processes and the estimated relative amounts of petroleum flowing to each during the course of refining. Values given are for the United States as a whole. (*Holaday and Happel, Trans. SAE, Vol. 51, 1943.*[1])

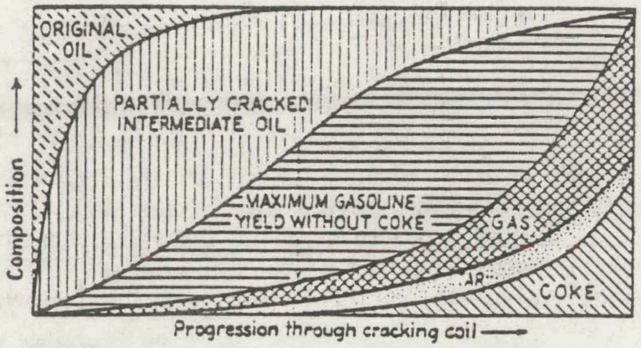


FIG. 133. Effect of temperature on the composition of the products of a thermal cracking unit.

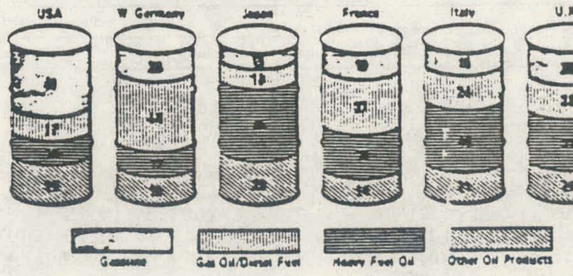
TABLE 15. PROPERTIES OF REPRESENTATIVE COMPOUNDS IN HYDROCARBON FUELS[4,7]*

	Mol formula	Mol wt	Melting point at 14.7 psia, °F	Boiling point at 14.7 psia, °F	Density of liquid			Specific gravity (air = 1.00)	Ratio gas vol per liquid vol	Lower heating value		Combustibility limits		Ft³ air to burn 1 ft³ gas	Ignition temperature, °F	Heat of vaporization 14.7 psia, Btu/lb at boiling point	Specific heat 14.7 psia			Octane rating	Cetane rating
					Specific gravity at 60/60, °F	°API	Lb/gal at 60°F			Btu/lb	Btu/gal liquid at 60°F	Lower F/A	Upper F/A				C_p vapor, Btu/(lb)(°F)	C_v vapor, Btu/(lb)(°F)	C_p liquid, Btu/(lb)(°F)		
Hydrogen	H_2	2.016	...	−423	...	...	...	0695	...	43.000	...	0.029	0.172	2.38	1076	192					
Carbon	C	12.010	...	...	...	...	...		...	14.600											
Methane	CH_4	16.042	−296.5	−258.5	0.3	340	2.5	0.554	443	21.597	...	0.028	0.088	9.55	1346	245	0.526	0.402	...	110	
Ethane	C_2H_6	30.068	−297.8	−128.2	0.374	247	3.11	1.038	294.5	20.597	...	0.031	0.131	16.71	1050	211	0.415	0.347	...	104	
Propane	C_3H_8	44.094	−305.9	−43.3	0.508	147.0	4.23	1.522	272.7	20.015	...	0.031	0.131	23.87	995	183	0.390	0.346	...	100	
n-Butane	C_4H_{10}	58.120	−216.9	+31.1	0.584	110.8	4.86	2.006	237.8	19.795		0.030	0.155	31.03	961	156	0.396	0.363	0.55 at 32	92	
n-Pentane	C_5H_{12}	72.146	−201.5	97.0	0.631	92.7	5.25	2.491	207.0	19.745	101,000	0.008	0.172	38.19	933	153	0.402	0.375	0.55	61	
n-Hexane	C_6H_{14}	86.172	−139.7	155.7	0.664	81.8	5.53	2.975	182.4	19.432	...	0.035	...	45.35	909	146	0.406	0.384	0.536	95	
n-Heptane	C_7H_{16}	100.198	−131.1	209.1	0.688	74.2	5.73	3.459	162.5	19.408	...	0.033	0.165	52.06	893	138	0.415	0.397	0.522	0	57
n-Octane	C_8H_{18}	114.224	−70.0	258.1	0.706	68.5	5.89	3.943	146.5	19.329	...	0.038	...	59.67	880	131	0.420	0.404	0.519	−17	
n-Nonane	C_9H_{20}	128.250	−64.7	303.3	0.722	64.5	6.01	4.428	133.2	19.292	...	0.037	...	66.35	871	125	0.429	0.415	0.518	−45	
n-Decane	$C_{10}H_{22}$	142.278	−21.5	345.2	0.734	61.5	6.11	4.912	122.1	19.205	...	0.033	...	73.99	866	120	0.436	0.424	0.517		
n-Cetane	$C_{16}H_{34}$	226.4	65	536	0.774	51.5	6.43	...	...	19.091	...			...	390	...	...	...	...	...	100
Pentatriacontane	$C_{35}H_{72}$	492.3	176	628	0.781	49.5	6.51	...	...	19,032											
Isopentane, or 2-methylbutane	C_5H_{12}	72.1	−256	82	0.613	99.0	5.17	...	...	19.597	100,000	0.034	...	...	...	146	...	...	...	90	
Triptane, or 2,2,3-trimethylbutane	C_7H_{16}	100.2	−13	178	0.690	72.9	5.78	...	...	19,100	110,000	...	...	...	...	125	...	...	...	140	
Isooctane, or 2,2,4-trimethylpentane	C_8H_{18}	114.2	−162	211	0.692	73.5	5.77	...	...	19.159	110,000	...		...	1350	117	...	...	...	100	
n-Pentene	C_5H_{10}	70.1	−230	86	0.642	87.0	5.39	...	...	18.034	...	...	...	...	...	...	...	...	...	90	
n-Octene	C_8H_{16}	112.2	−152	251	0.731	...	...	3.87	...	19.190	...	...	...	...	...	132	...	...	0.486	34	
Cyclopentane	C_5H_{10}	70.1	−138	121	0.746	56.7	6.22	...	...	17,494	117,000	...	...	...	...	...	...	...	...	82	
Cyclohexane	C_6H_{12}	84.1	44	177	0.778	51.5	6.50	...	...	18.300	122,000	...	...	...	...	156	...	...	...	77	
Benzene	C_6H_6	78.1	42	176	0.88	29.0	7.34	...	...	17,190	126,000	0.038	0.234	35.7	1364	169	...	...	0.40	97	−10
Toluene	C_7H_8	92.1	−139	231	0.87	31.0	7.23	...	...	17.460	126,000	0.064	0.230	42.9	1490	156	...	...	0.40	104	−21
Naphthalene	$C_{10}H_8$	128.2	177	424	0.975	...	...	4.42	...	16,730	...	...	...	57.1	...	...	...	...	0.306		
Cumene, or isopropyl benzene	C_9H_{12}	120.2	−141	306	0.862	32.6	7.19	...	...	17,700	128,000	...	...	...	...	134	...		...	73	
Aniline	$C_6H_5NH_2$	93.1	+21	364	1.022	...	8.53	...	...	15,000	128,000	...	...	...	...	137					
2,4-Xylidine	$C_6H_3NH_2(CH_3)_2$	121.2	...	420	0.974	~~12.8~~	~~8.13~~	...	...	15,700	128,000	...	...	...	...	150					
α-methyl naphthalene	$C_{11}H_{10}$	142.2	−7.6	470	1.025	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0
Tetraethyl lead	$PB(C_2H_5)_4$	323.4	−213	360	1.653	...	13.8	...	...	...	...	...	...	...	...	73					
Ethylene dibromide	$C_2H_4Br_2$	187.8	+50	269	2.181	...	18.2	...	...	...	...	...	...	...	...	82					
Methanol	CH_3OH	32.0	−144	149	0.792	46.4	6.62	...	...	8,644	58,000	0.064	0.310	...	...	502			...	98	
Ethanol	C_2H_5OH	46.0	−179	172	0.785	47.1	6.58	...	...	11,504	78,000	0.058	0.350	...	...	396			...	90	
Ether	$(C_2H_5)_2O$	74.08	−177	94	0.714	...	...	...	...		...	0.052	0.72	...	...	...	...	...	...	...	185
Diethyl-diglycol ether	...	...	...	340	0.91	...	...	...	...	12,420											
Acetaldehyde	CH_3CHO	44.0	−190	68	0.781		...				...	0.062	2.00		732						

* Much of the data in this table came in the form of isolated fragments from dozens of widely scattered papers, most of them in the *SAE Transactions* or the *Petroleum Refiner*.

Fig. 2: Market Profiles of Mineral Oil Products in Various Countries

(% by volume of total consumption)



1)

Fuels for Spark Ignition (SI) Engines

* * * * *

Gasoline

The gasoline sold on the market, as shown in Fig. 8-6, is a blend of a number of products produced in several processes. By such blending, the properties of the fuel are adjusted to give the desired operating characteristics, and it is these characteristics that are of special interest to the engineer. Thus, the gasoline, irrespective of its origin, should have the following properties:

* * * * *

Antiknock - To reduce or eliminate the knock in SI engines. Here TEL and scavengers are added (Sec. 9-9). (But see Secs. 10-10 and 10-11.)

Deposit Modifers - To alter the chemical character of combustion chamber deposits and so reduce surface ignition and spark plug fouling. (Phosphorus and boron compounds, Sec. 9-7.) (But see Sec. 10-10.)

Antioxidants - To reduce gum formation and decomposition of TEL. [Amines (derivatives of ammonia with formula $R \cdot NH_2$) of amount 1 to 15 lb/1,000 bbl.]

Detergents - To prevent deposits in carburetor and manifold. (Alkyl amine phosphates, of amount, 12 lb/1,000 bbl.)

Lubricants - To lubricate valve guides and upper cylinder regions. (Light mineral oils, of amount, 0.1 to 0.5 percent.)

Metal Deactivators - To destroy the catalytic activity of traces of copper. (Amine derivatives, of amount, 1 lb/1,000 bbl.)

Antirust Agents - To prevent rust and corrosion arising from water (and air). (Fatty-acid amines, sulfonates or alkyl phosphates, of amount 1 to 15 lb./1,000 bbl.)

Anti-icing Agents - To prevent "gasoline freeze" from water in the fuel, and throttle-plate icing from water in the air. (Methyl alcohol, of amount, 1 percent, is added to the gasoline to absorb water and so prevent ice forming in the fuel line between tank and carburetor. Isopropyl alcohol, of amount, 1 percent, or else a "surface-action" agent such as ammonia salts or phosphates, of amount, 0.005 percent, is added to prevent ice from forming or adhering to the throttle. The alcohol acts by lowering the freezing point of the condensate on the throttle; a surface-action additive forms a film on the metal which discourages adhesion of ice. Some of the surface-action additives also have detergent qualities.)

Dyes - To identify TEL in the fuel. (A dye is added in amount 0.2 to 3.0 lb/1,000 bbl.)

Fig. 8-6

GASOLINE CHARACTERISTICS

Requirement	ASTM Specification D439-60T	Airline Requirements† MIL-G-5572C	Tests of Commercial Gasoline‡		
			Regular	Premium	Super Premium
Octane Rating:					
Research, F-1	87 (Reg), 96 (Prem) (min)	115/145§	93.0	99.8	102.5
Motor, F-2	No specifications		85.0	91.0	92.5
Volatility:					
10%	158°F max (summer) 140°F max (winter)	167°F max	125°F summer 111°F winter	125°F summer 111°F winter	131°F summer 123°F winter
50%	284°F max	221°F max	210°F (S), 201°F (W)	217°F (S), 210°F (W)	216°F (S), 211°F (W)
90%	392°F max	275°F max	341°F (S), 337°F (W)	327°F (S), 322°F (W)	310°F (S), 305°F (W)
End point	No specifications	338°F max	413°F (S), 410°F (W)	406°F (S), 402°F (W)	389°F (S), 385°F (W)
Residue, percent	2.0 max	1.50 max	0.9	0.9	0.9
Vapor pressure	10.0 max (summer)	5.5 to 7.0	8.9 summer	9.0 summer	8.2 summer
Reid psig	15.0 max (winter)		11.6 winter	11.7 winter	9.7 winter
Gum, mg/100 ml	5.0 max	3.0 max	1.0	1.0	1.0
Sulfur, percent by weight	No specifications	0.05 max	0.048	0.028	0.025

* * * * *

Summary of Gasoline Characteristics

Because of the great number of variables, it is impossible to correlate each characteristic of the fuel for the best operation of an engine. If each specification for the fuel were made too rigid, the resulting fuel would be too expensive for general use. Hence, the specifications for motor fuels must be flexible enough for the fuels to sell at a cheap price. The manufacturer designs and builds the engine to use the fuels that are commercially available. If the designed compression ratio is low in order that cheaper low-octane fuels may be used, the purchase of high-octane fuels will give no better performance and is an economic waste. If the carburetion system has a large hot spot to evaporate high-boiling-point gasolines, a highly-volatile gasoline may not be necessary, and such a gasoline may cause poor performance of the engine.

* * * * *

1. Knock Characteristics - The present-day measure is the octane rating. The fuel should have an octane rating to fit the engine requirements (Fig. 9-15).
2. Volatility
   a. Starting Characteristics - The gasoline will start the engine readily if a protion of the fuel has a low boiling point that will enable a combustible mixture to be formed at the surrounding air temperature.
   b. Vapor-Lock Characteristics - The fuel should have a low vapor pressure at the existing fuel-line temperatures to avoid vaporization in the feed lines and carburetor float bowl, which would prevent or reduce flow of the liquid fuel.
   c. Running Performance - In general, the fuel with the lowest distillation temperatures is the best.
   d. Crankcase Dilution - Dilution of the lube oil may occur when the fuel condenses or fails to vaporize in the engine, and a low distillation temperature range is desirable.
3. Gum and Varnish Deposits - The fuel should not deposit either gum or varnish in the engine.
4. Corrosion - The fuel and the products of combustion should be noncorrosive.
5. Cost - The fuel should be inexpensive.

* * * * *

Octane Rating*

It has already been remarked that the first step in refining is to separate the crude oil into fractions by selective distillation ("fractionating" Fig. 8-2). By 1910 it was apparent that to supply sufficient straight-run gasoline for the growing automotive industry required the refiners to turn out excessive quantities of kerosene and heavier oils. As a consequence, the fraction sold as gasoline had an uncertain octane rating that probably ranged from about 10 to 80 (F-1 rating throughout this chapter). (The octane scale and knock studies were to come many years later.)

* * * * *

With the advent of World War II, a high-octane fuel (100) was required for combat. This fuel was first made by blending alkylate, isopentane, Houdry gasoline, and straight-run gasoline (plus 4.6 ml TEL/gal). Since the usual straight-run gasoline has a low-octane rating, precise fractionating was developed to cut the gasoline into low- and high-octane fractions. Even then, roughly 30 percent of the aviation gasoline had to be alkylate to achieve the necessary octane rating. The bottleneck was broken by the rapid development of catalytic refining processes.

* * * * *

Present engines, to avoid air pollution, are below the optimum compression ratio for efficiency hence the octane ratings can decrease in the future. To raise 93 octane gasoline to 100 costs about 3 cents per gallon and to 105, about 7 cents per gallon (Fig. 8-5).

Modern gasoline (Fig. 8-6) may be made up of straight-run gasoline (from fractional distillation), cracked gasoline (from catalytic cracking), reformate (from catalytic reforming), alkylate and polymerized gasolines (produced from gases), with some butane or propane to achieve the desired Reid vapor pressure. Furthermore, additives are invariably required for many purposes:

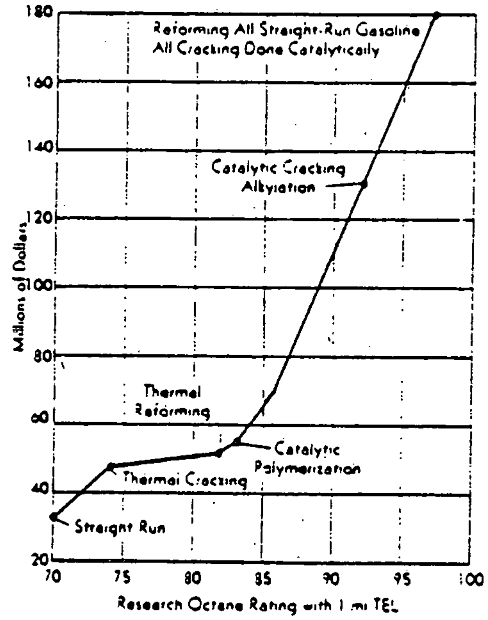


FIG. 8-5. Investment for 100,000-bbl-per-day refinery vs. octane rating of gasoline produced.

* * * * *

Exotic Fuels and Additives

To improve the power output of the SI engine, an alcohol (in particular, methanol) can be substituted for gasoline. The primary source of the power gain is the high latent heat of the engine with greater cooling of the mixutre than if gasoline were the fuel. This cooling decreases the compression work and tends to induct a greater mass of air (higher volumetric efficiency) hence the output is increased.

When the SI engine is operated at high speeds, the peak pressure from combustion may occur relatively late since the piston is rapidly descending. To achieve maximum pressure near the start of the expansion stroke, explosives such as the nitroparaffins (Table 8-13) can either be added to the fuel (such as methanol) or used undiluted (rare). The nitroparaffins contribute significant energy to the engine since the Btu/ft^3 mixture is about double that of gasoline. Here the oxygen in the nitroparaffin adds to that in the air so that more fuel can be burned with consequent greater energy release. Explosive additives, of course, reduce the octane rating, but knock is not a problem at racing speeds (5,000 rpm). Such fuels however are dangerous and their use is restricted.

Explosives (Table 9-8) can also be added to diesel fuel to reduce ignition delay and therefore to reduce knock.

TABLE 8-13
HIGH-ENERGY FUELS AND ADDITIVES

Name	M	Formula	$-\Delta H^\circ$, Btu/lb$_m$	Density, lb$_m$/ft^3	State	Temperature, °F	
						Melting	Boiling
Hydrogen	2.016	H_2	51,500	0.0054	Gas		
Beryllium	9.01	Be	29,100	112	Solid	2340	5020
Boron	10.82	B	25,400	125	Solid	3812	4620
Diborane	27.69	B_2H_6	31,300	0.0720	Gas	−266	−135
			31,100	29	Liquid		
Pentaborane	63.17	B_5H_9	29,100	39	Liquid	−52	136
Decaborane	222.31	$B_{10}H_{14}$	28,000	59	Solid	210	415
Alkyborane	—	(BCH)	25,000	51	Liquid	—	—
Nitromethane	61.04	CH_3NO_2	5,150	70	Liquid	−20	214
Nitroethane	75.07	$C_2H_5NO_2$	7,800	65	Liquid	—	239
1-Nitropropane	89.09	$C_3H_7NO_2$	9,720	62	Liquid	−135	269
Amyl nitrite	117.12	$C_5H_{11}NO_2$			Liquid	—	204

Fuels for Compression Ignition (CI) Engines

Three Stages in Combustion:

The tremendous expansion in high speed Diesel applications has been made possible through an understanding of the actual combustion process. The simplification of this theory is credited to H.R. Ricardo, who was the first to develop the fact that combustion takes place in three stages; first, a delay period, during which no appreciable combustion occurs but the fuel is being heated up to the ignition point; second, the rapid burning of the fuel which has been injected during the delay period; third, the instantaneous ignition of the remainder of the fuel as it blows into the flaming gases.

Fuel Oil and Gas Oil

Nature and Source of Hydrocarbon	Specific Gravity
Petroleum Products:	
Benzine (Pennsylvania)	0.700 to 0.710
Benzine (India)	0.715 to 0.725
Benzine (Roumania)	0.745 to 0.755
Lamp oils and naphthas	0.850 to 0.950
"Solar oil"	....
"Gas oil"	0.800 to 0.730
Lima fuel oils, as Eagle oils, gas oil, tar distillates, and Austrian and Russian fuel-oil residues	0.943 to 0.952
Paraffin-oil residues	0.860 to 0.890
Fuel-oil distillates from California and Texas	0.840 to 0.900
Asphaltum oils containing as high as 21 per cent. asphaltum	0.878
Mexican oils	....
"Steinkohle" Oils:	
"Steinkohle" oils	1.04
Anthracene-oil distillates	1.1
Tar-oil mixed distillates	1 to 1.1
Bituminous Oils:	
Tar oils (vertical oven)	1.10 to 1.18
Tar oils (horizontal oven)	1.16 to 1.25
Lignite Oils:	
Light benzine	0.800 to 0.820
Solar-oil	0.820 to 0.850
Tar-oil (light)	0.845 to 0.870
Tar-oil (heavy)	0.875 to 0.900
Paraffin-oil distillates	0.898
Creosote-oil distillates	0.957
Turf (peat) Oils:	
Tar-oil distillates as low as	0.8533
Shale Oils:	
Shale oils (Scotland)	0.740 to 0.980
Vegetable Oils:	
Peanut oil	0.916 to 0.920
Cocoanut oil	0.925
Castor oil	0.960 to 0.967
Cottonseed oil	0.913 to 0.930
Palm oil	0.850 to 0.860
Animal Oils:	
Lard	0.913 to 0.919
Alcohol:	
Mixture of 80 per cent. alcohol and 20 per cent. benzine	....
Wood Oils:	
Wood oils or creosote distillates	0.841 to 0.877

Note. All the above oils, and mixtures of them, have been used more or less successfully in low speed heavy-oil-engines, provided they were mobile, free from free carbon, grit and water, and were low in sulphur. Oils from mineral sources have been proven the most practical and less apt to gumming parts of engine interior.

The high speed C.I. engine uses certain grades of heavy petroleum distillation known under various trade names, e.g. Diesel Oil, Gas Oil, Solar Oil, Diesoleum, etc., of specific gravities ranging from 0·84 to 0·89 (see Table ___).

Although the term "crude oil" is frequently used in connection with C.I. engines, it is a misnomer, for the crude or virgin oil as it comes from the well is never sold to the general public.

The fuel used in C.I. engines is generally an unrefined distillate which is distilled out of crude oils after the kerosene; it is as unlike crude oil as kerosene is.

The fuel largely used in the United States is a petroleum distillate representing the small distillation fraction band between paraffin and the residual oil; it is known as Fuel or Furnace Oil.

Some of the larger and slower marine and stationary engines, however, use heavier grades of fuel, but these are not crude oils, usually residual fuel oils, i.e. the oil remaining after the lighter fractions have been removed by distillation. In some cases they are blends of residual fuels with gas oils. These heavier grades are unsuitable, however, for the small high speed C.I. engines forming the subject of the present book.

Vegetable Oil Fuels.

Apart from the mineral hydrocarbon fuels it is possible to operate C.I. engines on certain oils of vegetable origin, notably, the oils derived from ground nuts, cotton seeds and soyabeans; palm oil has also been used. In this connection some thousands of road miles have been run by vehicles in this country using the four oils in question. In general, however, there is a reduction in efficiency in the use of vegetable and animal fat oils amounting to about 12 to 15 percent, due to the lower calorific values of these fuels. Palm oil has been used on Perkin engines with satisfactory results, the exhaust being free from smoke; a fuel consumption of 0·39 lb. per b.h.p. hour was obtained. Other tests with this oil were made on a 110 h.p. Gardner engine, 10-ton vehicle, over a distance of 3,000 miles. It was found that preheating was necessary in order to reduce the viscosity of the fuel to suit the injection equipment; it was also found necessary to start and warm up the engine on ordinary Diesel oil. The fuel consumption on palm oil was about 10 percent greater than for the latter oil. Somewhat similar results have been obtained when using cotton seed and ground nut oils on C.I. engines.

In all cases the oils needed pre-heating to about 90°F, and cold starting and warming up with Diesel oil was necessary; the warming up period was from 2 to 4 minutes. No undue wear in the engine or fuel pump parts was experienced, but special attention was necessary to ensure filtering the oils thoroughly, in order to avoid wear of the fuel pump parts. Certain vegetable oils—notably palm oil—have corrosive effects on copper, brass and nickel, so that these oils must not come into continued contact with such metals in the engine and fuel equipment. No effect of any consequence is noticeable upon the engine lubricating oil when vegetable fuel oils are employed.

Ignition Quality of C.I. Engine Fuels.

As a result of investigations into the suitability or otherwise of various fuels for C.I. engines by methods* involving physical and chemical tests, and also actual tests, of the fuels in various types of engines, certain conclusions have been arrived at, the following being a brief summary of these:

If the various fuels are arranged in the order corresponding to their tendency to ignite, it is found that this order is correct for all types of engine. The order is also constant for various methods of measuring, provided the compression-ignition principle is adhered to.

It is therefore concluded that any one fuel has a definite "ignition quality," some engines being very sensitive to this quality, whilst others are not.

The "ignition quality" can conveniently be measured by the ignition delay shown by the indicator diagram. Thus, in the case of the Thomassen engine used for some of the tests, a direct measurement of ignition lag or delay period (B) (Fig. 425) was found to give satisfactory results when compared with that obtained with mixtures of standard fuels.

"Knocking" is denoted by the portion (A) of the diagram and coincides on the whole with the ignition delay. (The greater the delay, the larger the part of the fuel charge which will "knock" at the beginning of combustion. When ignition sets in, immediately a pilot flame is formed which ignites the rest of the fuel charge as it enters the cylinder, thus ensuring smooth running.)

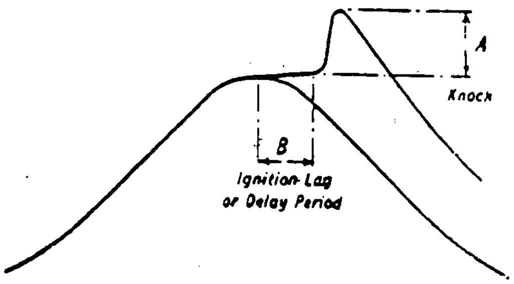


FIG. 425.—Ignition delay on the indicator diagram.

The "ignition quality" depends, in the first place, on the so-called "thermal stability" of the fuel, and only in the second place on its oxidizability.

The desirable quality of any fuel for C.I. engine use is a low self-ignition temperature, or low critical compression ratio. Similarly, for smooth operation, a high Diesel Index is necessary; the higher this number, the better will be the ignition quality of the fuel, within limits.

The Cetene Value of a Fuel.

In the case of modern automobile and aircraft engines using petrols it is now usual to define the suitability of the fuels used by means of a value, known as the Octane Number; the higher this number the less will be the tendency for detonation when this fuel is used in a petrol engine.

A somewhat similar method has been suggested by the Shell-Mex Laboratory authorities of Delft, Holland, to express the suitability of fuels for high speed C.I. engines.

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*G.D. Boerlage, Director, Proefstation Delft, Holland.

The method in question is to take two fuels, one of very high and the other of very low ignition quality as standards. By mixing these fuels in various proportions it is always possible to match the ignition qualities of any other C.I. engine fuel. Thus, for example, if it is ascertained that the same ignition quality is obtained by using a high proportion of the high ignition quality fuel, then the fuel in question is said to have a high ignition quality.

Cetene ($C_{16}H_{32}$) is the high ignition quality fuel employed and a-methyl-naphthalene is the low ignition quality one. The former gives the minimum and the latter the maximum ignition lag.

It is always possible to find a mixture of these two fuels that will give the same ignition quality as any of the petroleum fuels in ordinary use. The percentage of cetene in this mixture is then termed the Cetene Number.

The results so far obtained show that a fuel and its equivalent cetene mixture, as determined by tests in one particular C.I. engine, remain equivalent in ignition quality in all types of high speed C.I. engine.

In regard to the ignition quality of a fuel, the higher the cetene number of this fuel, the lower will be the ignition lag in a high speed C.I. engine.

There is no direct connection, however, between the cetene and the octane values of fuels, for a fuel having a high octane value will generally be found to possess a low cetene value. Conversely, a fuel having a high cetene value in a C.I. engine would, if it were sufficiently volatile for use in a standard petrol engine, be found to have a low octane value.

The cetene number of fuel depends upon its origin and constituents, these being determined largely by the nature of the crude oil from which the fuel is extracted. Generally those fuels derived from paraffinous crude oils have high cetene numbers, whilst those obtained from high aromatic content crude oils have low cetene value.

Cetane Number Method.

More recently in America the primary fuels employed are made up of blends of cetane ($C_{16}H_{34}$), which has a high ignition quality, and a-methyl-naphthalene ($C_{11}H_{10}$), which has a low ignition quality. The percentage of the cetane by volume is termed the Cetane Number. For economical reasons, secondary reference fuels calibrated against the standard fuels are employed for routine testing. A typical secondary series is made up by mixing high-cetene fuel referred to as dupo with commercial methyl-naphthalene.

In this connection tests were made in the Pennsylvania State College Engineering Station with seven fuels on nine commercial C.I. engines of various types and sizes, and the results obtained were compared with the ratings of the same fuels determined by the Co-operative Fuel Research (C.F.R.) engine. It was found that the C.F.R. laboratory method underrates the fuels by an average of 3 cetane numbers, relative to the commercial engines. Comparison of the different commercial engine ratings among themselves shows that the average deviation is 2·8 dupo numbers (1·56 cetane numbers). The accuracy of rating is about the same for both the required compression ratio and the air intake throttling methods. The accuracy of the variable lag method is much lower for the higher ignition quality fuels. The engine type apparently has a greater effect on the ratings than the particular method used. The ratings by the air intake throttling method agree reasonably well both with the required compression ratio ratings and the variable lag ratings when they are compared for the same engine.

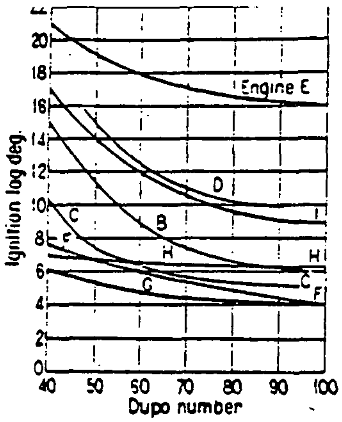

Fig. 426.—Combined ignition lag curves of various C.I. engines.

Commercial engines may be compared by noting the slope of the ignition lag versus ignition quality curves. Engines (B), (D), and (I) have the steepest curves, as shown in Fig. 426, indicating their suitability as test engines. Engines (H) and (G) have the flattest curves, indicating that they are less sensitive to changes in ignition quality of the fuels; this is an advantage in service engines.

Cetene and Cetane Numbers.

From the preceding considerations it will be evident that both the terms cetene and cetane are employed in connection with fuel ratings. The former term, however, has now been replaced in this country and the U.S.A. by the latter, and it is now customary to regard the Cetane Number as being the percentage by volume of cetane in a mixture of cetane and a-methyl-naphthalene which has the same ignition quality as the fuel.

In order to convert the previously used Cetene Numbers into cetane ones the relationship established by the Petroleum Diesel Panel* is employed, namely, "That the cetane-number—cetene number relationship is a straight line from the origin passing from the origin through the point 80 cetene number = 70 cetane number."

The ignition quality is obtained only by the results of engine tests, namely, the ignition delay test (or running test) or the throttling test.

In regard to fuels for automobile C.I. engines the normal cetane number in this country is about 55, but it should be pointed out that there appears to be a disadvantage in using fuels of too high a cetane value since the delay periods are reduced too much, with the result that a less efficient cycle results. For this reason it is sometimes necessary to specify both the minimum and maximum cetane numbers. It has been found, with certain direct injection engines, that when fuels of 57 cetane and above are employed the exhausts become smoky; for this reason a limit of 60 cetane has been fixed for such engines. It will be apparent, however, that the design of the combustion system has a marked influence upon the maximum permissible cetane value.

Desirable Fuel Characteristics.

Consideration in the choice of high speed C.I. engine fuels should be given more particularly to the ignition lag, or delay factor. Whilst it is desirable to reduce this delay period to a certain minimum value, this should not be overdone. It is not difficult to imagine the state of affairs corresponding to a zero delay period. The fuel would burn immediately as it entered from the injector, and the whole process of combustion would occur around the injection nozzle; the remaining air in the combustion chamber would therefore be prevented from finding its fuel. Thus one would obtain extremely smooth running, with perfect control but with very little power.

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*J.R. McGregor and W.V. Hanley (Standard Oil Co., California).

A definite delay period is required in practice to enable the fuel to penetrate sufficiently into the combustion chamber before the combustion commences.

In regard to C.I. engine fuels, it is believed that in the majority of combustion systems a moderately (but not too) high cetane value is advantageous, as it serves to shorten the delay period, and thus allows better control over the rate of burning and pressure rise. As with petrol, the cetane value of various fuels depends mainly on their source or origin, but it can be varied somewhat by varying the distillation range or by doping with such substances as amyl nitrite, ethyl nitride and certain peroxides. Generally speaking, any source which yields a bad--that is low-octane—petrol will yield a high-cetane Diesel oil, and vice versa. As a volatility in general, within limits, the lower the volatility the better, since too volatile a fuel is liable both to cause detonation and to give rise to gassing trouble in the fuel injection system. At the other end of the scale, if the volatility is too low, a further delay period will be introduced, due to the greater time taken to form a gas envelope on the outside of the droplets, as has been pointed out by Boerlage and Broeze.

In regard to the viscosity of C.I. engine fuels, this is important since it affects pump leakage and the power required to operate the pump. It has also an influence upon the size of the fuel particles sprayed by the injection nozzle, since at low injection pressures the size of the droplets increases roughly in proportion to the viscosity of the fuel, whilst surface tension does not appear so important.

The specific gravity of the fuel has a bearing upon the depth of penetration of the spray and also upon the spray cone angle. Thus a lighter fuel will have a smaller depth of penetration into the air charge and will give a wider cone angle.

In regard to fuel volatility, if this is excessive it will affect the smooth running of the engine by providing more fuel ready for combustion when ignition occurs. If too low, however, late burning and incomplete combustion may occur. In some respects volatility appears to be an influencing factor on ignition quality--more especially is this so for heavier fuels.

Fuel Dopes.

As mentioned in the preceding section, it has been found that the addition of small proportions of certain chemical substances to the fuels used in C.I. engines have a somewhat analogous effect upon the ignition lag, to that of petrol engine anti-knock fuel dopes, e.g. tetraethyl-lead, in eliminating detonation.

Thus, the addition in small amounts (about 1 percent) of ethyl nitrate or amyl nitrate to a C.I. engine fuel will raise the cetane value of the fuel. If the fuel is of low cetane value it will be necessary to add a somewhat larger proportion, vix. from 3 to 5 percent; this, incidentally, increases the cost of the fuel. It may here be mentioned that the addition of about 3 percent of ethyl nitrate to a certain fuel was found to reduce the ignition temperature from 360° to 300°C.

Fig. 428 shows two indicator diagrams, supplied by the Associated Equipment Company, taken from an Acro pre-combustion chamber engine, at a speed of 1,000 rpm, both with the same b.m.e.p. of 83·5 per sq. in. The firm line diagram was obtained with an Asiatic fuel as delivered; the broken line diagram was obtained with the same fuel to which 5 percent of ethyl nitrate had been added. The improvement in the performance, both as regards the reduction in the maximum pressure and in the rate of pressure rise in striking; this was naturally borne out by the much more satisfactory running observed with the doped fuel.

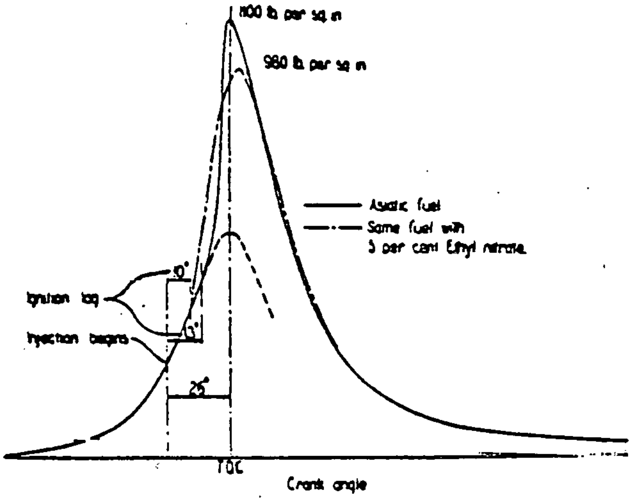

FIG. 428.—Illustrating effect of fuel " dopes " upon the pressure-rise rates.

Institute of Petroleum Test for Ignition Quality.

More recently the ignition quality of Diesel fuels has been investigated and standard methods of test laid down. These tests are described in the Institute's publication, Standard Methods of Testing Petroleum and its Products, and have been adopted in the British Standards Specification, B.S. 209: 1947, Fuels for Oil Engines.

It is reiterated that the ignition quality of a Diesel fuel for C.I. engines is a measure of the relative time required for combustion to start after the commencement of injection; the shorter the time, the higher is the ignition quality. High ignition quality indicates ease of starting and smoothness of running, but the ignition quality of a fuel is not an indication of its combustion quality in various engines. The ignition quality, however, is independent of engine conditions, or of the engine, and under any given engine conditions the delay angle is a function of the ignition quality. This delay angle is defined as the angle in degrees of crankshaft rotation between the start of injection and beginning of discernible combustion, as determined by pressure rise from the compression line. It is affected by engine characteristics and running conditions; it can vary for a given fuel over a wide range.

The ignition quality is expressed as a cetane number. It is numerically equal to the percentage, by volume, of cetane in a mixture of cetane and a-methyl-naphthalene which has the same ignition quality as the fuel. Two methods of test (A) and (B) are described. Method (A) is recommended for routine cetane-number determinations, but method (B) has the special advantage of being readily applicable to a large range of C.I. engine types. It was not found necessary to standardize any particular engine for the determination of ignition quality, but when the methods are applied to doped fuels the test should be carried out in the engine in which the fuel is to be used.

Mention is made in the test specifications of the use of secondary reference fuels instead of the primary reference fuel, mentioned previously, and details of suggested fuels are given.

CHAPTER II
FUELS SUPPLY AND EXPECTATIONS

AUTOMOBILE FUELS - OUTLOOK FOR THE FUTURE

Introduction

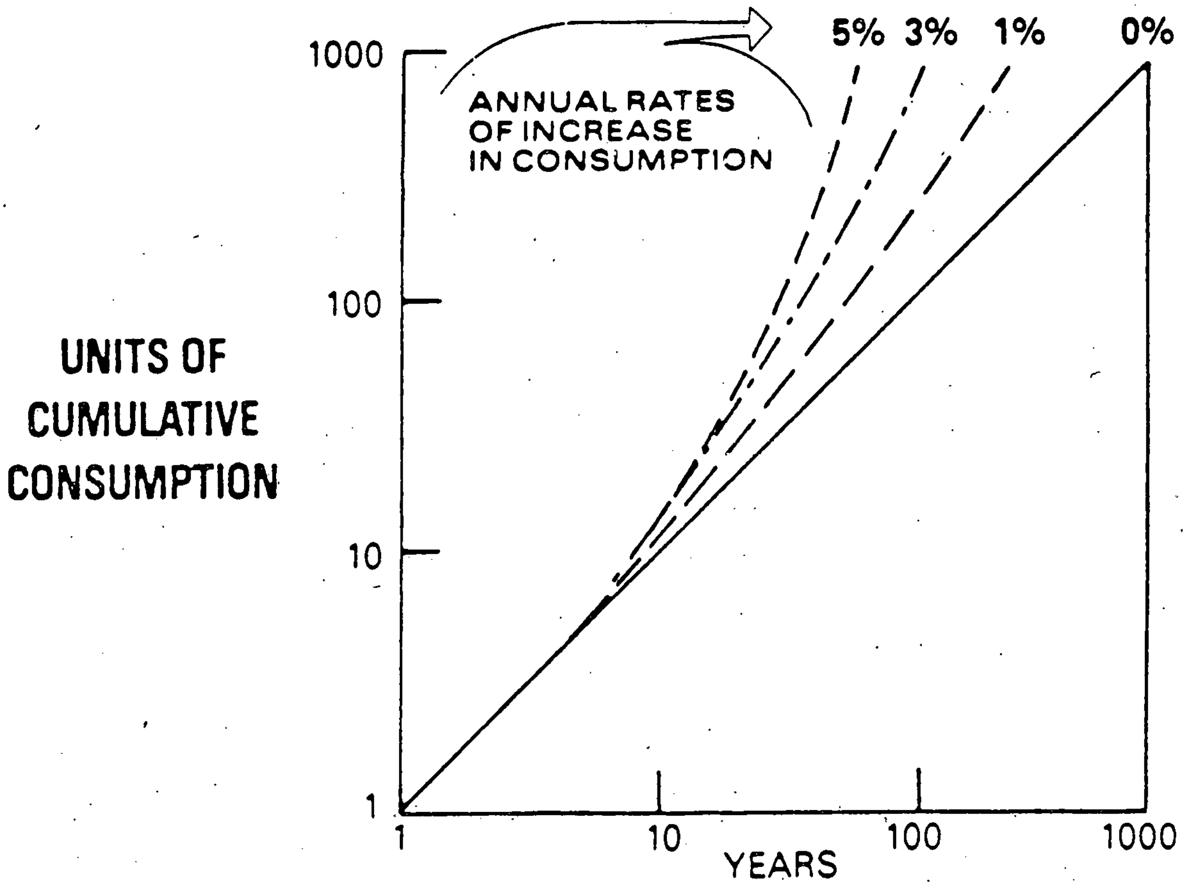

Figure 1. Cumulative Consumption As A Function of Annual Rate of Growth (Initial Rate of Consumption is 1 Unit During Year 1).

AUTOMOTIVE FUELS -- OUTLOOK FOR THE FUTURE

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INTRODUCTION

Scope

This paper examines the current and future supply of petroleum-based and alternative fuels suitable for use in passenger cars and light trucks. Petroleum-based fuels presently provide all of the energy for these vehicles. Therefore, the current and future availability of petroleum will first be considered. Next, this paper will examine the supply of alternative primary energy resources we might employ beyond the "petroleum age." Since many of these alternative primary energy resources are not suitable for direct mobile use, secondary energy storage media will be discussed. Finally, prime movers and power trains compatible with various alternative fuels - and GM's experience with these systems - will be reviewed.

Terminology

Published estimates of reserves of energy resources differ widely - to a large extent because of differences in definitions. To avoid misunderstanding, this paper considers only two kinds of reserves; "Proven Reserves" and "Ultimate Reserves." "Proven Reserves," as the name implies, have been carefully confirmed and represent quantities which are recoverable with current techniques and product costs. Additional reserves are known to exist in already discovered oil fields or deposits, but the quantity is known with somewhat less certainty. Estimates of these quantities plus estimates of as-yet undiscovered reserves based on geological information and past exploration experience are termed "Ultimate Reserves."

A further source of confusion exists with respect to forecasting how long a given resource will last. This problem frequently results from differing assumptions about the growth rate of energy consumption. The significance of this assumption is shown in Figure 1. This figure shows the cumulative consumption of a resource (in multiples of the present rate) over any time period for various assumed rates of growth of consumption. For example, if reserves are equal to 100 times the current consumption rate of a particular energy resource, it would last 100 years at zero growth rate. At a 3 percent compound growth rate, the same energy resource will last only 47 years and the annual consumption will have increased by a factor of four. (The foregoing assumes no production rate constraints.) Figure 1 shows that when the resource base is only a few times the rate of consumption, growth rate has relatively little effect on how long the resource will last, but it has a very large effect when the resource is large. Caution should be exercised in the assumption of large growth rates over long time periods. Many factors tend to self-limit the size of real physical systems.

For comparative purposes, in this paper we will frequently quantify reserves in terms of "years supply." Tables will be provided to show the effect of growth rate, but assumptions concerning this variable are left to the reader.

To further facilitate comparisons, throughout this paper reserves and total consumption are given in "quads." One quad equals one quadrillion (10^{15}) BTU. In metric units a quad is also almost equal to one exajoule (10^{18} joule). Use of quads for all energy forms does not mean that they are equivalent and interchangeable. In this paper energy reserves are given in quads of thermal energy which can be produced from that particular resource.

Current Consumption Rates

For comparison purposes, 1976 energy consumption data are given in Figure 2. World energy consumption of all forms of energy was estimated at about 290 quads, with 135 quads, or about 47 percent, supplied by petroleum. Most of the remainder was supplied by coal, 77 quads, and natural gas, 54 quads (1).* The United States consumed a total of 74 quads, or about one-fourth of the world's total. Of this, 35 quads were supplied by petroleum. An additional 20 quads were supplied by natural gas, which is a less significant energy source for the rest of the world (2).

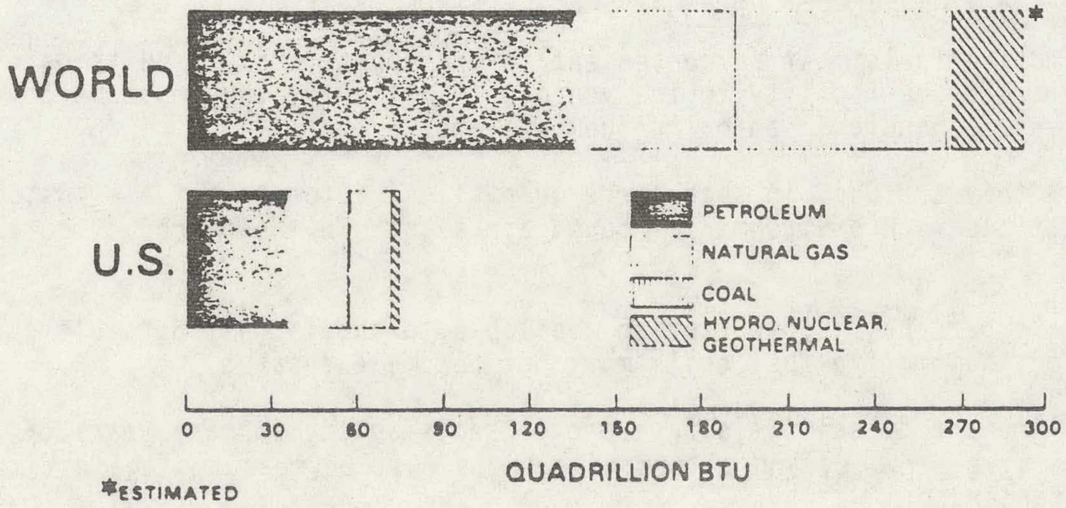

Figure 2. 1976 World and U.S. Energy Consumption (1, 2).

Automotive Fuel Requirements

Some of the more significant criteria for fuels to be used in mobile applications are shown in Figure 3.

High energy density with respect to both mass and volume is a particularly important characteristic for automotive fuels. The mass energy density must be sufficiently high to provide a reasonable vehicle range with a fuel mass that is a small fraction of the total vehicle gross mass. Similarly, because of vehicular space limitations, the volumetric energy density must be as high as possible.

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* Numbers in parentheses designate References at end of paper.

- Energy Density
- Safety
- Convenience
- Environmental Influence
- Economics

Figure 3. Fuel Criteria.

The widespread distribution and handling by relatively untrained individuals dictates that automotive fuels be safe to distribute and use. This implies a need for low toxicity and a reasonable level of flammability to avoid having to take extreme precautions.

Automotive fuels must be convenient to transport, store, and transfer from a storage facility to the vehicle. Similarly, they must be convenient to handle in on-board fuel systems.

Since they are used in such large quantities, automotive fuels must be compatible with environmental constraints both in their production and use.

To make personal transportation available to the largest possible population, automotive fuel costs must not become excessive.

Gasoline and diesel fuels have proven satisfactory in many years of automotive service, and alternative fuels must be measured against them as standards.

THE PETROLEUM SITUATION

Reserves

How long can we continue automotive use of petroleum-based fuels? The answer depends on a large number of factors, but the most important of these is how much petroleum is still in the ground and recoverable. An estimate of these reserves and their distribution around the world is shown in Figure 4 along with cumulative production (3,4). Cumulative world production of oil through 1976 was more than 2000 quads. Almost twice this much exists as proven reserves, and estimates of the world's ultimate reserves are around 9,500 quads. Crude oil price increases, additional exploration, and development of new recovery techniques can further increase the magnitude of proven reserves.

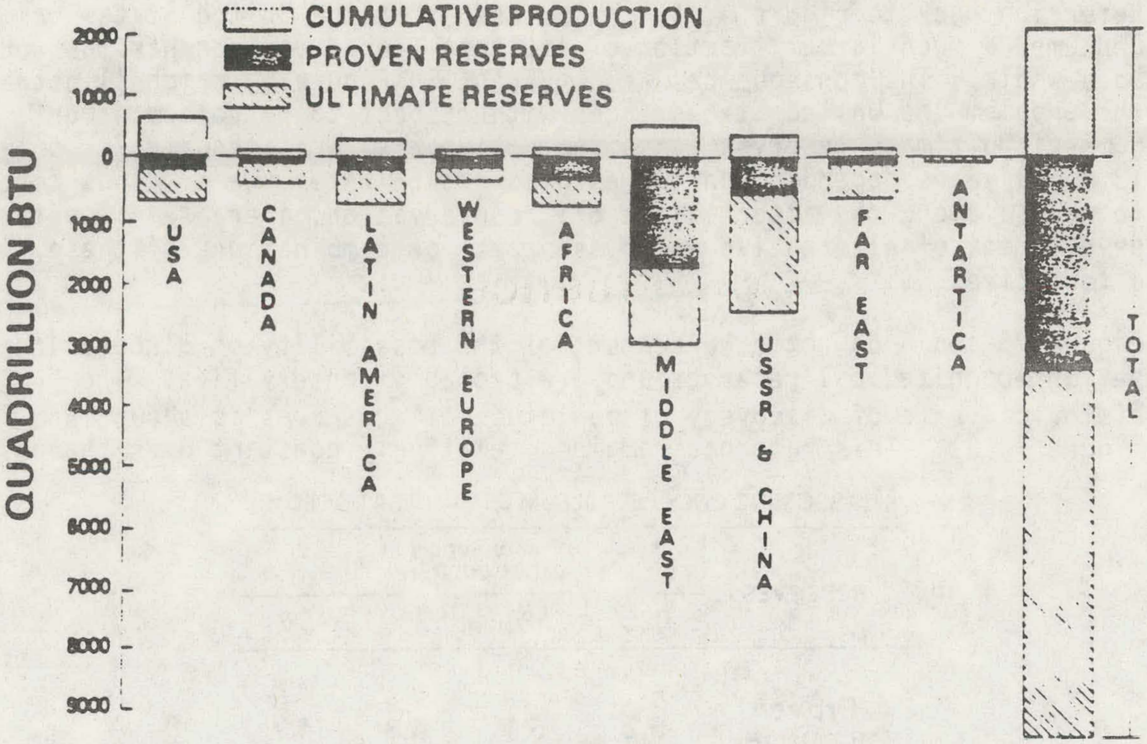


Figure 4. 1976 World Oil Production and Reserves (3, 4).

Assuming no increases in reserves beyond those currently estimated, and neglecting constraints on production rate, Figure 5 shows the number of years supply of proven and ultimate reserves at various assumed growth rates, starting from the present rate of consumption of petroleum. Depending on assumptions, present world ultimate reserves are adequate for 30 to 70 years.

(ASSUMING ONLY PETROLEUM DEMAND SATISFIED*)

RESERVES	Years Supply at Growth Rate			
	0%	1%	3%	5%
Proven (3,480 Quads)	26	23	19	17
Ultimate (9,540 Quads)	71	54	38	31

*1976 Base Year Petroleum Consumption = 134 8Q

Figure 5. Years Supply of World Petroleum Reserves.

Referring back to Figure 4, it can be seen that the United States has consumed a much larger fraction of its total reserves than has the world as a whole. The consequences are apparent in Figure 6, which illustrates the problem the United States faces with respect to petroleum. Our domestic ultimate reserves (assuming no imports) are adequate for only 13 to 19 years depending on the assumed growth rate. We are thus forced to choose among the alternatives of: conservation; increased imports; development of alternative energy sources, or combinations of these alternatives.

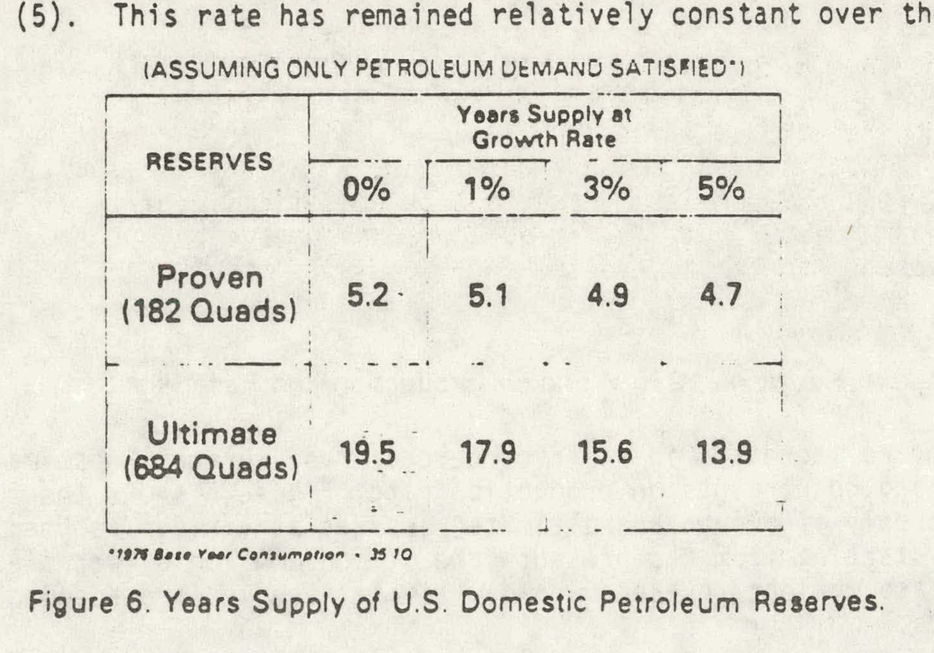
Figures 5 and 6 do not take account of the possibility of discovering as yet unrecognized oil reserves and are probably conservative. The historical rate of discovery of new crude oil reserves is shown in Figure 7 (5). This rate has remained relatively constant over the past

(ASSUMING ONLY PETROLEUM DEMAND SATISFIED*)

RESERVES	Years Supply at Growth Rate			
	0%	1%	3%	5%
Proven (182 Quads)	5.2	5.1	4.9	4.7
Ultimate (684 Quads)	19.5	17.9	15.6	13.9

*1976 Base Year Consumption - 35.1Q

Figure 6. Years Supply of U.S. Domestic Petroleum Reserves.



*EXCLUDING COMMUNIST AREAS

Figure 7. Rate of Discovery of World Crude Oil Reserves*.

30 years and has exceeded annual production, thus adding to reserves, every year with the exception of the past few. From the mid-1930's until about 1965 most of the new discoveries were in the Middle East. This has enabled the Middle East to become the largest supplier of petroleum to the rest of the world. Recently, more extensive exploration outside of the Middle East has increased proven reserves in these areas. With the exception of Alaska and some Continental Shelf reserves, most of these discoveries are outside the United States. The rate of future discoveries will depend on the level of exploration activity which will be decided by the incentives or disincentives provided.

Oil Imports

Changes in U.S. petroleum imports between 1970 and 1976 are shown in Figure 8 (6,7). Imports did not become a significant fraction of our total petroleum requirement until about 1965. In the past few years, our oil imports have replaced continuously larger fractions of the demand that had previously been met by domestic sources. By 1976, almost 42 percent of our total petroleum consumption was met by imports, and this is estimated to be about 47 percent for 1977 (8). During the last few years, not only the percent of imports has been rising, but also the absolute amount imported.

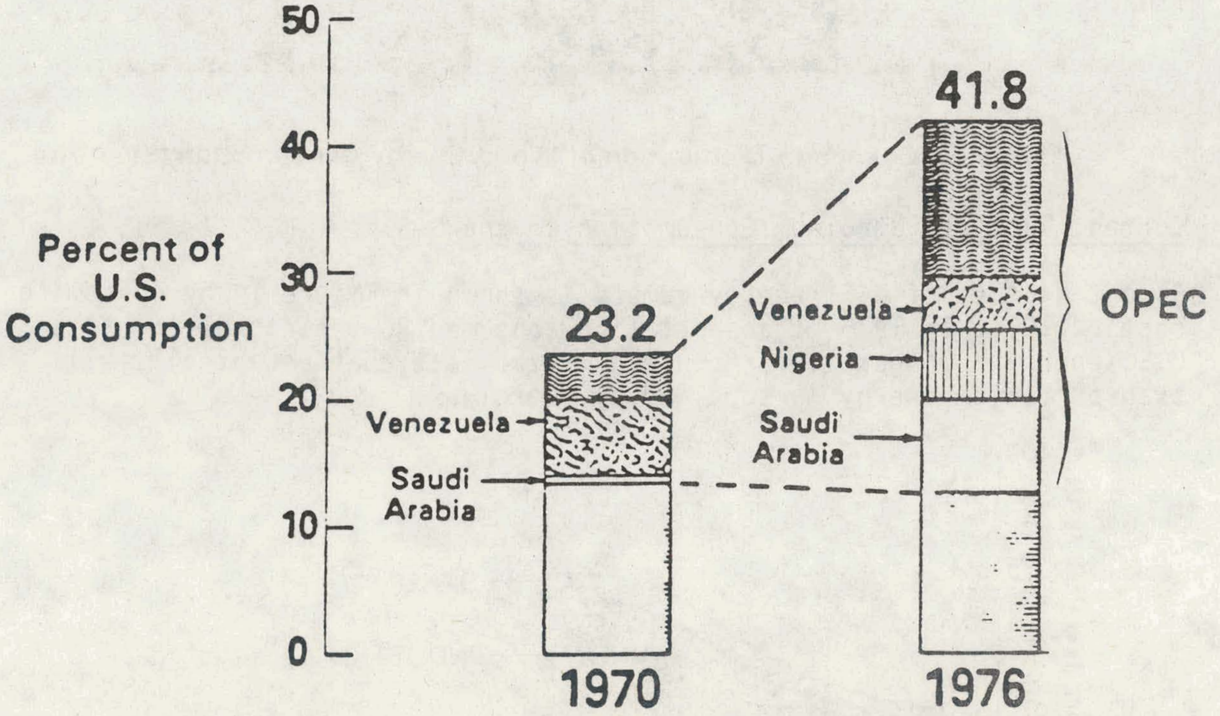


Figure 8. Sources of U.S. Petroleum Imports (6, 7).

A further cause for concern is the large increase in our reliance on the OPEC countries. Imports from Saudi Arabia have increased markedly. Further decreases in imports from non-OPEC countries, such as Canada, are forecast for the near future. Heavy reliance on petroleum imports has made the U.S. vulnerable to economic or political action by foreign governments or combines such as OPEC. These potential actions present a threat both to the national defense and the economy.

Another critical factor affecting the future availability of imported oil is competition for this resource from other industrialized and developing nations. Figure 9 is a projection of the trend in distribution of world energy consumption (9). As a consequence of the more rapid growth in energy usage by other countries, especially developing countries, the United States percentage of the total world energy consumption is expected to decrease from 32 percent in 1970 to 22 percent in 2000. Although our fraction of world energy will decrease, our absolute energy needs are expected to continue to increase. Our need for increasing imports, and stronger competition for available world oil resources, makes the future supply of petroleum in the U.S. uncertain at best.

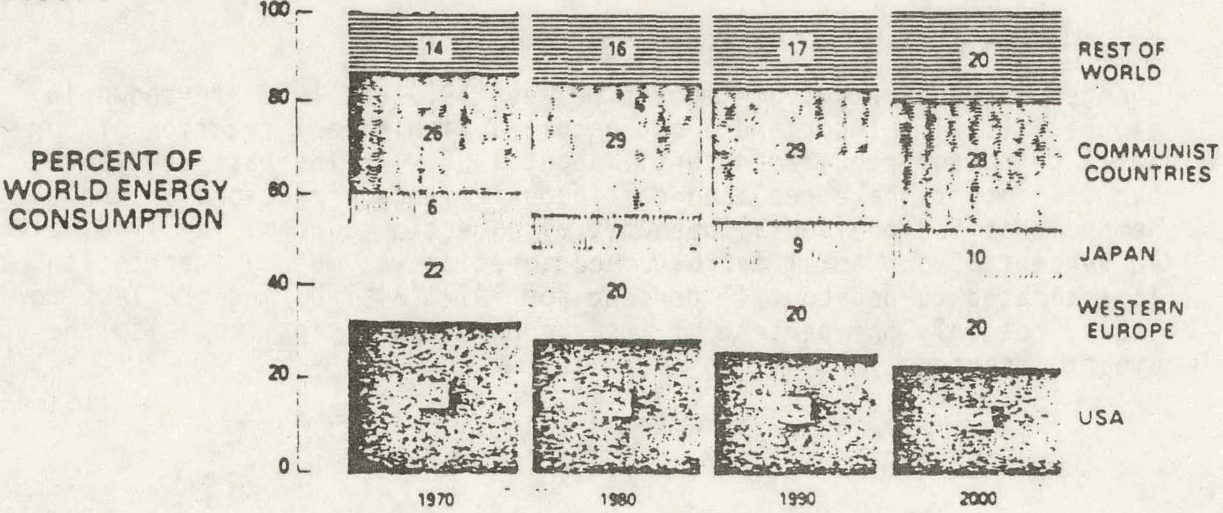


Figure 9. Change In Distribution of World Energy Consumption (9).

Current Rate of Petroleum Consumption in the U.S.

Recent history of U.S. energy demand is shown in Figure 10 by consuming sector (10). In 1975, transportation consumed 26 percent of the total U.S. energy. Of particular concern is the fact that essentially all transportation energy is supplied by petroleum.

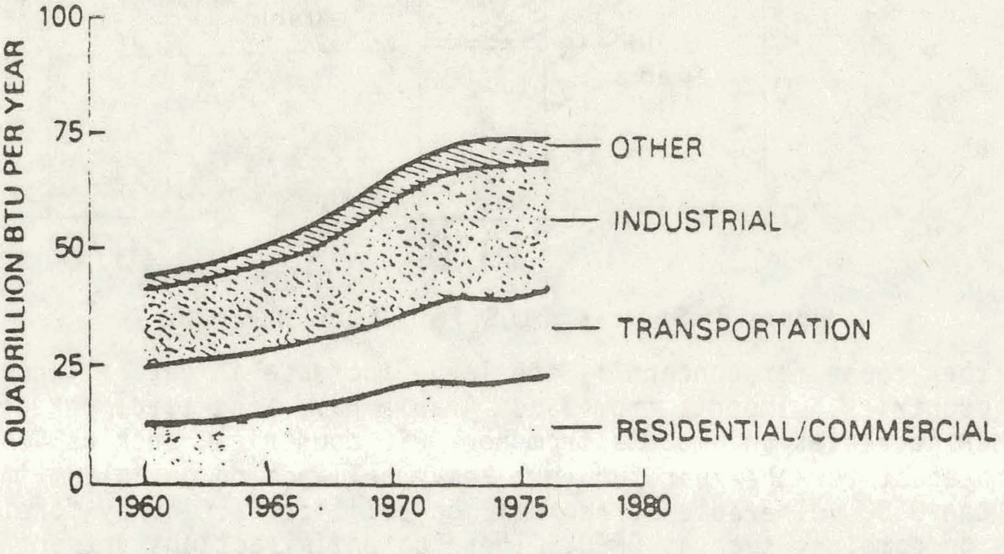


Figure 10. U.S. Energy Demand By Consuming Sector (10).

The 1975 petroleum supply and usage is shown in Figure 11 (11). Transportation consumed more than half of total petroleum, with the automobile using 30 percent. Much of the petroleum used by the residential, industrial, and commercial sectors is utilized for space heating and boiler fuel. Some stationary installations of this nature could theoretically utilize other primary energy resources, such as coal, thereby releasing petroleum for transportation use. Conversion of these installations is severely limited both by environmental restrictions and by the capital investment required. These factors are likely to limit the transfer of petroleum for transportation use from these applications in the near term.

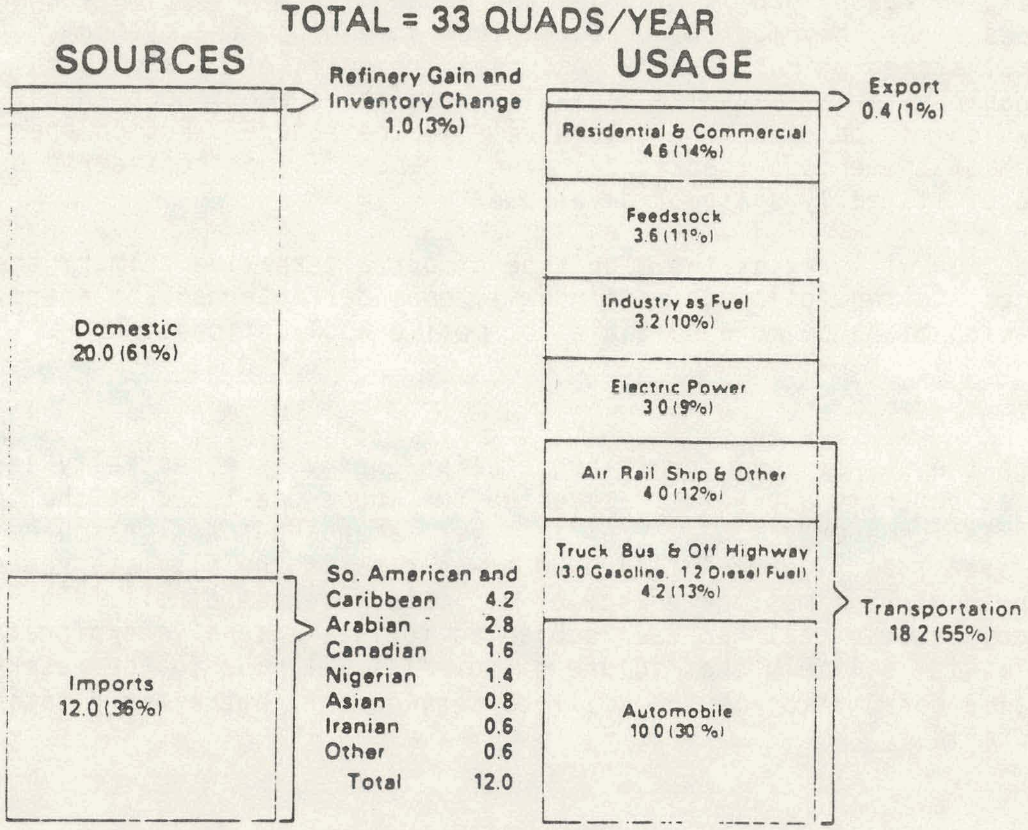


Figure 11. U.S. Oil Supply and Demand — 1975 (11).

Summary of Petroleum Situation

Assuming a 3 percent rate of growth in petroleum consumption, the world's ultimate petroleum reserves would be adequate for about 38 years. While there is considerable uncertainty about the exact magnitude of petroleum reserves, it is clear that they are finite and will some day be depleted. U.S. domestic reserves are severely limited and if consumption increases at 3 percent, our ultimate reserves are sufficient for only about 16 years.

Forecasting the quantity of imported petroleum which will be available to the United States in the future is risky because of the many political and economic actions which cannot be anticipated. It is clear, however, that competition from the developing countries and other industrial countries will reduce the amount of petroleum available to the United States.

Finally, even if a long-term supply of petroleum existed in the United States, the rate at which it could be made available as fuel would depend on exploration rates, production rates, and refinery capacity.

ALTERNATIVE PRIMARY ENERGY SOURCES

Primary and Intermediate Fuels

Although petroleum has proven to be an ideal source of liquid fuels - especially for transportation - there are other primary energy resources which could either supplement or replace it in the future. It is necessary to distinguish between primary energy resources and intermediate energy forms which may be better suited for use in mobile equipment. For example, fuels such as hydrogen and methanol are not primary energy resources since they must be produced from some other energy form. The principal stored primary energy resources are coal, oil shale, and fissionable materials. Solar radiation provides a continuous energy input which may be used more extensively in the future. Fusion energy, although of tremendous theoretical significance, is not considered here because of its early state of development.

This section will review the magnitude of our alternative primary energy resources and the following section will consider intermediate energy forms which might be more suitable for mobile applications.

Coal

Although the use of coal for transportation energy is essentially zero today, as recently as 1947 it accounted for about one-third of the total transportation energy (16). Coal is a very abundant fossil resource as can be seen from Figure 14 (17). On a world basis the ultimate reserves contain about 25 times the energy of ultimate reserves of oil. In addition, because coal has been subjected to less intensive exploration than oil, it is likely that future discoveries will add to the reserves. Cumulative consumption is too small to see, except in the world total of Figure 14.

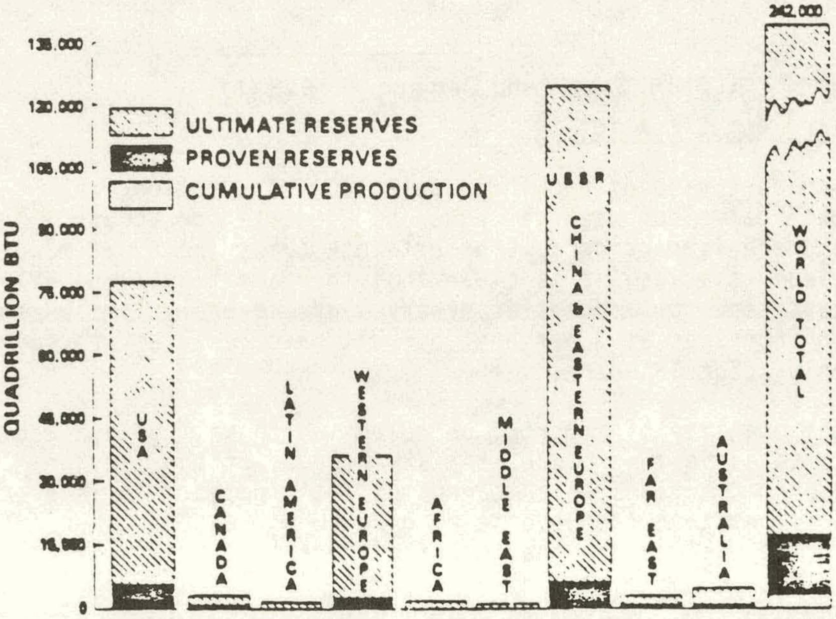
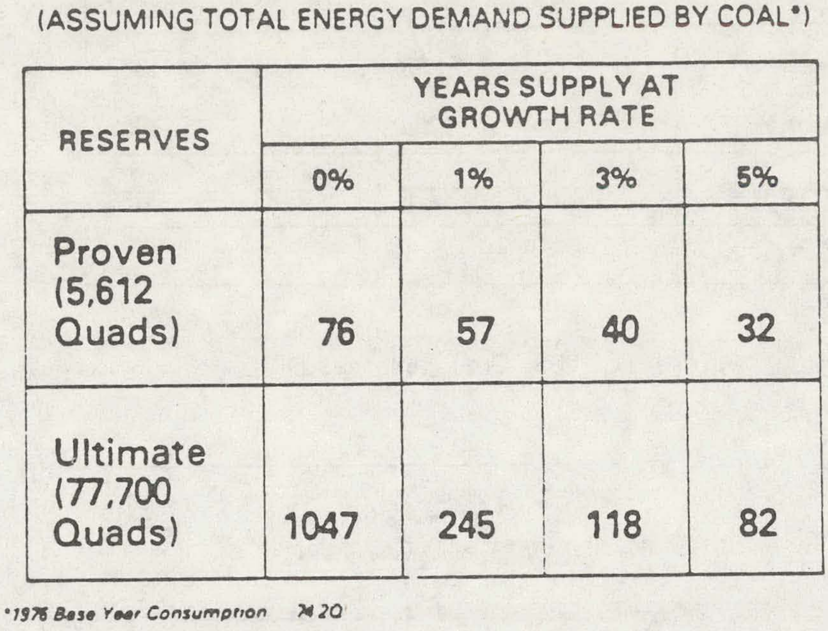


Figure 14. World Coal Resources, 1974 (17).

Unlike its position with respect to petroleum, the United States is especially favored with large coal reserves - almost one-third of the world proven reserves. Figure 15 shows the number of years supply of domestic coal assuming, for comparison only, that all U.S. energy needs are supplied from this resource. On this basis, U.S. ultimate reserves would satisfy our needs for from 80 to over 1000 years, depending on energy consumption growth rate.



(ASSUMING TOTAL ENERGY DEMAND SUPPLIED BY COAL*)

RESERVES	YEARS SUPPLY AT GROWTH RATE			
	0%	1%	3%	5%
Proven (5,612 Quads)	76	57	40	32
Ultimate (77,700 Quads)	1047	245	118	82

*1976 Base Year Consumption 74.2Q

Figure 15. Years Supply of U.S. Domestic Coal Reserves.

Although the existence of large coal reserves is reassuring, the problems in developing this resource must be recognized. Environmental problems exist both with the production and ultimate use of coal. Figure 16 shows that the most desirable coal reserves exist in the western United States (18). The western coal reserves are largely accessible by surface mining. They generally have a low sulfur content. However, the western coal resources are located in low population density areas, and the development of the needed physical resources and manpower involve sociological and environmental problems in addition to large investments. The further problem of transporting coal to consuming areas must be faced. These are obviously massive problems which are not going to be resolved simply and in a short time.

Oil Shale

Oil shale is another fossil resource which is relatively widely distributed over the world, although Africa and Asia have the largest reserves (19). The richest U.S. deposits are located in Colorado, Utah, and Wyoming. The magnitude and distribution of U.S. shale resources containing more than 25 gallons of oil per ton are shown in Figure 17 (20). Our proven reserves of this high grade ore are about half as great as our proven coal reserves. These reserves are attractive because of the relative ease of producing products similar to petroleum from shale oil.

QUADRILLION BTU

	Mining Methods		% Sulfur	
AREA	SURFACE	UNDER-GROUND	1% OR LESS	GREATER THAN 1%
Western	1425	1119	1894	650
Gulf	57	—	—	57
Midwestern	443	969	14	1397
Appalachia	311	1288	541	1059
SUB TOTALS	2236	3376	2449	3163
TOTAL	5612		5612	

Figure 16. U.S. Coal Reserves (18).

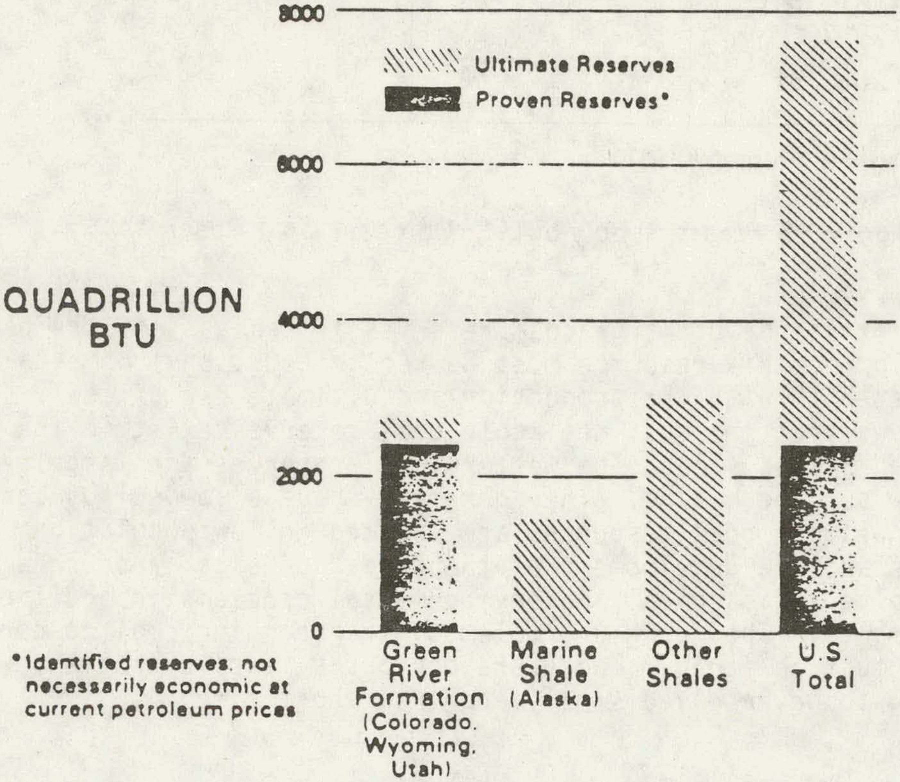


Figure 17. U.S. Oil Shale Resources (25-100 Gal/Ton Oil Yield)(20).

Ultimate reserves of shale containing over 25 gallons of oil per ton would satisfy total U.S. energy demand at a 3 percent growth rate for almost 48 years. Very large deposits of lower grade oil shale yielding from 10 to 25 gallons of oil per ton of shale are widely distributed over the United States. The magnitude of these resources, more than twice as great as

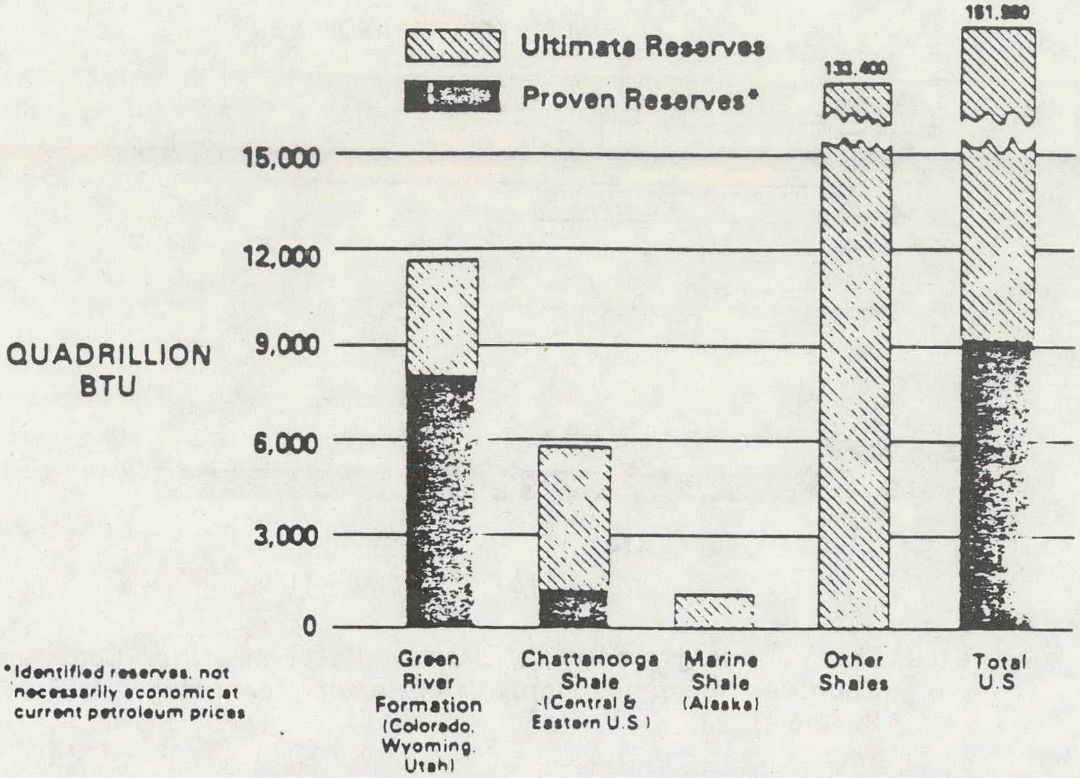


Figure 18. U.S. Oil Shale Resources (10-25 Gal/Ton Oil Yield) (20).

coal, is shown in Figure 18. Although they exist in large quantity, the low yield of these shales prevents economical recovery.

Like coal, because of limited exploration, the amount of oil shale ultimately recoverable is known with little certainty. Similar problems exist with respect to the development of oil shale resources as for coal. The oil shale deposits in the eastern United States have simpler transportation, labor, and water-requirement problems than western shales.

Nuclear

Although some electricity was produced in nuclear plants by 1957, it was not until 1968 that nuclear plants produced electricity equivalent to 0.1 quad of thermal energy (21). In recent years, the on-stream capacity of nuclear plants has risen rapidly so that by 1975 they supplied about 1.6 quads (thermal) of our total energy demand (22). Recent resistance from environmentalists, and government regulations have greatly increased the capital costs and the time required to get a plant on stream.

The energy available from uranium depends on the technology used to convert it. Figure 19 shows the worldwide distribution of proven reserves (in terms of thermal quads) producible at $15/pound of U_3O_8 (1975 estimate) when used in light water reactors (23). Australia and the United States are particularly well endowed with uranium reserves when compared to the rest of the free world.

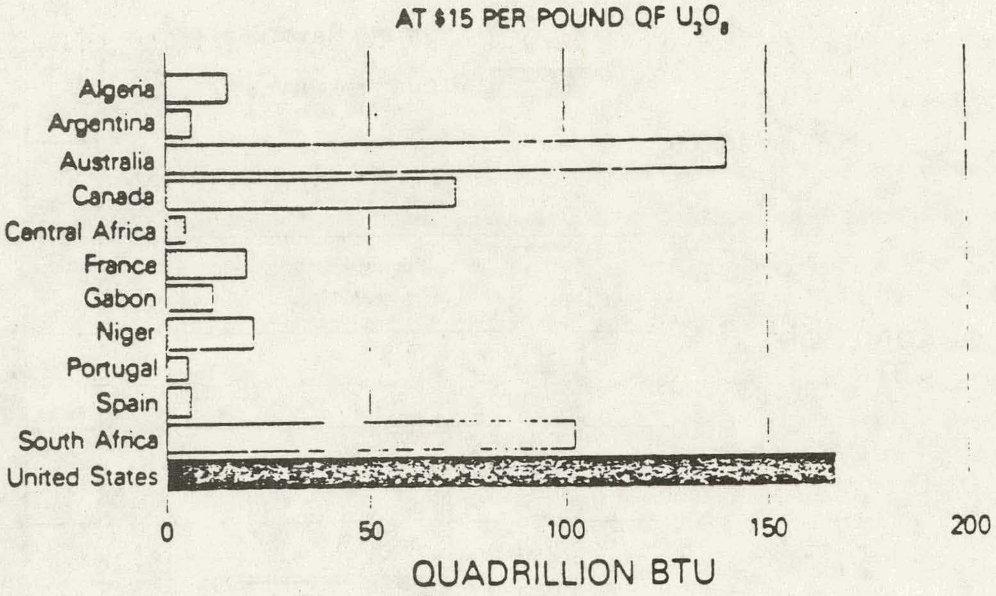


Figure 19. Thermal Energy Content of Uranium Reserves of Non-Communist Countries (Assuming Light Water Reactor Technology, No Breeder Reactors) (23).

Figure 20 shows the magnitude of U.S. reserves at different uranium prices (24). This figure also is based on the use of light water reactors and indicates the energy available from lower grade ore.

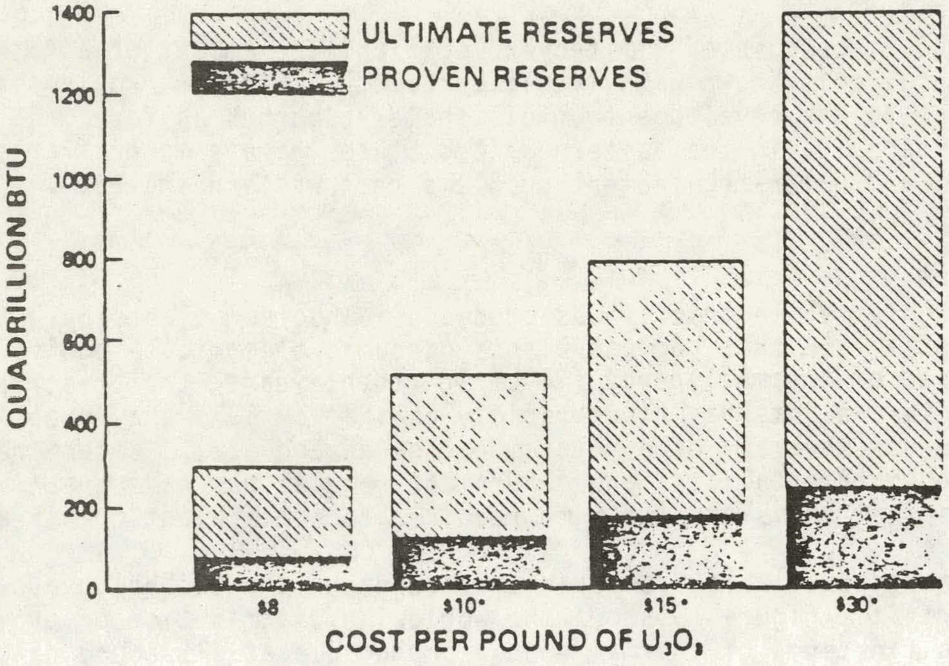


Figure 20. Thermal Energy Content of U.S. Uranium Resources By Cost Level (Assuming Light Water Reactor Technology, No Breeder Reactors) (24).

Figure 21 shows the number of years supply of uranium if used in light water reactors to satisfy, for comparison only, all of the energy needs of the United States. Even zero growth in energy demand results in a life of our ultimate reserves with \$15 per pound U_3O_8 of less than 11 years.

USED IN LIGHT WATER REACTORS
(ASSUMING TOTAL ENERGY DEMAND SUPPLIED BY URANIUM*)

RESERVES	Years Supply at Growth Rate			
	0%	1%	3%	5%
Proven (168 Quads)	2.3	2.3	2.2	2.2
Ultimate (780 Quads)	10.5	10.0	9.2	8.7

*1976 Base Year Consumption 74 2Q

Figure 21. Years Supply U.S. Domestic Reserves of Uranium (\$15/lb.).

If breeder reactors were to be employed rather than light water reactors, the thermal energy available from the same ore would be increased by a factor of about 100. The effect of the use of breeder technology on the life of our uranium supply is shown in Figure 22. Because of the compounding effect, the lifetime of the uranium supply is not multiplied by 100 (except at zero growth rate). Considering ultimate reserves available at \$15/pound and a growth rate of 3 percent a year, the domestic reserves of uranium could satisfy our needs for 118 years. From this comparison it is clear that breeder technology must be employed if uranium is to provide a significant fraction of our future energy needs.

Strong resistance to the development of breeder technology, based on security concerns with control of plutonium, has been evident in recent years. Storage and disposal of nuclear wastes have also been the subject of continuing debate. Unless answers to these questions are found, we will be unable to exploit the full potential of our uranium reserves.

Solar Energy

Solar radiation is an essentially constant source of energy. The total amount of energy reaching the surface of the contiguous 48 United States amounts to almost 50,000 quads each year, about 700 times our current total energy consumption (25). Solar energy is directly utilized by

USED IN BREEDER REACTORS
(ASSUMING TOTAL ENERGY DEMAND SUPPLIED BY URANIUM*)

RESERVES	Years Supply at Growth Rate			
	0%	1%	3%	5%
Proven (16,800 Quads)	226	119	70	51
Ultimate (78,000 Quads)	1050	246	118	82

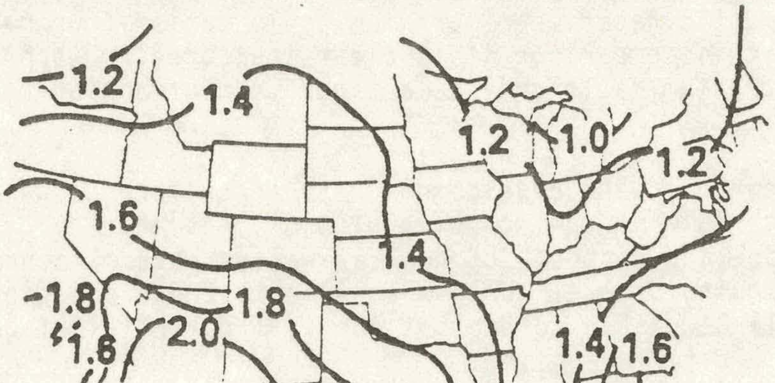
*1976 Base Year Consumption = 74.20

Figure 22. Years Supply U.S. Domestic Reserves of Uranium ($15/lb.).

plants, but its utilization specifically for energy production has been relatively limited. One of the most severe limitations is the need for some form of storage because of the diurnal, seasonal and weather-related variations in the intensity of the radiation reaching the ground. In addition to the storage problem introduced by the unsteady nature of the radiation, the technology to convert the radiant energy to other useful forms is not well developed.

On an annual average basis, most of the United States receives from 400 to 800 kilojoules per square centimetre at the surface, the higher values occurring in the relatively low population density southwestern parts of the United States. Figure 23 shows the distribution of solar energy over the United States (26). The contours of constant annual average energy normalized with respect to Michigan, show that Arizona and parts of New Mexico receive about twice that of Michigan. Viewed on a shorter time scale, this ratio could even be greater.

NORMALIZED WITH RESPECT TO MICHIGAN = 1.0*

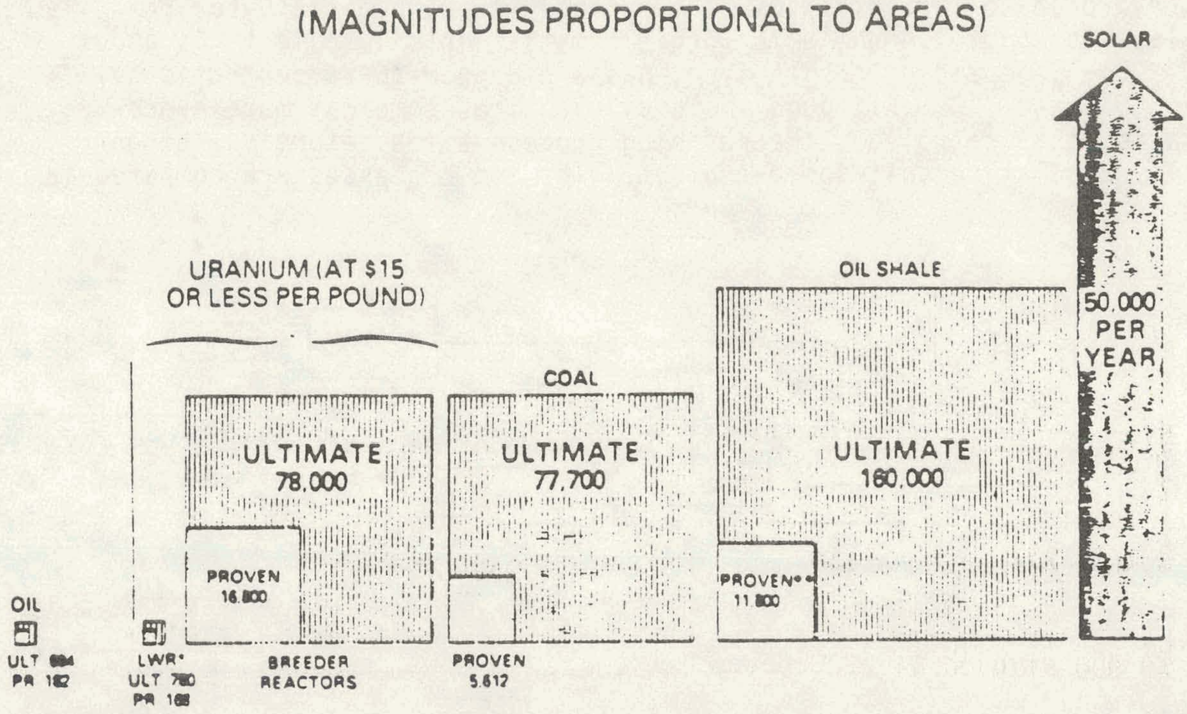


*Value of 1.0 Corresponds to
415 KILOJOULES/CM^2 • YEAR (= 1000 BTU/FT^2 • DAY)

Figure 23. Average Distribution of Solar Energy Over the United States (26).

Summary of Primary Energy Reserves

Figure 24 summarizes our domestic ultimate reserves of primary energy resources. These reserves may be compared to our 1976 annual energy consumption of 74 quads. Coal and oil shale represent very large energy potential compared to petroleum, but nuclear energy, unless breeder technology is developed, is seriously limited. Using breeders, ultimate uranium and coal reserves are about equal. Solar radiation, as noted previously, presents an almost inexhaustible source of energy.



*LWR = Light Water Reactors

**Identified Reserves, Not Necessarily Economic At Current Petroleum Prices

Figure 24. U.S. Energy Reserves, Quadrillion BTU.

Such a superficial view provides a much more reassuring picture than in fact exists. Current transportation equipment cannot use coal, nuclear, or solar energy directly. Our present heat engines have been designed to utilize specific liquid fuels produced from petroleum. The problem then remains of how to utilize the abundant primary energy resources available to us for transportation purposes.

HEAT ENGINE FUELS FROM PRIMARY ENERGY RESOURCES

The purpose of the following section is to look at the technical problems of producing transportation fuels from our primary energy resources. Coal, nuclear, and perhaps even solar energy, might be employed to produce electricity which could then be utilized with some storage system for transportation purposes. However, because of their greater utility as transportation fuels, we will concentrate primarily on those liquid and gaseous fuels which might be considered for automotive use. Flow charts will be used to indicate schematically the inputs, processes, and outputs. The various conversion processes to be discussed are in different states of development and not all are likely to be commercially feasible.

Fuels from Oil Shale

Oil shale, and to an even greater extent coal, differs from petroleum in its hydrogen-to-carbon ratio. The hydrogen-to-carbon ratio for petroleum is about 1.8 while for organic matter in oil shale it is about 1.6. Coal, depending on its type, has a hydrogen-to-carbon ratio between 0.6 and 0.8. Although shale oil requires somewhat more hydrogenation than petroleum, the refining process after retorting is generally similar to that for petroleum. The two processes are compared in Figure 25.

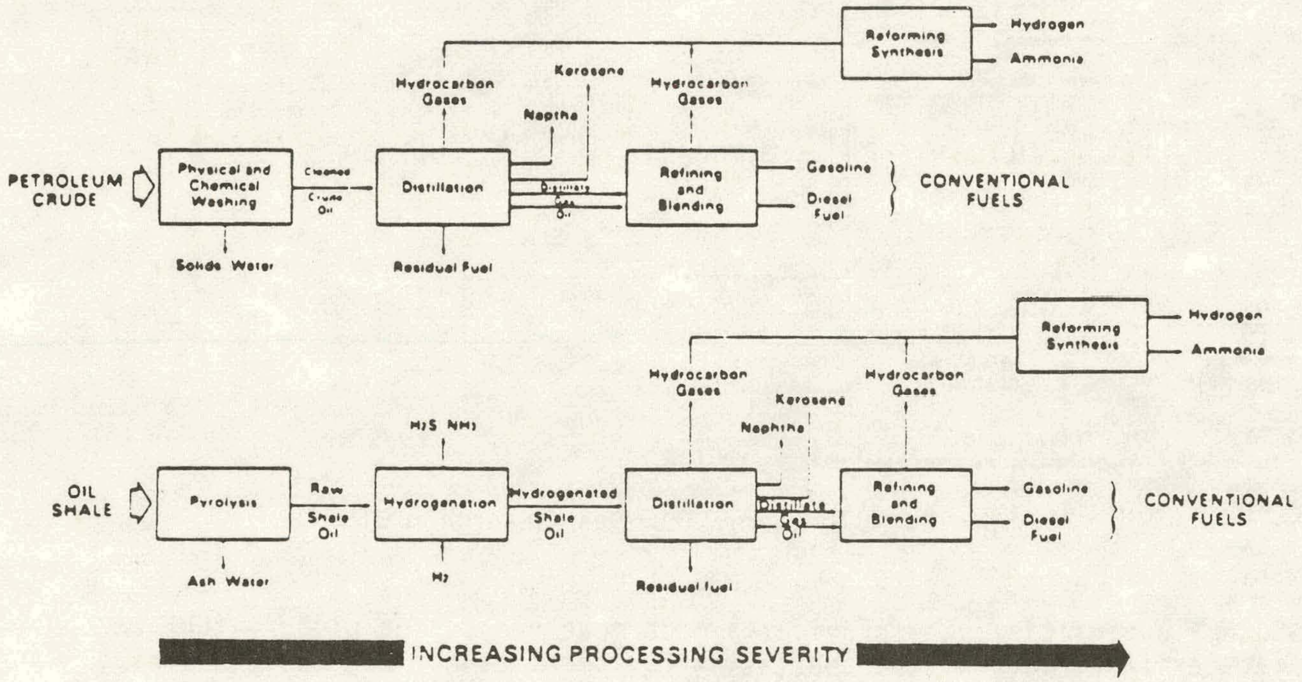


Figure 25. Obtaining Fuels From Petroleum and Oil Shale.

Oil shale is a nonporous, impermeable rock containing over 10 percent by weight of organic matter called kerogen. Raw shale oil is obtained by pyrolysis of oil shale. Kerogen in oil shale undergoes thermal cracking during pyrolysis to yield raw shale oil which is high in nitrogen and sulfur and relatively low in hydrogen. Catalytic hydrogenation of raw shale oil is used to remove impurities (S and N) and to increase its hydrogen content. Hydrogenated shale oil may be refined to obtain conventional fuels such as gasoline and diesel fuel or, as with petroleum, other liquid and gaseous fuels may be obtained at intermediate processing stages.

Fuels from Coal

Before the introduction of natural gas for home use, coal regularly served to produce manufactured gas for this purpose. During the later stages of World War II most of Germany's military equipment was operated on synthetic liquid fuels produced from local coal. Today, South Africa continues to use similar processes to avoid the need for large petroleum imports.

The conversion of coal to liquid fuels is brought about by decomposing the complex coal structure and by increasing the hydrogen-to-carbon ratio to the desired level. Impurities such as mineral matter, moisture, nitrogen, sulfur and oxygen are removed to obtain an acceptable product. Processes for making liquid and gaseous fuels from coal are shown in Figure 26. Basically two approaches are taken to obtain liquid fuels from coal; direct and indirect. Direct approaches are pyrolysis, solvent extraction, and catalytic hydrogenation of coal. The indirect approach involves gasification of coal followed by synthesis.

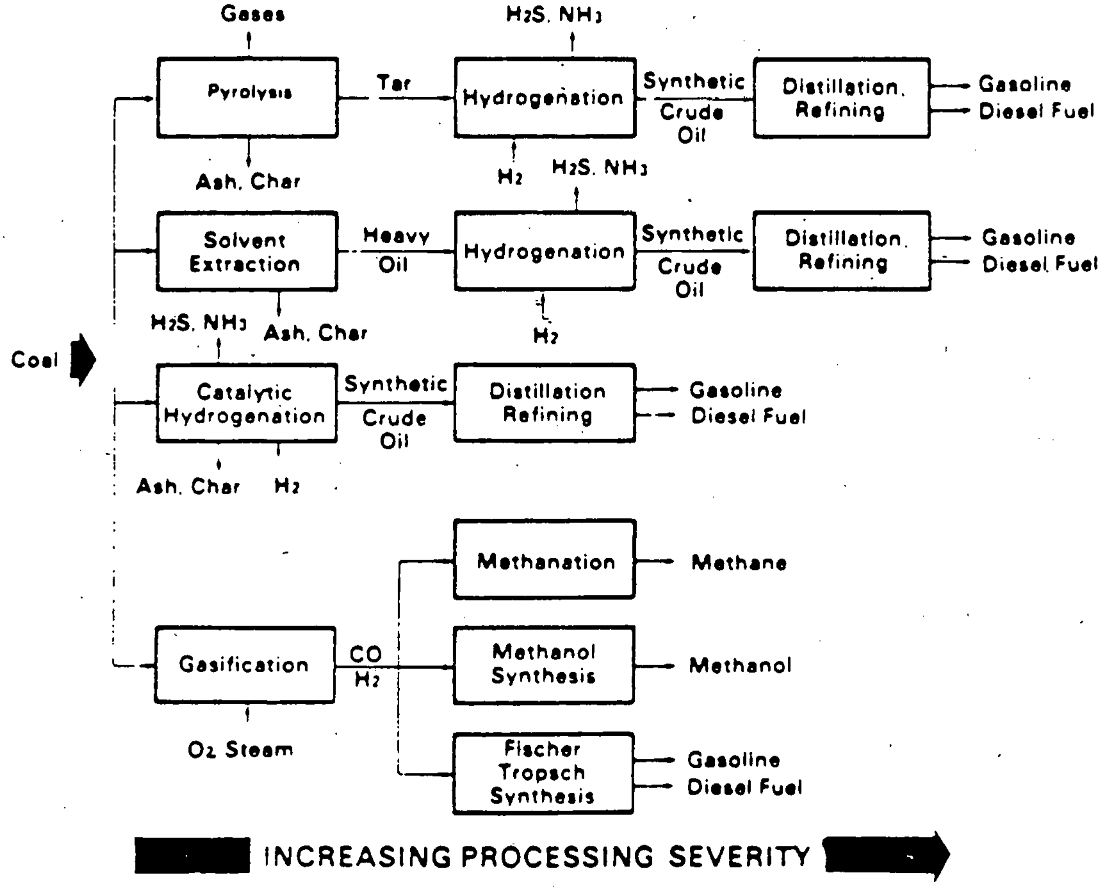


Figure 26. Obtaining Liquid Fuels From Coal.

In a pyrolytic process, coal is heated in the absence of air to obtain tar which can be hydrogenated to synthetic crude. In a solvent extraction scheme, coal is mildly hydrogenated via a hydrogen donor solvent. The resulting product is heavy oil which can be upgraded to synthetic crude oil via further hydrogenation. Direct catalytic hydrogenation of coal gives synthetic crude oil as a primary product. Coal-derived synthetic crude may be refined to obtain gasoline and diesel fuel. These conventional fuels and methanol may also be obtained by gasifying coal to a mixture of carbon monoxide and hydrogen (synthesis gas) which then can be used to synthesize either hydrocarbon fuels via the Fischer-Tropsch process, or methanol.

Fuels from Nuclear Resources

Nuclear energy can also be used to obtain liquid fuels such as methanol and hydrocarbons. The processes are shown schematically in Figure 27. Heat generated in a nuclear reactor may be used directly to decompose water into oxygen and hydrogen. This hydrogen can be combined with carbon monoxide obtained via thermal decomposition of a carbonate, such as lime, to produce either gasoline and diesel fuel via the Fischer-Tropsch process, or methanol.

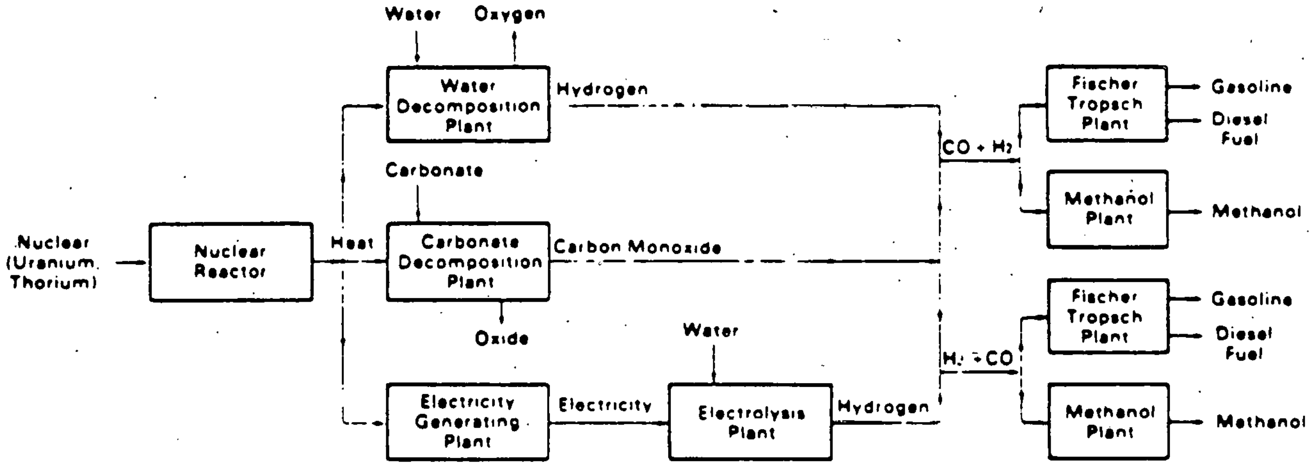


Figure 27. Fuels Obtainable From Nuclear Resources.

Alternatively, nuclear heat may be converted to electricity which can be used to obtain hydrogen from water via electrolysis. This hydrogen can be combined with carbon monoxide from a carbonate to produce methanol, gasoline or diesel fuel.

Fuels from Solar Energy

There are two routes from solar energy to automotive fuels. These are diagrammed in Figure 28. One alternative involves the production of electricity either by direct photovoltaic conversion or by a more conventional heat engine-generator system obtaining its heat energy via some form of solar concentrator. The electricity can then be used in the same fashion as that produced by nuclear power to synthesize the same variety of liquid fuels.

Perhaps the most frequent proposal put forth for converting solar energy to automotive fuels is via the intermediate of biomass. Biomass (vegetation and organic wastes) is composed of cellulosic materials, which can be converted to alcohols (ethanol and methanol) and liquid hydrocarbons.

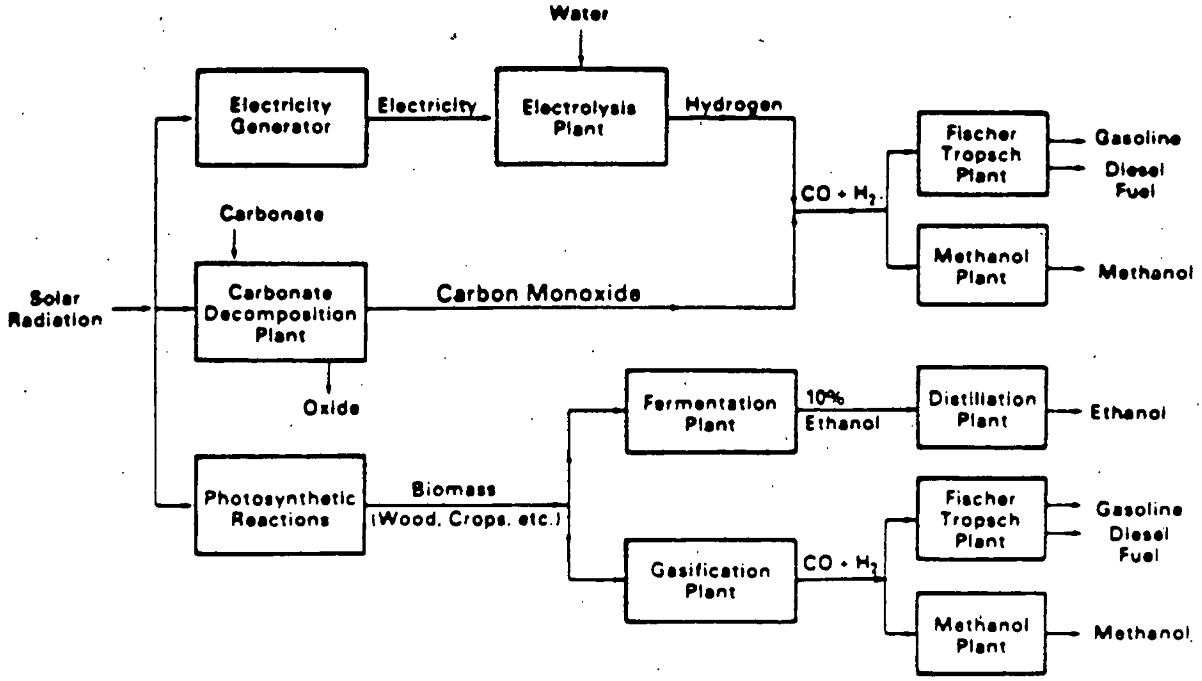


Figure 28. Fuels Obtainable from Solar Energy.

Cellulosic materials, although very high in oxygen content, are low in sulfur and nitrogen content and, therefore, could be an attractive source of fuels.

Ethanol from biomass is obtained via fermentation followed by distillation. This process is well known, and is used commercially in the case of sugar cane and grain.

The scheme for obtaining methanol and liquid hydrocarbons from biomass is similar to the one used for coal. Biomass is gasified to obtain a mixture of carbon monoxide and hydrogen which may be used to produce either gasoline and diesel fuel via the Fischer-Tropsch process, or methanol. Destructive distillation of biomass (wood) also yields methanol, but the quantity of methanol obtained in the process is relatively small and hence it is unlikely that this process would be used for obtaining commercial quantities of methanol fuel.

Energy Efficiency of Conversion Processes

Although the processes involved in production of alternative fuels from primary energy resources are in various states of development, Figure 29 provides some estimates of their energy conversion efficiencies (27). The values shown represent estimates of the ratio of the energy in the finished product to the energy contained in the primary resource. It is desirable for this value to be high since: high conversion efficiency will conserve energy resources, and a high conversion efficiency is also likely to be associated with lower capital investment (since for a given energy output the plant will have to handle a smaller throughput).

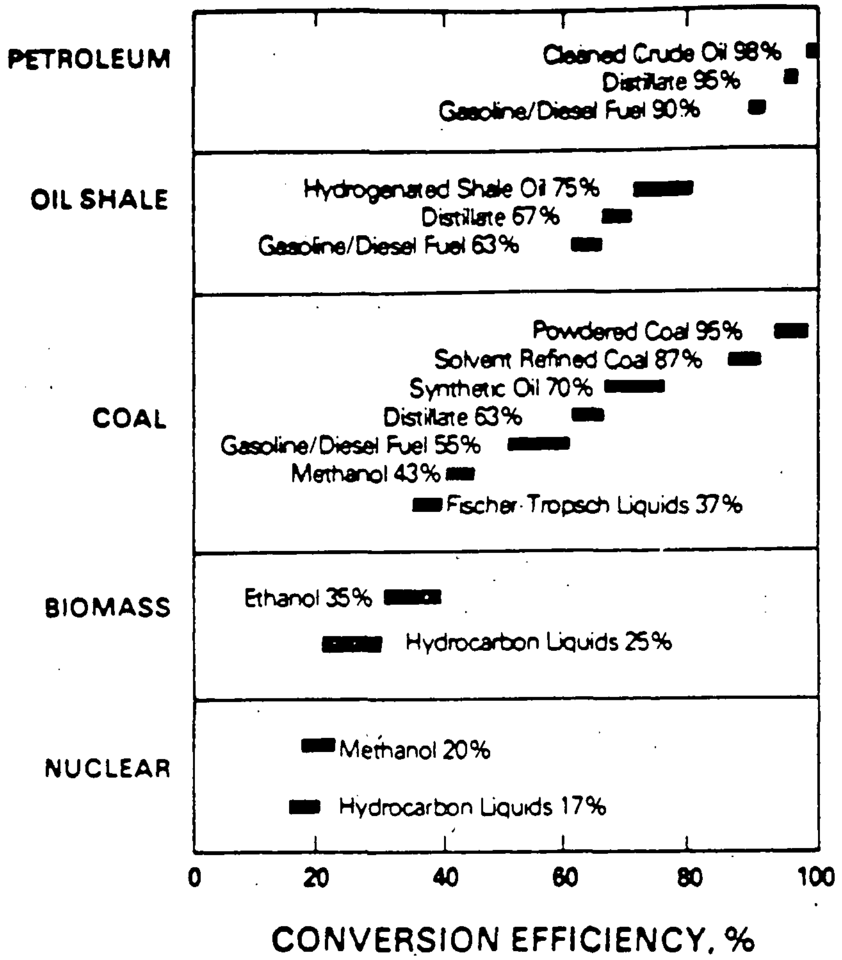


Figure 29. Fuel Conversion Efficiencies (27).

It should be recognized that conversion efficiency alone may not indicate the most desirable form for intermediate fuels. Perhaps a more significant measure is the overall energy efficiency starting from the primary resource to energy in the final form desired. In the case of the automobile, mechanical energy is the final form. The contribution of the heat engine involved in the chemical to mechanical conversion process must also be considered and there may be a trade-off between efficiency of the engine and efficiency of the fuel conversion process.

For example, a 25 percent thermal efficiency engine which could burn powdered coal would have a system efficiency of 25 x 0.95 = 23.75 percent. An engine burning gasoline produced from coal at an efficiency of 55 percent would have to exhibit an efficiency of about 43 percent to achieve an equivalent system efficiency. Economics is also a determining factor and overall lowest cost may not be associated with the most energy efficient combination of engine and fuel.

Properties of Fuels from Alternative Primary Resources

The preceding section has shown the technical possibility of producing fuels similar to our current gasoline and diesel fuel starting from any of our future alternative energy resources. Depending on the nature of the primary resource, more or less severe processing is required to achieve octane number, cetane number, and sulfur and nitrogen contents equivalent to the fuels produced from petroleum.

Other liquid and gaseous fuels can be made from these same resources. As noted earlier, one of the considerations in selecting a fuel-engine combination is the overall system thermal efficiency. For transportation use, however, one of the most important properties of a fuel is its energy density. Energy density on a mass basis is shown for a number of potential liquid and gaseous fuels in Figure 30. Figure 31 provides similar information, but on a volumetric basis. The liquid fuels, ethanol, methanol, ammonia, and hydrazine all have lower energy density on both bases than gasoline and diesel fuel.

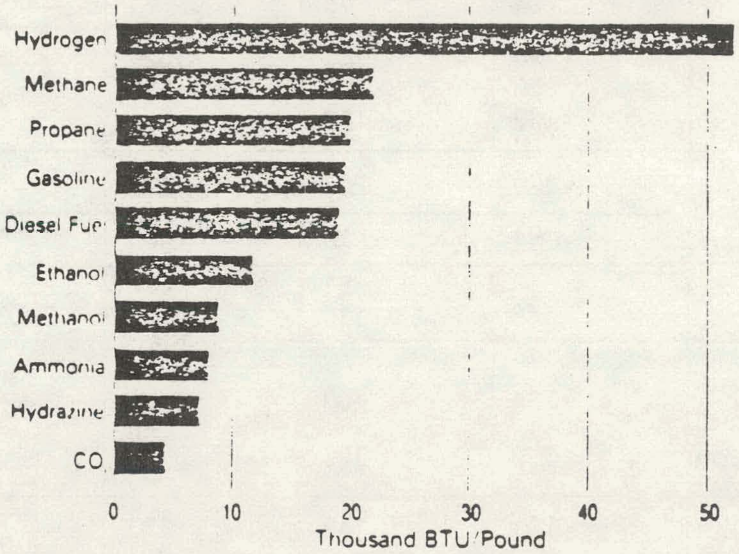


Figure 30. Heats of Combustion of Several Fuels On Mass Basis

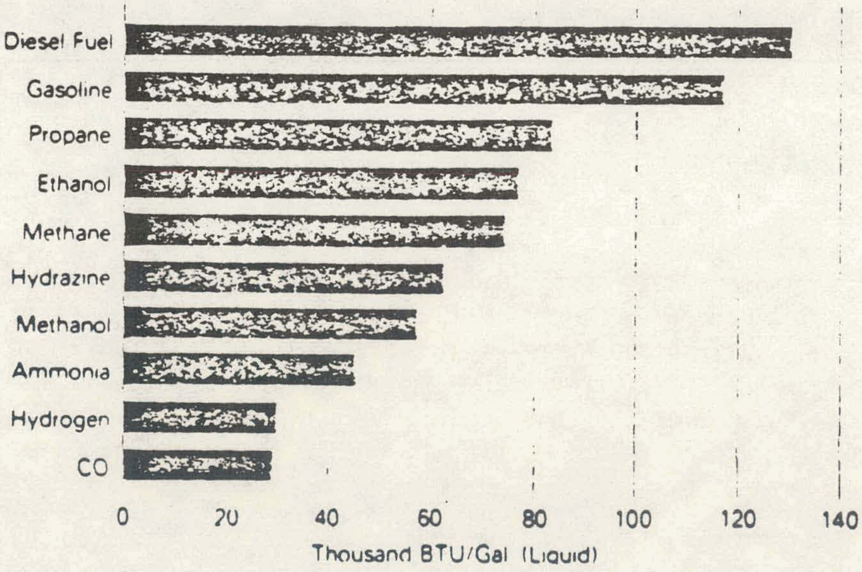
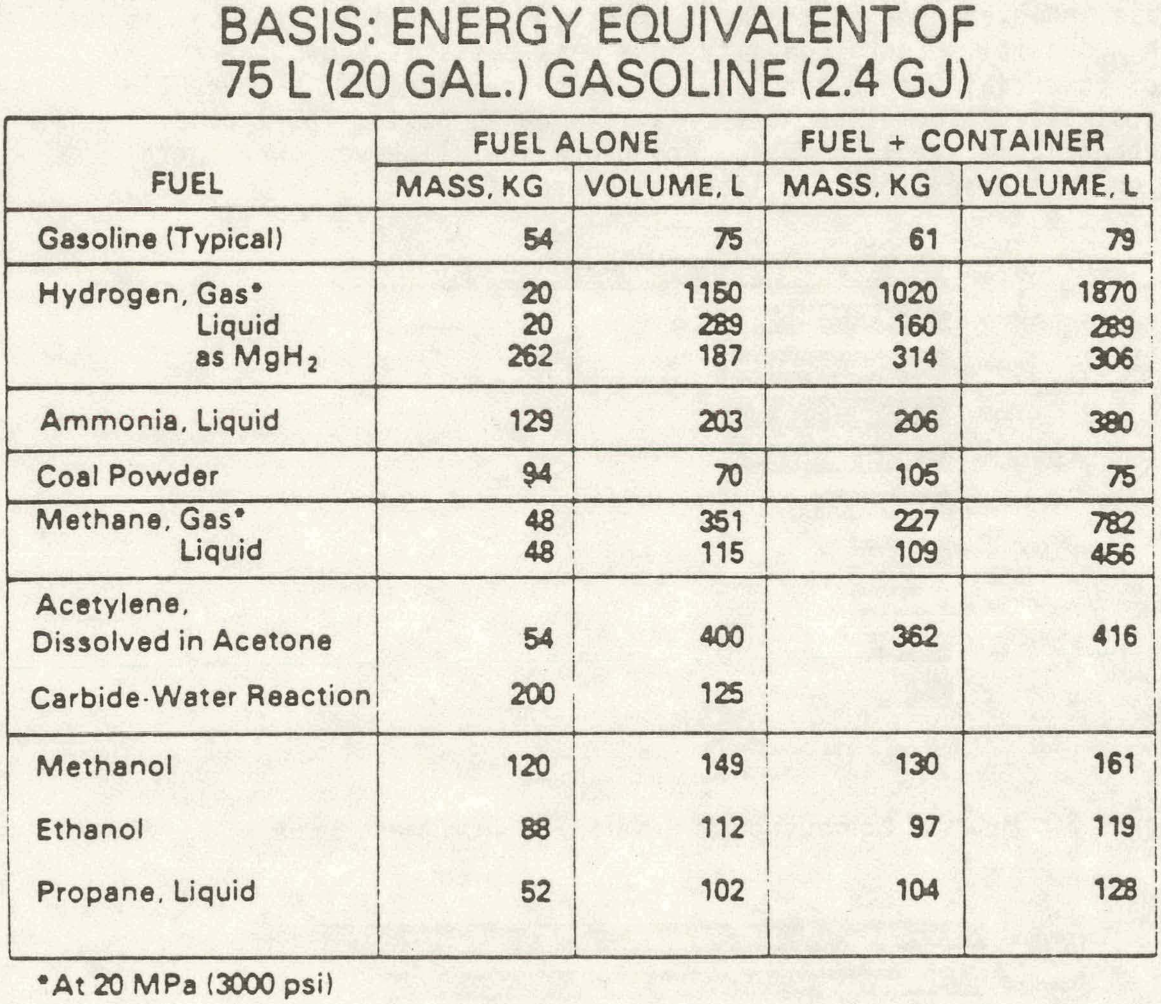


Figure 31. Heats of Combustion of Several Fuels On Volume Basis

The high mass energy density of hydrogen shown in Figure 30 makes it appear attractive for mobile use until the problems of containment are considered. This is a problem that hydrogen shares with other gaseous fuels. The effect of including the container is shown in Figure 32 (28, 29). The equivalent either mass or volume of a variety of alternative fuels are compared with those required for an equivalent amount of energy in the form of gasoline. The gaseous fuels are at a serious disadvantage.



BASIS: ENERGY EQUIVALENT OF
75 L (20 GAL.) GASOLINE (2.4 GJ)

FUEL	FUEL ALONE		FUEL + CONTAINER	
	MASS, KG	VOLUME, L	MASS, KG	VOLUME, L
Gasoline (Typical)	54	75	61	79
Hydrogen, Gas*	20	1150	1020	1870
Liquid	20	289	160	289
as MgH_2	262	187	314	306
Ammonia, Liquid	129	203	206	380
Coal Powder	94	70	105	75
Methane, Gas*	48	351	227	782
Liquid	48	115	109	456
Acetylene, Dissolved in Acetone	54	400	362	416
Carbide-Water Reaction	200	125		
Methanol	120	149	130	161
Ethanol	88	112	97	119
Propane, Liquid	52	102	104	128

*At 20 MPa (3000 psi)

Figure 32. Vehicular Storage Requirements of Fuels (28, 29).

CHAPTER III

ENGINE-FUEL COMPATIBILITY

POWER PLANTS ALTERNATIVE

Remote Combustion

Figure 39 is an attempt to classify automotive powerplants in a manner related to their ability to operate with different fuels. In the upper left are remote combustion systems which utilize stationary facilities for converting primary energy resources into electrical, thermal, or mechanical energy. Stationary powerplants may be fueled with coal or nuclear energy without the need for conversion to liquid intermediates, unless this step is needed for environmental reasons. The output from central power stations is generally electricity, but it could also be in the form of thermal or mechanical energy. The potential vehicle on-board storage schemes associated with central power stations have been discussed.

On-Board Combustion

On-board heat engines have been divided into internal and external combustion engines. Internal combustion engines, with the exception of the gas turbine, employ intermittent combustion. These engines have the most restrictive fuel requirements. The compression ignition engines, for example, require a minimum cetane number fuel for satisfactory

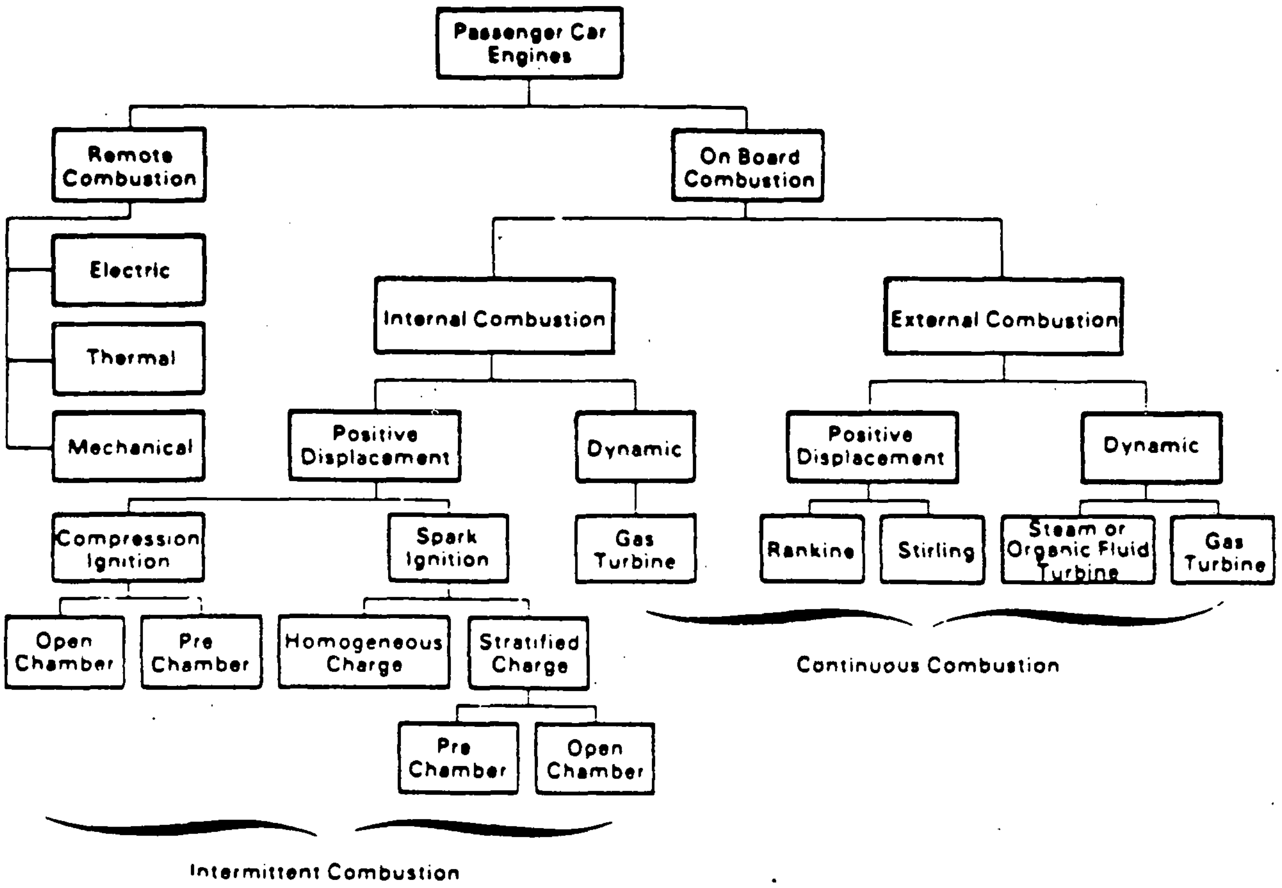


Figure 39. Classification of Automotive Engines.

operation. Most spark ignition engines have an octane requirement which limits the range of fuels that they can use. An exception in this class of engines are some stratified charge engines which do not use a preformed mixture, but rather inject the fuel into the chamber at the same time it is ignited. Such engines, typified by the Texaco TCCS engine, can operate with a relatively wide range of liquid fuels.

The gas turbine and the external combustion engines employ continuous combustion. Although a clean liquid fuel is required for the internal combustion gas turbine, almost any heat source which is reasonably controllable can be employed with the external combustion engines. These engines can in principle utilize stored thermal energy. Some engines, such as the Rankine and steam or organic fluid turbines can be operated from boilers fueled with solid fuel. The Stirling engine has also demonstrated the capability of operating with solid fuel when a heat pipe is interposed between the heat source and the engine.

The use of less refined fuels in combination with external combustion engines may be an attractive possibility from the standpoints of cost and overall energy efficiency. Such combinations may not be viable however, because of exhaust emission problems. For example, less refined coal liquids are likely to be high in both nitrogen and sulfur compared to our present automotive fuels. This could result in high nitrogen oxide and sulfur oxide emissions, unless some exhaust or combustion control scheme can be devised to reduce their levels.

GM EXPERIENCE WITH ALTERNATIVE FUELS

From the very beginning of the automotive industry, there has been a continuous effort to better understand the combustion process. This motivation has prompted many experiments with a wide range of liquid and gaseous fuels. As contrasted with conventional gasoline and diesel fuels, many of these experimental fuels were single organic or inorganic compounds. In more recent years, the prospect of ultimate depletion of petroleum resources as well as considerations of atmospheric emissions have prompted an examination of some of these same fuels and others as potential future fuels. The following will briefly describe some of this work.

Hydrogen

Hydrogen (H_2) has the highest energy content per unit mass of any of the fuels. It is responsible for a large fraction of the energy produced by the combustion of nearly all liquid and gaseous fuels where it may be combined with carbon, nitrogen, and perhaps oxygen.

Hydrogen is not a primary energy resource, but it can be produced by chemical reaction utilizing energy from either coal or nuclear sources. Its first documented use in GM was in late 1930 in a study of knock (38). Over the years it has subsequently been employed in additional experiments on engine combustion including investigations of gaseous exhaust emissions.

In recent years pure hydrogen has been employed in single-cylinder engine tests and hydrogen has been used to supplement conventional gasoline-air mixtures in both engine and vehicle experiments (39, 40).

Hydrogen-air mixtures burn with a very high flame speed and over wide air-fuel ratio ranges. These characteristics are desirable for efficiency and lean operation reasons, but maximum power mixtures exhibit very high rates of pressure rise and flame propagation back through the intake system. The ability to burn very lean improves efficiency at part load due to reduced throttling losses and lower peak combustion temperatures. Pure hydrogen eliminates hydrocarbon emissions except from crankcase oil burning. During very lean operation NO_x is very low because of low combustion temperatures. However, if power is increased by burning richer mixtures, NO_x can rise to levels higher than those observed with gasoline-air mixtures as shown in Figure 40.

When used as a supplement to gasoline-air mixtures, NO_x reductions and fuel economy improvements can be achieved, but because of flame quenching near the combustion chamber walls, hydrocarbon emissions are very high near the lean limit.

The most significant deterrent to use of hydrogen for vehicular energy is the on-board storage problem. Storage as a metal hydride appears to be the most feasible method at this time (41).

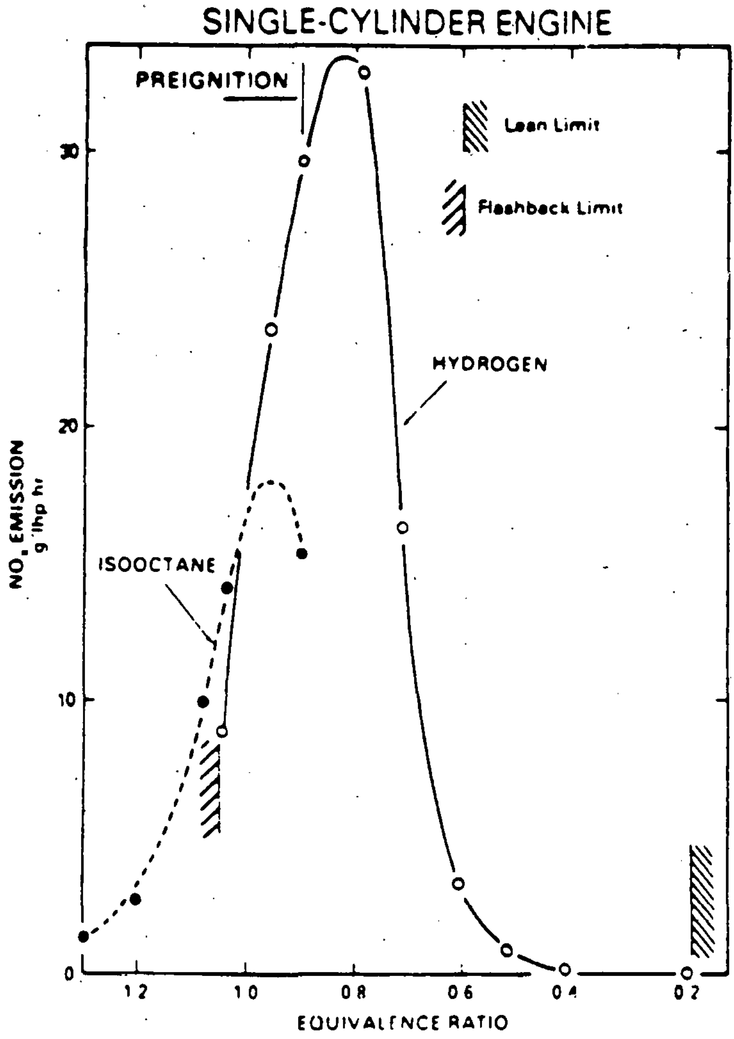


Figure 40. NOx Emissions From Hydrogen and Isooctane Combustion (39).

If, in fact, hydrogen does become available as a fuel, it will also be necessary to assess whether it should be burned in a heat engine, or whether developments in fuel cell technology make that approach more attractive. Unlike the heat engine, fuel cells do not have a Carnot efficiency limitation and, therefore, higher conversion efficiency may be achieved.

Methane

Methane (CH_4) is one of the gaseous fuels which could be produced from coal. Natural gas, which is composed primarily of methane, was used by GMR as a spark ignition engine fuel as early as 1923 to study distribution of fuel in the intake manifold. Its combustion characteristics were studied intensively in 1950. Automotive engines have been run on natural gas for many years in pumping applications. GM had extensive experience with a large natural gas engine developed by Cleveland Diesel. The engine was coupled to a generator for producing electricity for aluminum reduction. These experiences confirmed the high octane number and wide flammability range of methane, both of which can contribute to good efficiency. Although methane has an energy density even greater than gasoline on a mass basis, like other gaseous fuels it suffers from the problems of on-board storage and, as shown in Figure 41, limited power output which seriously limits its automotive applications (42).

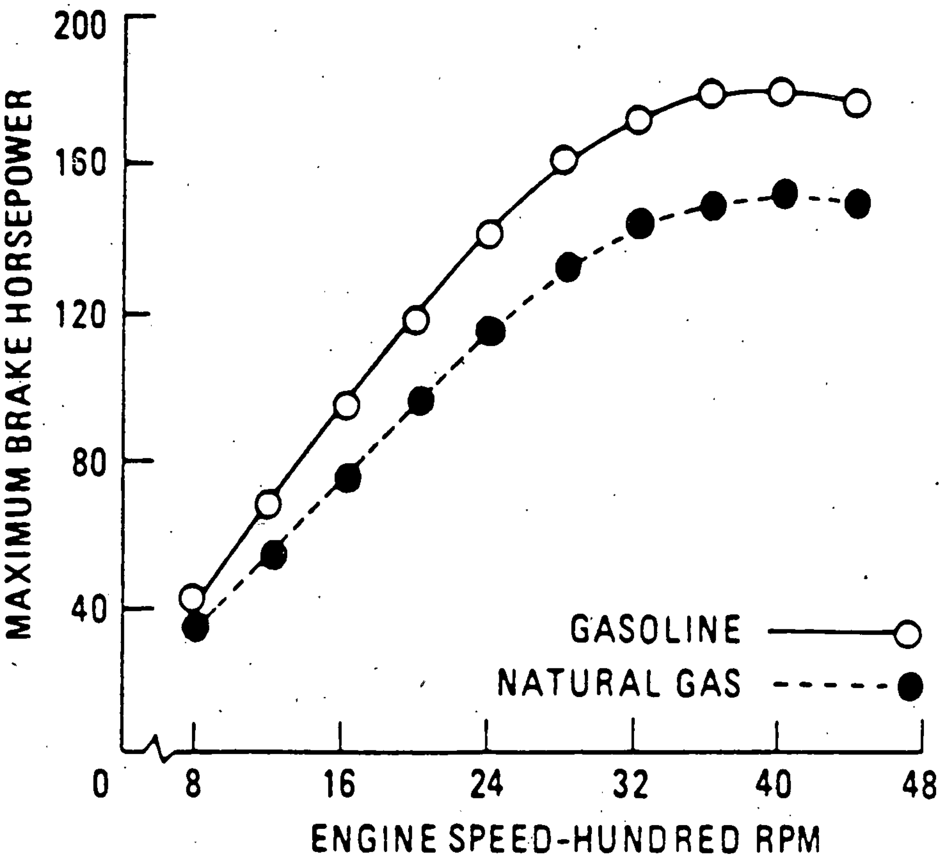


Figure 41. Maximum Brake Horsepower as a Function of Engine Speed for Natural Gas and Gasoline (42).

Carbon Monoxide

Carbon monoxide (CO), unlike the other fuels considered here, contains no hydrogen. Pure carbon monoxide was used in engine combustion studies around 1930 (43). Carbon monoxide is a principal constituent of the low BTU gas which is available from some coal gasification processes similar to those used many years ago to produce city gas. There are records of a Chevrolet engine having been operated on such a fuel as early as 1922. More recently, in connection with studies of hydrogen-supplemented systems, a single-cylinder engine has been run on the products from a catalytic reformer (44). These products contained a large amount of carbon monoxide. In these tests it was observed that the engine carbon monoxide emissions were very high as a result of carbon monoxide contained in the quench layer. Results are shown in Figure 42.

Aside from the potential for producing carbon monoxide readily from coal, it has no other attributes to recommend it as an automotive fuel. The energy density on a mass basis is less than one-quarter that of gasoline, it has low specific energy per unit volume, it has similar storage problems as other gaseous fuels, and it is extremely toxic.

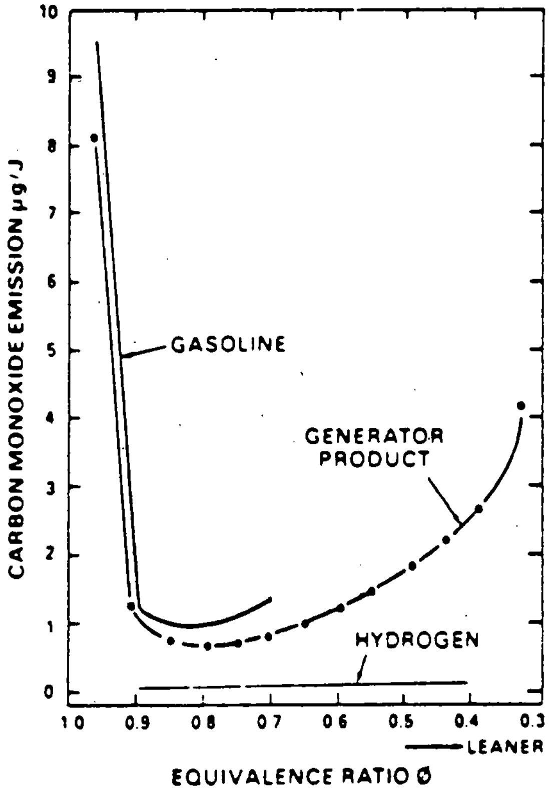


Figure 42. Exhaust Carbon Monoxide Emission With Simulated Hydrogen Generator Product As Fuel (44).

Propane

Propane (C_3H_8) is the principal constituent of LPG (liquefied petroleum gas), which has been used fairly extensively in automotive engines. The applications have been principally in fleets where the necessary refueling provisions can be made. Much of the General Motors interest in propane has been related to engine exhaust emissions. In addition to a number of single-cylinder engine experiments (45-47) and studies with bus fleets (48, 49) fueled with propane, Oldsmobile Division developed a propane conversion in the late 1960's (42). With proper manifold distribution, engines fueled with propane can run considerably leaner than with gasoline and retain good driveability. The extended lean limit results in low CO and NO_x emissions, although hydrocarbon emissions are similar to those with liquid fuels. Propane has a high octane number and its energy density on a mass basis is about the same as gasoline. Unlike other gaseous fuels, propane can be liquefied at modest pressures and normal ambient temperatures. As a result, the on-board storage problem is significantly less severe than for other gaseous fuels.

Other Hydrocarbons

A large number of pure hydrocarbons have been investigated as spark ignition engine fuels. A study of knocking behavior conducted at the Research Laboratories beginning in the 1920's involved more than 100 hydrocarbons (50). A number of these hydrocarbons, including isooctane, benzene, ethane, ethylene, diisobutylene, cyclopentane, and heptane have been used for a variety of combustion and emission studies (38, 43, 46, 51-55).

During World War II General Motors built a pilot plant and produced triptane, a very high octane fuel, proposed for aircraft engine use (56). This is the only GM venture into fuel production. Since production of any of these pure hydrocarbons from alternative primary energy resources involves considerably more processing than the production of mixtures similar to gasoline and diesel fuel, there is little interest in their general use.

Acetylene

Acetylene (C_2H_2) is a gaseous fuel that has not been mentioned previously. It can be produced from a reaction between calcium carbide and water. The calcium carbide can be obtained as the product of a reaction between carbon from coal and some naturally occurring calcium compound. Single-cylinder engine tests conducted recently (57) indicate that spark ignition engines can be made to run over a narrow range of very lean air-fuel ratios with relatively high flame speeds. Acetylene has a very low octane number which limits the compression ratio at which it can be burned. Figure 43 illustrates these air-fuel and compression ratio problems. In addition, acetylene is unstable and it is difficult to store in gaseous form. Vehicular use would only be feasible if the acetylene could be generated by the water-calcium carbide reaction on board.

Ammonia

GMR's first interest in ammonia (NH_3) as an engine fuel was in connection with a military application, the Energy Depot, proposed by the Allison Division in the early 1960's (58). The idea utilized a transportable nuclear reactor to produce fuel for military ground vehicles close to the point at which it was to be used. Unlike most of the other fuels, ammonia contains no carbon, but rather combines hydrogen with nitrogen. It is possible to produce ammonia without any fossil fuel if nuclear energy is available.

The Research Laboratories conducted experiments using ammonia to fuel both single-cylinder and multicylinder engines (59). As a result of its very slow flame speed and low heating value, poor combustion and a power

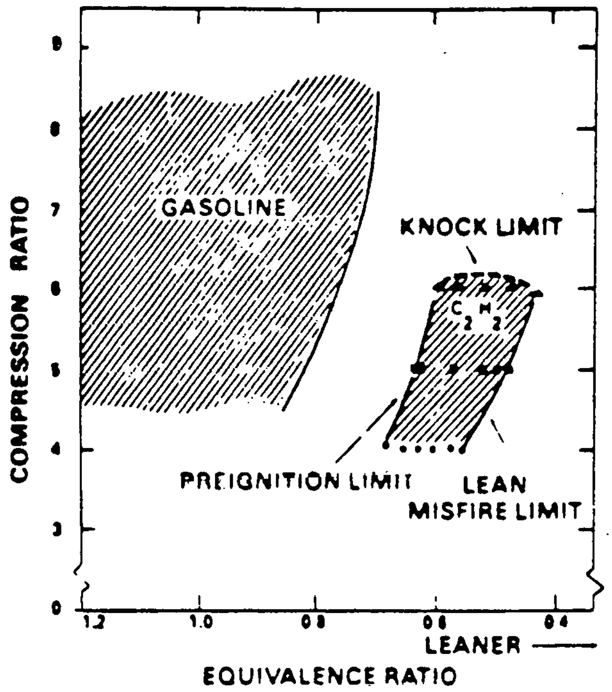


Figure 43. Acetylene and Gasoline Operating Ranges (57).

output only about one-quarter that of the gasoline engine resulted. Increased compression ratio, supercharging and the addition of supplemental hydrogen significantly improved both combustion and power output as shown in Figure 44. Ammonia has a high octane number. No CO

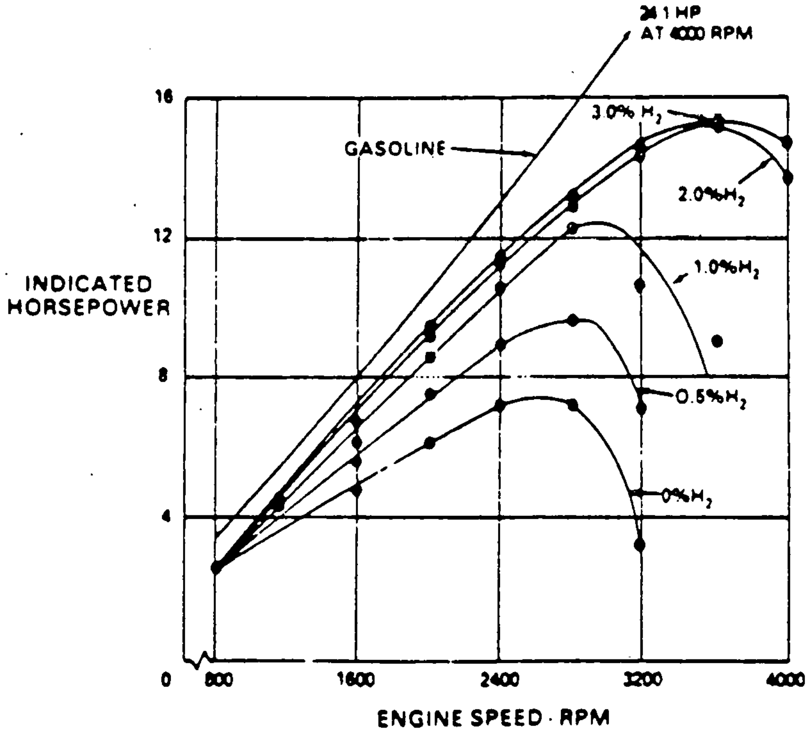


Figure 44. Effect of Hydrogen Addition On Performance Ammonia-Fueled Single-Cylinder Engine (59)

and hydrocarbon emissions are produced, but poor combustion efficiency results in high levels of ammonia emission. Ammonia has a low energy density and handling problems which make it unattractive for automotive applications.

Hydrazine

Another hydronitrogen compound, hydrazine (H_2N_2) has also been proposed as an automotive fuel. While hydrazine has had fairly extensive use as a rocket fuel, its use as a spark ignition engine fuel is extremely limited. In 1974, GMR contracted with the Rocket Research Corporation for an analytical study of hydronitrogen fuels. Some preliminary tests with a small single-cylinder engine were conducted by Rocket Research using hydrazine and hydrazine-water mixtures (60). Hydrazine, like ammonia, has the desirable characteristic of being producible without any fossil fuel resource. However, it is toxic and corrosive, and a number of serious questions remain with respect to handling it. Extensive engine experiments would be required to establish its performance characteristics.

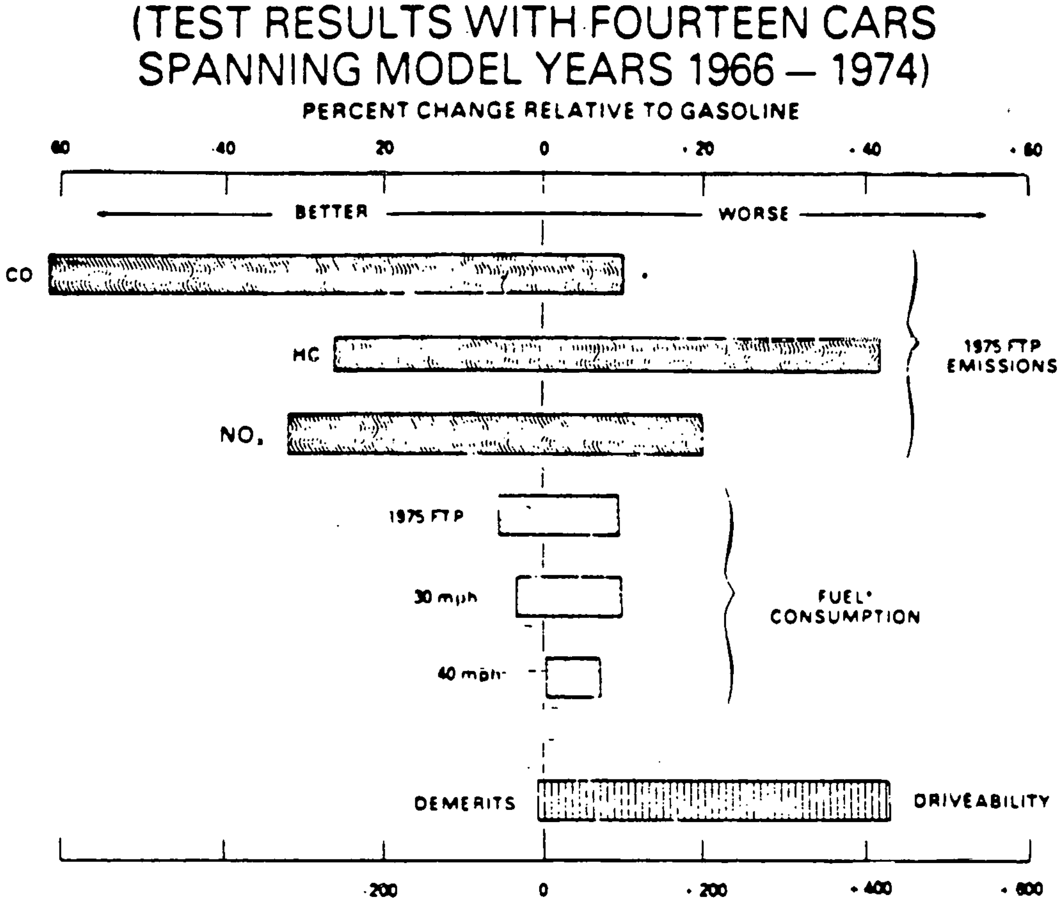
Ethanol

Motivated by the desire to find new markets for farm produce, the use of ethanol (C_2H_5OH) as an additive for gasoline has been frequently proposed since the early days of the automobile. Both ethanol and methanol were employed in combustion studies in 1930 and 1931 (43), and a few years later a fleet test was conducted with 10 percent ethanol added to gasoline. This fleet test uncovered some minor problems, but in general confirmed the technical feasibility of such mixtures. Ethanol, produced from surplus sugar cane, is currently used in Brazil in concentrations up to 25 percent of the ethanol-gasoline mixture. Because of the lower heating value of ethanol (about 66 percent that of gasoline on a volumetric basis), significant changes in stoichiometry occur with these large ethanol additions. Unless changes are made to carburetor calibration, serious deterioration in driveability occurs. Significant emission changes, depending on the initial carburetor calibration, also result from substitution of the mixture for gasoline (61).

Relatively little work has been reported utilizing ethanol alone as a motor fuel. It would be expected that its performance characteristics would not differ much from those of methanol, although cold-starting problems might be aggravated by ethanol's lower vapor pressure.

Methanol

Methanol (CH_3OH) has probably received more attention in recent years than any other alternative fuel. As with ethanol, much of the emphasis has been on blends of methanol and gasoline. Extensive tests of 10 percent methanol-gasoline blends have been carried out in vehicles (62). The volumetric heating value of methanol is only about one-half that of gasoline so that the changes in stoichiometry are even more significant than with ethanol. Without carburetor recalibration, some recent production cars suffer serious depreciation in driveability with 10 percent methanol additions. At equivalent stoichiometry, performance and emissions are similar to gasoline-fueled vehicles. Typical results are shown in Figure 45.



*Volumetric

Figure 45. Comparison of 10% Methanol-Gasoline Blend with Gasoline (62).

In order to assure uniform fuel properties from tank to tank and avoid depreciation of past model performance, it would be desirable to utilize neat methanol in vehicles designed to use it, rather than methanol-gasoline mixtures in vehicles designed for gasoline. Dynamometer and vehicle tests of neat methanol have uncovered a number of problems, most of which seem soluble with some engineering effort (63-65). Starting and warm-up have generally been poor because of methanol's low vapor pressure and high heat of vaporization. These characteristics can also cause poor air-fuel mixture distribution. While these problems have not been completely solved, a good deal of progress has been made by induction system development. Typical emissions, driveability, and fuel economy results with a fuel injection car are shown in Figure 46. Note that with spark retardation the NO_x and CO emissions are close to the original Clean Air Act standards (0.41 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x). The potential for producing methanol from either coal or biomass, combined with its high octane number, its low NO_x emissions, and its ease of handling, make it an attractive motor fuel.

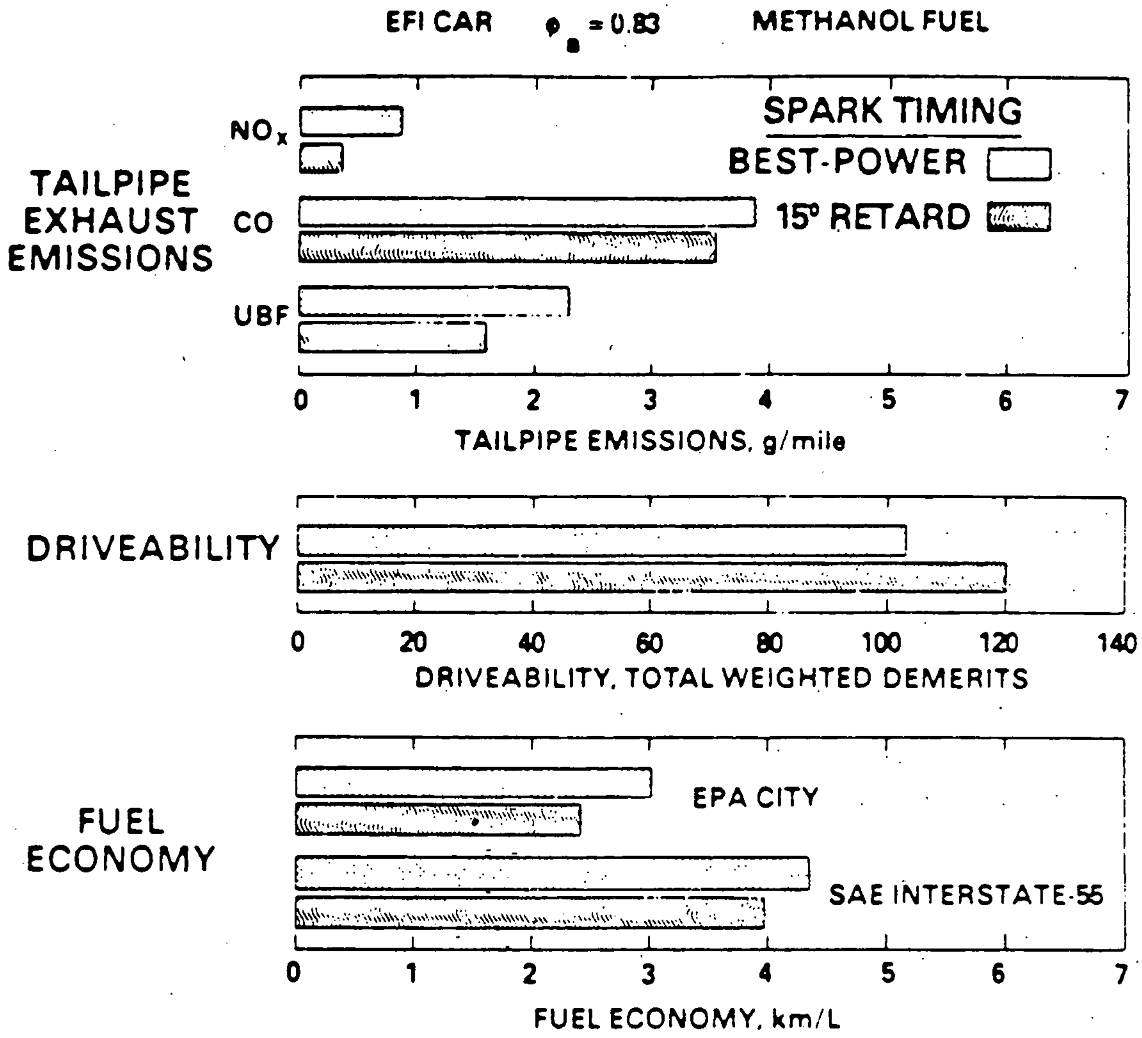


Figure 46. Emissions, Driveability and Fuel Economy of Methanol-Fueled Car Equipped With Fuel Injection (65).

Less Refined Liquid Fuels

High compression ratio, large, compression ignition engines appear to be very fuel tolerant and can be run on a wide range of fuels. During the period 1953 to 1961 GM carried on an extensive free piston engine program (66-68). Engines of this type were run on a variety of fuels ranging from vegetable oils to crude oil and residual fuels. Although we installed an engine of this type in an experimental vehicle (Figure 47), it is not well suited to automotive applications.

GM's interest in automotive gas turbines dates from about 1949, although work on high temperature alloys was initiated some time earlier. The first engine, a nonregenerative design, was installed in a transit coach. A series of more sophisticated engines, incorporating regeneration and other techniques to improve part-load fuel economy, has been constructed over the intervening years and installed in a variety of trucks, coaches, military vehicles, and experimental passenger cars. Figure 48 shows such an installation.

CONCLUSION CHAPTER III

With respect to GM's alternative fuel experience:

1. GM has wide experience with a large number of gaseous and liquid fuels in spark ignition, compression ignition, Rankine, stratified charge, Stirling and gas turbine engines. For heat engines similar to those currently employed, gasoline and diesel-like fuels are most desirable. Less refined could be used in continuous combustion engines, such as the gas turbine, or in external combustion engines, but high levels of nitrogen oxide and sulfur oxide emissions might result.

With respect to transition:

1. If synthetic gasoline and diesel fuel replace their petroleum derived counterparts, transition is greatly simplified. If an unconventional fuel such as an alcohol appears more attractive, its introduction would be facilitated by the gradual introduction of vehicles designed for its use, preferably in fleet operation.

2. At the present time, economic incentives do not exist for the production of synthetic fuels. Recognizing the federal government's reliance on regulation, it is likely that at least the initial development of alternative automotive fuels will be carried out through government supported development programs and possible subsidy of the fuel products.

CHAPTER IV
ALCOHOL FUELS AND GASOLINE BLENDS

Foreword

In order to commercialize any alternative fuel that might replace or extend the supply of petroleum, it is essential to achieve an extremely high degree of reliability. This requires solutions to many real and potential problems. Problems in use of alcohol fuels may be addressed by modifying the fuel composition, the mechanical system or a combination thereof. The work reported herein deals with the former. It was aimed at alcohols as a class, with emphasis on methanol as a 'worst case' situation. Ethanol is specifically addressed only where it is anticipated that the actions or reactions might not fit within the bounds of the effort.

This project is continuing with activity focused on ethanol, straight and blended with gasoline. In essence, specific data on ethanol will be derived of a nature similar to that reported herein for methanol. In addition, a combination of ethanol and methanol will also be addressed.

HCP/W3683-18

FINAL REPORT
U.S. Department of Energy
Assistant Secretary for Conservation and
Solar Applications
Division of Transportation Energy Conservation
Washington, D.C. 20545

July 1978

ABSTRACT

A number of problems that might occur if methanol were used as a blending stock or replacement for gasoline in present cars are identified and characterized as to the probability of their occurring and the severity of their consequences. Possibilities for correcting several problems are reported. Some problems are responsive to fuel modification but others require or are better dealt with by modification of vehicles and the bulk fuel distribution system. Phase separation on exposure to water and increased tendency to vapor lock, two major problems with blends, can both be alleviated by incorporation of cosolvent higher alcohols, ones which can be produced with methanol when it is manufactured from synthesis gas. Fuels consisting mostly of methanol require some modification of gasoline engines if the engines are to operate. If such modifications were made, starting cars at low temperatures would still be a problem. Startability can be provided by adding gasoline or light hydrocarbons; these increase the susceptibility of the fuel to vapor lock but not beyond tolerable limits. Addition of gasoline also alleviates other problems related to toxicity and safety hazards. Still other problems of both blends and methanol-rich fuels can be treated with selected additives. Some observations have been made on differences between methanol and ethanol in gasoline blends. An extension of the work is planned to study problems and corrective measures with ethanol-containing fuels.

METHANOL IN MOTOR GASOLINE - IMPACT ON OIL REFINING

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ABSTRACT

The effects on oil refinery operations of blending methanol into motor gasoline are considered in hydroskimming and catalytic cracking refineries. When methanol is included a greater production of gasoline is possible, with significant improvements in quality. Alternatively, with constant gasoline production, crude consumption is reduced. Catalytic reformer throughput and operating severity are reduced. Some reformulation is necessary, mainly to overcome the increase in volatility. RON and $\text{RON}_{100^\circ\text{C}}$ are increased whilst benzene content and MON are decreased. Although the methanol blends considered meet the normal quality specifications, it should be noted that no account has been taken of the problems of water tolerance, increased fuel consumption and changes of specification which may be necessary to ensure adequate road performance. Economics are not considered.

A. Introduction

In view of the interest being shown currently in introducing methanol and higher alcohols into motor gasoline, studies have been made to assess the impact of such components on gasoline composition and quality and on the operation of the oil refinery. The incentive to use alcohols, whether economic or logistic, is not considered.

B. Hydroskimming Refineries

The first study, prepared for Svensk Metanolutveckling AB, considered a number of basically hydroskimming refineries (catalytic reformate as the major high octane component) with a proportion of steam cracker gasoline returned from a chemicals complex. For simplicity they were considered as one refinery.

Three cases are presented in Table 1:

(1) Base case without alcohol, 0.15 g Pb/l lead content.

(2) Gasolines with 16 per cent methanol 4 per cent isobutanol and 0.15 g Pb/l lead content. (For simplicity the alcohol mixture is referred to as methanol throughout the paper).

(3) As (2) but with zero lead content.

1. Without Methanol - Lead 0.15 g Pb/l

The base case shows the typical problem for the hydroskimming refinery with only 0.15 g Pb/l lead allowed, that is a deficiency of low boiling high octane components, resulting in inability to produce gasoline of adequate $RON_{100^{\circ}C}$ (Research Octane Number of the fraction of the gasoline boiling below 100°C). With too low a value for $RON_{100^{\circ}C}$, low speed acceleration knock occurs in the engine. (Further details of the effects of lead reduction on gasoline composition and quality may be found in references 1 and 2.)

With the plant available, it is not possible to meet all product requirements. The deficits, including the 628 000 t/a of premium gasoline, would be met by imports.

Figure 1 shows that in the premium gasoline of Case 1 the distribution of octane number through the boiling range is uneven, largely because of the relatively low octane number of the lower boiling part of the reformate. With higher lead contents the volatile lead alkyl, tetra methyl lead, would have been used to improve $RON_{100^{\circ}C}$, but with the low lead content of this case, reformulation to replace low octane by high octane components boiling below 100°C is required.

To improve the $RON_{100^{\circ}C}$, consideration could be given to the use of more butane, less straight run gasoline and less reformate boiling below 100°C. The quantities of any of these components that can be used may be influenced by their availability or by lack of alternative uses or by quality considerations. Construction of reformate splitters may be advantageous in those refineries not already possessing them: the light straight run gasoline and less reformate boiling below 100°C. The quantities of any of these components that can be used may be influenced by their availability or by lack of alternative uses or by quality considerations. Construction of reformate splitters may be advantageous in those refineries not already possessing them: the light straight run gasoline could then be replaced by light reformate giving an increase in $RON_{100^{\circ}C}$.

Such reformulation must take account of gasoline volatility parameters also. In the blend under consideration, rejection of light straight run gasoline would reduce the "$D+L_{100^{\circ}C}$" (distillate plus loss to 100°C) giving poorer engine warm up characteristics.

Inclusion of more butane would increase the RVP (Reid Vapour Pressure) which could lead to vapour lock or carburettor icing.

An increase in catalytic reforming severity (reformate RON) would improve $RON_{100^{\circ}C}$ but would also wastefully increase the RON of the total gasoline above that required. Increase of reforming severity has financial and energy conservation repercussions. The yield of reformate is decreased and conversely that of gas increased and, for a given quantity of reformate, more feedstock is required. This may require that more crude oil is processed resulting in surpluses of other products for which there is no demand. More process fuel will be used. The throughput of a catalytic reformer is lower at higher severity, and some older units are limited to relatively low severity and could not produce the 95 - 100 RON reformate required at 0.15 g Pb/l lead.

The problems could be overcome, at a cost, by the building of new process units for the production of low boiling high octane components such as isomerisate and isopentane. The use of methanol may, however, provide a more economical or logistically attractive solution, provided that problems of reaction with water, poorer road performance and fuel economy can be reduced to acceptable levels (3,4).

2. Use of Methanol - Lead 0.15 g Pb/l

In Case 2, 20 percent weight of methanol is included in the motor gasoline. This enables the full requirement of premium motor gasoline to be met, avoiding the import of 628 000 t/a in Case 1. Figure 2 shows the composition and quality of the premium grade.

The more important changes from Case 1 are:

(a) Catalytic reforming severity is reduced from 100 RON to 92 RON for premium grade (Figs 1 and 2) and from 90 to 85 RON for regular, giving advantages of increased reformate percentage yield and reduced process fuel consumption.

(b) Catalytic reformer throughput is reduced. (Table 1)

(c) Butane and light straight run gasoline are displaced (Figs 1 and 2) and, in regular gasoline, straight run naphtha is introduced in order to compensate for the high volatility of methanol.

(d) The steam cracker gasoline is displaced from premium to regular grade, reducing the reformate content of the latter.

(e) In premium grade RON is higher and MON is reduced to the minimum requirement. (Table 1 and figures 1 and 2)

(f) RON_{100^oC} is increased, and now exceeds the minimum. (Table 1 and figures 1 and 2)

(g) Benzene content is reduced in both grades.

It is emphasised that the blend qualities in this case were assessed against the normal specification limits for RON, MON, $D+L_{100^oC}$ etc. Difficulties have been experienced in some cars using gasolines with relatively high concentrations of methanol eg with respect to cold start, warm up and hot fuel handling characteristics, although the fuels met specification requirements. Poorer fuel consumption has also been noted. It may be necessary to amend gasoline specifications in order to obtain a product of equivalent road performance.

3. Methanol in Unleaded Gasoline

With the plant available it was found impossible to make premium grade to the required quality without methanol and no case is presented. Case 3 shows that with methanol, 93 per cent of the premium gasoline and all of the regular grade can be made, meeting all of the quality criteria.

The effects of lead reduction with methanol present are shown by comparison of Case 3 with Case 2. In order to meet the MON minimum requirement, it is necessary to use a higher reforming severity than in Case 2. In consequence the RON and RON_{100^oC} are higher despite the absence of lead. Benzene contents are higher than in Case 2 but still lower than in Case 1.

4. Supply/Marketing Considerations

At 0.15 g Pb/l, by importing an extra 26 000 t/a of crude oil and providing 800 000 t/a of methanol, the 628 000 t/a deficit of premium grade has been made good and chemicals feedstock production has been increased, thus reducing import requirements. The crude slate change includes some replacement of North Sea crude by Iranian Light with a cost saving. Decreases in gas oil and fuel oil occur, but these are much smaller than the increase in the lighter products.

With unleaded gasoline, methanol has permitted an impossible problem of blending premium grade from the components available, to be overcome almost entirely. The alternatives, without methanol, would be to invest in plant to produce low boiling high octane components, import components or reduce quality.

Figure 1:
Premium gasoline without methanol

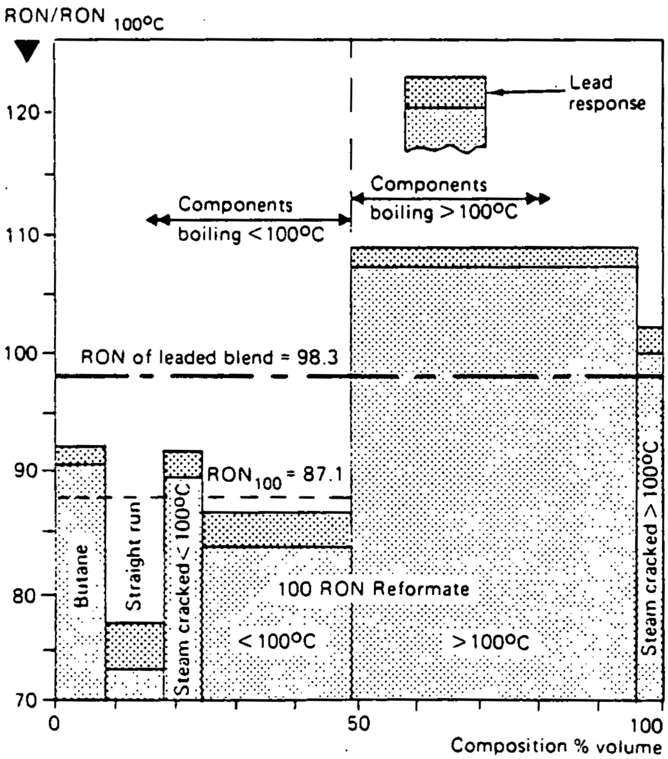
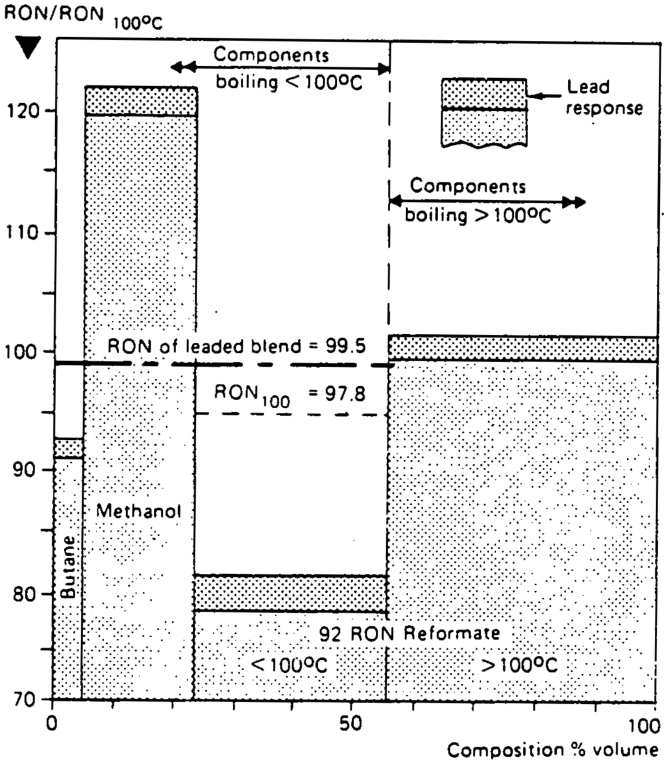


Figure 2:
Premium gasoline with methanol



Note: for the purpose of illustration, reformate and steam cracker gasoline are shown in two parts, as < 100°C and > 100°C. In practice they are not separate.

C. Other Refineries - Catalytic Cracking

The conclusions above are dependent on the particular crude/product/plant configuration. Had there been spare crude capacity, more crude would have been run to reduce imports. The reformer throughput saving might appear to be of no significance since there is spare capacity in the base case, but in another situation, with the capacity fully utilised, the use of methanol could be an alternative to building more catalytic reforming. However, these cases show the broad principles of methanol allowing decreased reforming severity and throughput and/or gasoline and chemicals feedstock production increases, together with improvement in RON$_{100^\circ C}$. The benzene content reduction could be of importance in cases with high availability of high benzene content components and low benzene limitations. Whilst the MON decrease was acceptable in this instance, it might not be in other markets and further reformulation would need to be considered.

A limited study of the inclusion of methanol in gasoline from a refinery with both catalytic reforming and catalytic cracking has also been made. The results are given in Table 2.

In the base case without methanol, Case 4, it is not possible to make the full requirement of gasoline from the components available and the balance of 256 000 t/a of premium grade would need to be imported. The premium grade quality is below requirement for RON and RON$_{100^\circ C}$

Case 5 shows the inclusion of sufficient methanol (12.4 per cent volume) to avoid gasoline import and to meet the quality requirements. RON$_{100^\circ C}$ is increased by four numbers, MON is reduced to the minimum and D-L$_{100^\circ C}$ is increased to the maximum. These changes all reflect the characteristics of methanol. The gasolines are not merely the originals with added methanol. In order to meet quality requirements reformulation similar to that in Case 2 is necessary. Reforming severity is decreased from 93.5 to 88 RON and throughput reduced. This results in a reduction in the iso-butane available for feed to the alkylation unit and hence to a decrease in alkylate available.

In Case 6 extra gasoline is made by allowing higher concentrations of methanol on the assumption that demand would be higher at a later date. The premium grade contains 13.3 per cent volume methanol and the regular 19.8 per cent volume. Reforming severity is reduced to 86 RON. Once again all quality requirements are met.

Case 7 shows the effect of forcing 20 per cent volume of methanol in both grades, when surpluses of gasoline components are unavoidable.

These cases show many of the changes which occurred in the hydroskimming refineries; reformer throughput and severity reduction, butane contents are reduced, straight run naphtha is required to keep volatility down and in Case 6 light straight run gasoline rejected for the same reason. RON and RON$_{100^\circ C}$ are increased and MON reduced. Benzene has not been estimated as it would not be of significance, although the presence of methanol and reduction of reforming severity would reduce benzene concentration.

D. Conclusions

(1) The inclusion of methanol in motor gasoline can be advantageous technically in situations where an increase in motor gasoline production without building new plant or increasing crude consumption is required, or alternatively with constant production and reduced crude consumption. Economic and logistic factors have not been considered.

(2) Quality, in terms of RON and RON$_{100^\circ C}$, can be improved, MON is decreased and volatility increased necessitating reformulation of the hydrocarbon portion of the gasoline. No account has been taken of the problems of the interactions between water and methanol, poorer road performance and higher fuel consumption.

(3) Catalytic reformer severity and throughput are reduced.

(4) The effects are dependent on the plant available and products required, eg more naphtha for chemicals feedstock may be produced if required.

TABLE 1
METHANOL IN MOTOR GASOLINE
POTENTIAL EFFECT ON HYDROSKIMMING REFINERIES

Case No.			1	2	Change 2-1	3	Change 3-2
Methanol/isobutanol in gasoline	%wt		nil	20	+20	20	
Gasoline lead	g Pb/l		0.15	0.15		nil	-0.15
Input	'000 t/a						
Crude oils:							
North Sea			13 687	13 574	-113	13 776	+202
Iranian Light			7 575	7 714	+139	7 466	-248
Kuwait			1 296	1 296		1 296	
Total crude			22 558	22 584	+26	22 538	-46
Steam cracker gasoline			160	160		160	
Methanol			0	800	+800	770	
Total input			22 718	23 544	+826	23 468	-76
Production	'000 t/a	Required					
Liquefied petroleum gas		100	100	100		100	
Chemicals feedstock (naphtha)		1 800	625	944	+319	891	-53
Premium motor gasoline		2 400	1 772	2 400	+628	2 224	-176
Regular motor gasoline		1 600	1 600	1 600		1 600	
Kerosine		580	580	580		580	
Automotive and heating gas oil		10 000	4 255	4 240	-15	4 266	+26
Fuel oil		20 620	12 050	11 976	-74	12 109	+133
Bitumen		700	700	700		700	
Total products			21 682	22 540	+858	22 470	-70
Refinery fuel and losses			1 036	1 004	-32	998	-6
Total output = input			22 718	23 544	-826	23 468	-76
Process plant capacity	'000 t/a	Available					
Crude oil distillation*		24 800	24 800	24 800		24 800	
Catalytic reforming		4 500	3 173	2 694	-479	2 925	+231
Gas oil desulphurisation			1 904	1 938	+34	1 878	-60
Gasoline quality		Specification					
Premium							
RON		98.3 min	98.3	99.5		101.8	
MON		87.3 min	89.1	87.3		87.3	
RON_{100}		88 min	87.1	97.8		98.5	
$D+L_{100°C}$	%vol	49-62	49	53		53	
RVP	lb	11 max	11	11		11	
Benzene	%vol	-	4.9	3.5		4.2	
Regular							
RON		90.3 min	90.3	90.3		90.3	
$D+L_{100°C}$	%vol	49-62	59	62		62	
RVP	lb	11 max	11	11		11	
Benzene	%vol	-	3.7	1.7		2.7	

* In terms of Kuwait crude, making allowance for lower performance of unit on other crudes

TABLE 2

METHANOL IN GASOLINE - POTENTIAL EFFECT ON CATALYTIC CRACKING/REFORMING REFINERY

CASES 4 AND 5

Case No.				4			5		
				Basic Requirement No Methanol No Surpluses			Basic Requirement Methanol No Surpluses		
				P	R	Total	P	R	Total
Requirements	'000 t/a			1964.5	211.7	2176.2	1964.5	211.7	2176.2
Gasoline composition		**Available**							
Methanol	%vol			0	0	0	12.3	12.4	
	000 t/a			0	0	0	259.3	28.6	287.9
Butane		> 66.9*		83.5	4.2	87.7	30.9	3.4	34.3
Straight run gasoline C_5-80°C		290.7		190.0	100.7	290.7	271.9	18.8	290.7
Straight run naphtha 80-175°C		see below		0	0	0	59.4	63.9	123.3
Reformate		see below		702.5	106.8	809.3	721.0	0	721.0
(RON)				(93.5)	(93.5)	(93.5)	(88)		(88)
Alkylate				132.7	0	132.7	119.4	0	119.4
Catalytic cracker gasoline		599.6		599.6	0	599.6	502.6	97.0	599.6
Total				1708.3	211.7	1910.0	1964.5	211.7	2176.2
80-175°C Naphtha disposal									
Reformer feed						903.1			779.8
Gasoline blending						nil			123.3
Total		903.1				903.1			903.1
Gasoline quality		**Specifications**							
Lead 0.45 g Pb/l. TEL		P	R						
RON		98 min	91 min	97.1	91.0		98.0	91.0	
MON		87 min	-	88.5	-		87.0	79.3	
RON_{100}		88 min	-	85.3	-		89.7	86.5	
D·$L_{100°C}$	%vol	44-57		52	69		57	56	
RVP	lb	11.2 max		9.5	9.0		9.8	9.9	

* 66.9 plus make from reformer which varies between cases

** Tonnage varies - total availability used in all cases

P = premium gasoline

R - regular gasoline

Note: Naphtha disposal: 903, 100 t/a of naphtha available may be used as reformer feed or as a gasoline component as required.

TABLE 3

METHANOL IN GASOLINE - POTENTIAL EFFECT ON CATALYTIC CRACKING/REFORMING REFINERY

CASES 6 AND 7

Case No.			6			7			
			Increased Requirement Methanol No Surpluses			Basic Requirement 20 %vol Methanol Surpluses			
			P	R	Total	P	R	Total	Surplus
Requirements '000 t/a			1995.0	215.0	2210.0	1964.5	211.7	2176.2	
Gasoline composition	**Available**								
Methanol %vol			13.3	19.8		20	20		
000 t/a			265.6	46.2	311.8	417.8	46.0	463.8	-
Butane	> 66.9*		31.4	3.4	34.8	13.8	4.9	18.7	-
Straight run gasoline C5-80°C	290.7		272.7	18.0	290.7	148.0	16.2	164.2	126.5
Straight run naphtha 80-175°C	see below		36.3	81.3	117.6	44.0	82.0	126.0	below
Reformate	see below		739.4	0	739.4	690.3	0	690.3	
(RON)			(86)		(86)	(85)		(85)	
Alkylate			116.1	nil	116.1	113.6	0	113.6	0
Catalytic cracker gasoline	599.6		533.5	66.1	599.6	537.0	62.6	599.6	0
Total			1995.0	215.0	2210.0	1964.5	211.7	2176.2	
80-175°C Naphtha disposal									
Reformer feed					785.5 117.6			726.6 126.0	
Total	903.1				903.1			852.6	50.5
Gasoline quality	**Specifications**								
Lead 0.45 g Pb/1, TEL	P	R							
RON	98 min	91 min	98.0	91.0		100.3	91.0		
MON	87 min	-	87.0	78.6		87.0	78.6		
RON_{100}	88 min	-	89.9	87.9		94.9	88.1		
$\text{D·L}_{100^\circ\text{C}}$ %vol	44-57		57	57		57	57		
RVP lb	11.2 max		9.8	10.6		10.4	11.0		

* 66.9 plus make from reformer which varies between cases

** Tonnage varies - total availability used in all cases

P = premium gasoline

R = regular gasoline

Note: Naphtha disposal: 903, 100 t/a of naphtha available may be used as reformer feed or as a gasoline component as required

Acknowledgement

The author wishes to thank Svensk Metanolutveckling A.B., and the British Petroleum Company for their permission to prepare and present this paper.

Gasoline-Methanol Fuels; Blending Optimisation with Respect to Manufacturing Economics and Engine Performance

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Abstract:

Previous studies have shown that the addition of methanol to current motor gasolines and its use in todays car population could be disadvantageous from fuel manufacturing and handling, and also engine performance points of view, if such fuels are not carefully formulated. A joint Volkswagenwerk-Shell engine/fuels development programme, sponsored partially by the German Federal Ministry of Research and Technology, is at present being carried out to study the whole subject.

Initially premium and regular type blends have been prepared for various European refinery concepts i.e. hydroskimming, conversion and petrochemical. Components which these types of refineries can produce economically have been used to formulate candidate methanol containing fuels. Although these fuels do not meet current gasoline specifications, certain quality aspects such as antiknock performance and composition stability had to be ensured as only slight modifications to the engines, will be possible in the short-term.

Laboratory studies with respect to antiknock performance, composition stability and analytical performance parameters, as well as tests with current and modified cars and their effects on fuel composition are described in this paper.

The results given here and the results from further optimisation programmes will give guidelines for future quality requirements, should the need for widespread addition of methanol to automotive fuels ever arise.

1. Introduction

The traditional role of the oil industry has been to provide fuels and lubricants to meet the needs of transport and industrial machinery worldwide while at the same time supplying chemical feedstocks and bitumen. However, there is a growing awareness that oil will not last for ever, and steps must be taken to conserve energy and use alternatives wherever possible.

It is not possible to predict with certainty the pattern of demand for energy and oil products over the next ten to twenty years.[1] The policies of governments in oil producing and oil consuming countries relating to the rate of crude oil production and prices on the one hand, and energy conservation, environmental conservation and the development of alternative sources of energy on the other, are obvious important influences. Other factors which specifically affect the supply of automotive fuels are the product requirements of other industries such as the chemical industry, the impact of alternative hydrocarbon fuels such as liquified natural gas and changes in the fuel requirements of automotive engines. However, with the growing attention to energy conservation throughout the world it now seems likely that the crude oil supplies will be sufficient to meet the needs of fuels for transportation purposes well into the first half of next century.[2] In the case of West Germany (Fig. 1), for example, the future gasoline consumption is expected to increase at a significantly slower rate than the total oil consumption for this country.[3]

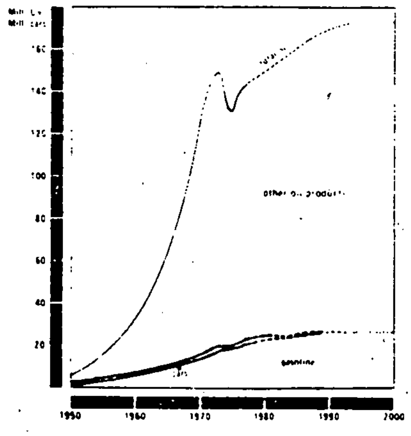
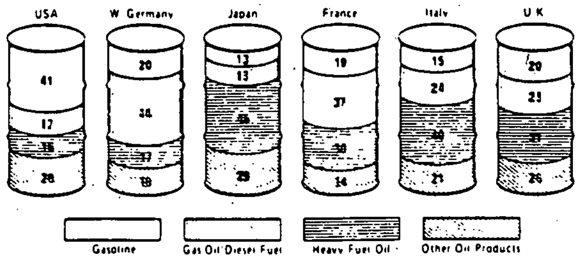


Fig. 1:
Total oil and gasoline consumption and development of car population in West Germany

Furthermore, it is anticipated that during this period, as alternative sources of energy such as coal or nuclear power are used more extensively for base power generation, that there will be a trend towards increasing conversion of heavy fuel oil into lighter materials such as motor gasoline. Fig. 2 illustrates the fact that Europe has, for example in comparison to the U.S.A., so far not exploited the potential in the manufacture of gasoline or gasoline components from a given barrel of crude oil.[4] However, there is also the possible strategic and financial advantage of using unconventional fuels from indigenous sources, such as methanol from coal. This is particularly true if the unconventional fuel can be produced locally. Among other alternatives pure methanol as a liquid fuel could be a rather attractive proposition when conventional crude oil derived fuels are no longer available. In the medium-term the use of methanol as a fuel component (i.e. as a gasoline extender) may be

Fig. 2: Market Profiles of Mineral Oil Products in Various Countries
(% by volume of total consumption)



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*) R. Sagawe, Deutsche Shell AG, PAE-Labor, has contributed to the investigations covered by this paper.

prefered by some governments for the Otto engine which will maintain its leading position in passenger traffic. Moreover, the relative high manufacturing cost of methanol means that it is only likely to be commercially viable in the high price, automotive sector of the market.

If methanol is to be used as a gasoline component, the fuel and the vehicle manufacturers must work together to optimise the blending of the fuel and the design of the engine. Both the manufacturers must make best use of the inherent benefits which methanol offers as a blending component and at the same time reduce the disadvantages associated with the resultant fuel and its use in current engines. To bring a „new product" to the market place the fuel manufacturer has to ensure a high degree of customer satisfaction. With automobile fuels three main areas have to be considered; octane quality, fuel stability, and volatility, i.e. driveability performance. Volkswagen and Deutsche Shell and other companies are therefore studying some of the aspects involved and establish how methanol may be used most economically in an automotive fuel. The work is partly sponsored by the German Federal Ministry of Research and Technology.

2. Objectives and Targets

This paper describes the study of gasoline-methanol blends, where an attempt has been made to optimise such fuels from a production and cost point of view. These fuels do not necessarily have to fulfil current specifications for conventional automotive fuel, but should broadly be suitable for use in gasoline engines. The fuels were used for engine tests to determine the minimum amount of modification needed to make methanol containing fuels acceptable.

In this context we discuss the following work:

- The best usage of the high octane quality of methanol in formulating fuel blends.
- Quantification of the parameters which determine gasoline–methanol stability.
- By combining the results of the two above mentioned studies the preparation of candidate methanol containing fuels from mimimum cost components of three typical refinery concepts.
- Controlled car tests with these fuels and others to investigate volatility related aspects at low and high ambient temperatures and also road antiknock performance.
- Finally, investigations on more meaningful analytical test techniques will be discussed.

The work has concentrated on gasoline components that will be manufactured in existing European refineries in the near term. Three types of refineries have been considered: hydroskimming, conversion and petrochemical concepts (Figure 3). The targets for the methanol containing fuels are given in Figure 4. Octane quality and lead level are in line with present German requirements.

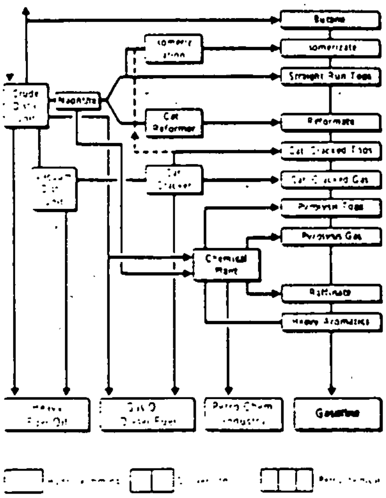


Fig. 3:
Flow scheme for gasoline production in three different refinery types

Fig. 4: Target properties for test fuels

Property	Target
Octane Quality	Premium 98 RON 88 MON min Regular 91 RON, 82 8 MON min
Lead level	0 15 g Pb/l max
Methanol level	15 % by volume
Fuel stability	Homogeneous at – 5°C with a water content of 0 1 %w

The methanol content has been selected at 15 % by volume. There may be a need to include in this 15 % higher molecular weight alcohols in order to provide the fuel with a higher degree of stability against phase separation. The question of production and economics of methanol plus higher molecular weight alcohols (or methyl fuel) on the one hand and the amount of water likely to be present in the storage and distribution system on the other hand are unknown at present. For this reason we have aimed at fuel blends being homogeneous at –5°C while containing up to 0.1 %w of water.

3. Laboratory Studies

As stated before some basic information about the blending properties of methanol in the fields of octane quality and fuel stability were needed before the preparation of candidate fuels for engine testing were possible. As far as possible typical gasoline components that varied widely in hydrocarbon composition have been used in this work.

3.1 Octane Quality

It is known that the octane value of a fuel component, i.e. its „Blending Octane Number" may differ widely from its octane number when it is measured alone [5]. Generally the Blending Octane Number of a component is high when it is used together with low octane quality paraffinic type components and it is low when it is used with aromatic or olefinic based components of high octane quality.

To study the blending octane quality of methanol, various base fuels for the refinery systems under consideration, i.e. hydroskimming, conversion and petrochemical refinery have been prepared. These blends covered a wide range of octane quality and were used leadfree and with a lead concentration of 0 13 g/l. The Research and Motor Octane Numbers (RON and MON) of these base blends were obtained. Methanol, 15 % by volume, was then added and again the RON and MON were obtained. From the increase in Research and Motor Octane Number of the blends the „Blending Octane Numbers" of methanol were calculated (Figure 5).

As expected the results demonstrate the excellent Research Blending Octane Number of methanol varying from 115 to 150 and at the same time the only moderate Motor Blending Octane Number (88 to 120).

Both, Research and Motor Blending Octane Numbers decrease strongly with increasing octane quality of the base blend. Largest Blending Octane Numbers were obtained in reformate type fuels and lowest in cat. cracked type fuels while those calculated from blends based on components from the petrochemical refinery lie in between. It appears that the Blending Octane Number of methanol is higher in leaded gasolines than in the unleaded blends. This can be explained by the use of lower octane grade components in the leaded base gasoline for a given final octane quality.

One further aspect which is worthwhile mentioning is the sharper decrease in Motor Blending Octane Number of methanol with increasing octane level

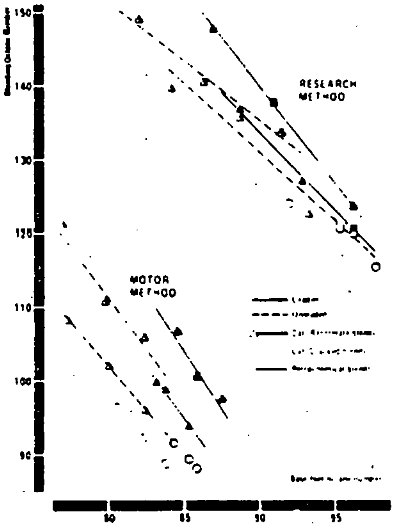


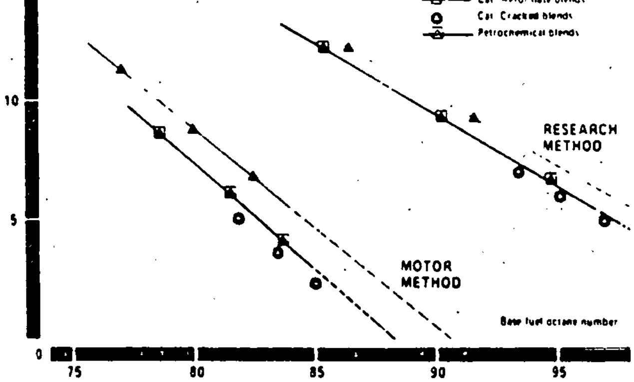
Fig. 5:
Blending Octane Numbers of methanol depending on base fuel octane level

when compared with the Research Blending Octane Number. This phenomenon is causing the increasing sensitivity (RON – MON) of the final gasoline-methanol fuels with increasing octane quality.

The Front End Octane Number RON 100°C, which is used to predict acceleration knock performance was checked for some of the blends. It was found as expected that it was often higher than the RON of the total fuel. As acceleration knock is therefore no problem with methanol containing fuels no further investigations in this direction were necessary.

The actual increase in octane quality by use of lead plus methanol to the three refinery type blends, Figure 6, shows that with the components selected, the Motor Octane Number in the conversion and petrochemical refinery cannot be raised above 88, whereas in the reforming refinery a MON of about 90 would be the upper limit. To ensure the motor octane level of 88, the RON of the blends based on the components from the conversion and petrochemical refinery will increase at the same time to a level of around 102. In this context it should be mentioned that in the future conversion type and petrochemical type refineries will increase in Europe and might even dominate in countries such as Germany.

Fig. 6: Increase in octane number due to the addition of lead (0.13 g/l) plus methanol (15 % v) for various base fuel octane levels



3.2. Fuel Stability

The use of gasoline-methanol blends presents the problem of how to keep the fuel stable against phase separation. Methanol has only a limited solubility in gasoline at low temperatures. The problem is further enhanced in the presence of very small amounts of water which are present due to both the hygroscopic nature of methanol and from adventitious water which is present for example in storage tanks and transfer pipelines. Phase separation may therefore occur in storage tanks (at both distribution and forecourt), vehicle tanks and in carburettor bowls. This could result in either loss of a high octane blending component (methanol) or give rise to a methanol rich phase. A loss of methanol would cause knock problems and an enrichment of methanol would cause driveability problems.

The level of water tolerance necessary for a gasoline-methanol blend to be distributed successfully is unknown; it depends on the type of distribution network and on climatic conditions. Until field trials are carried out to determine the water tolerance in gasoline-methanol blends it is not possible to assess with certainty the level but as Banks[6] has pointed out, it is unlikely to be less than 0.1 per cent and may be in excess of 0.5 per cent.

In order to be able to make a selection of appropriate base fuels we have investigated methanol/hydrocarbon miscibility and the influence that small amounts of water has upon the miscibility. The solubility of methanol in gasoline is influenced by the hydrocarbon composition of the blend. In general it is well known that an increase in aromatic content improves low temperature solubility of methanol and increase in paraffinic content deteriorates the low temperature solubility of methanol. The influence of olefinic material lies somewhere in between the two. High aromaticity, however, is no guarantee of a high degree of low temperature solubility, e.g. discrepancies between the components heavy aromatics and heavy reformate and between cat. cracked naphtha and full range reformate in Figure 7 illustrate this fact. The point is further illustrated in Figure 8 which shows a wide scatter of results when the total aromatic content of methanol/gasoline (15/85) blends (both experimental and marketed gasolines) are compared with their determined phase separation temperatures.

COMPONENT	HYDROCARBON TYPE*, %V			Phase Separation Temperature °C **
	Paraffins	Olefins	Aromatics	
ALKYLATE	100	0	0	> + 20
STRAIGHT RUN TOPS	94	1	5	> + 20
POLYMER GASOLINE	9	82	9	+ 19
RAFFINATE	92	1	7	+ 15
CAT CRACKED NAPHTHA	29	19	52	+ 10
CAT CRACKED TOPS	61	26	13	+ 8
HEAVY AROMATICS	0	2	98	– 6
PYROLYSIS TOPS	35	64	1	– 35
FULL RANGE REFORMATE	44	0	56	– 35
HEAVY REFORMATE	14	1	85	< – 50

* [illegible]

** [illegible]

Fig. 7:
Effect of hydrocarbon type on phase separation temperature in component plus methanol (15 % by volume) blends

High resolution gas liquid chromatographic (GLC) analysis on the aromatic distribution in the gasoline hydrocarbon components and comparisons of the phase separation temperatures in Figure 7 indicated that the low molecular weight aromatic material is most effective in increasing miscibility with methanol containing fuels. By use of a five variable linear regression analysis, equations were developed from which the phase separation temperatures from a knowledge of water content, low molecular weight aromatic content, high molecular weight aromatic content, and olefinic content can be predicted. For individual refinery type blends the equations have an accuracy within ± 2°C between predicted and determined values. The single equation for all three refinery type blends as given below is only accurate to within ± 6°C at a 90 % probability level as illustrated in Figure 9.

Fig. 8: Effect of aromatic concentration on the phase separation temperature of gasoline/methanol blends

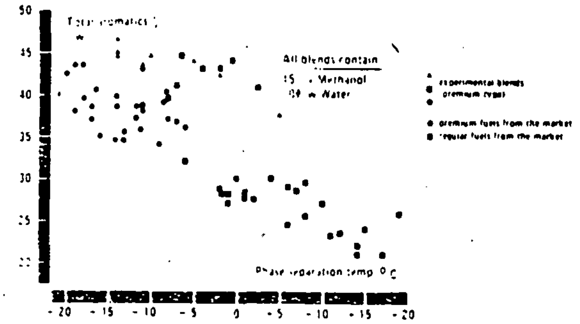
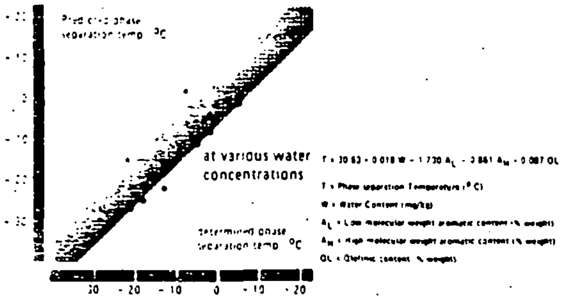


Fig. 9: Correlation between predicted and determined phase separation temperatures



$$T = 30.63 + 0.018\,W - 1.730\,A_L - 0.861\,A_H + 0.087\,OL$$

where T is phase separation temperature, °C
W is water content, mg/kg
A_L is low molecular weight aromatic content, %w
A_H is high molecular weight aromatic content, %w
OL is olefinic content, %w

The correlation could be possibly further improved by splitting the olefinic material in a similar way as the aromatic material was split. Again with reference to Fig. 7 it can be seen that with regard to low temperature solubility that although the components pyrolysis tops and polymerised gasoline have similar olefinic contents, their phase separation temperatures are vastly different. The pyrolysis tops behaves similar to an aromatic component and the polymerised gasoline similar to a paraffinic component.

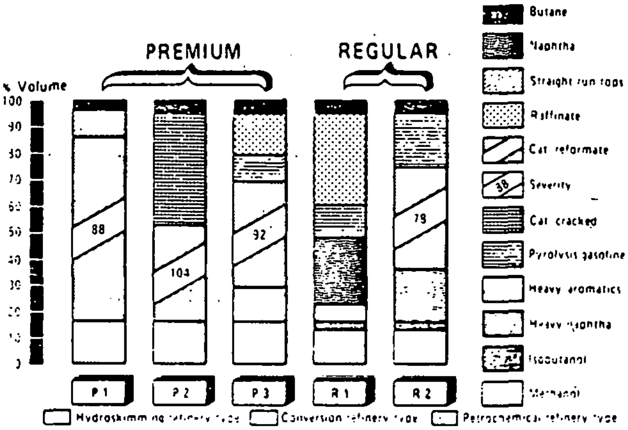
4. Resulting Fuel Blends and Economics

From the studies on octane quality and fuel stability it has been possible to formulate some candidate methanol containing fuels that met our targets.

4.1 Candidate Methanol-containing Fuels

Three premium-type methanol containing fuels and two regular-type alcohol containing fuels were prepared, Fig. 10. It was not possible to prepare economic regular-type fuels containing methanol alone. This is due to the conflict of using low octane quality basestocks which utilize the inherent octane benefits of methanol, but at the same time the low octane quality basestocks, by nature, have very poor low temperature miscibility with methanol and negligible water tolerance because of their low aromatic content. As a result of this the regular-type fuels have been blended with methanol and isobutanol (5.1).

Fig. 10: Optimised fuels for engine tests and development



The octane quality of the fuels is such that all meet the minimum MON specifications. Typical data obtained by conventional automotive inspection tests are summarised in Figure 11. Studies on the low temperature stability and water tolerance of the premium-type fuels, Figure 12, have shown to what extent the phase separation may be shifted to lower temperatures (higher fuel stability) with the part substitution of methanol with isobutanol (5:1 or 2:1 methanol-isobutanol mixtures). With the increased amount of isobutanol the differences in phase separation temperatures between the three blend types diminishes.

Fig. 11: Inspection Data on Experimental Fuels

Test	Unit	DIN Specification		Premium			Regular	
		Premium	Regular	P 1	P 2	P 3	R 1	R 2
Density at 15 °C	g/ml	0.730 to 0.780	0.715 to 0.755	0.747	0.776	0.764	0.749	0.753
Research Octane No.	–	98.0 min.	91.0 min.	98.9	102.4	101.0	91.6	94.0
Motor Octane No.	–	88.0 min	82.8 min.	88.3	88.1	88.0	83.2	83.0
Reid Vapour Pressure	mbar	Winter 600 to 900	Summer 450 to 700	830	840	860	820	990
E 70 °C	%v	20 to 45	15 to 40	58	46	53	46	57
E 100° C	%v	45 to 70	42 to 65	64	47	56	58	66
E 180° C	%v	> 90	> 90	100	93	92	97	78
FBP	°C	< 215	< 215	174	188	215	195	241
Phase separation temp. with 0.1 % w water	°C	–	-	– 8	– 14	– 7	– 7	– 9

An interesting feature from this latter work has emerged as illustrated in Figure 13. The experimental data for the premium-type and regular-type fuels have been plotted in more general terms and the influence on phase separation by isobutanol and water contents can clearly be seen.

4.2. Economics of the Candidate Blends

The experimental fuels have been formulated mainly from gasoline components which are produced commercially at minimum cost. The cost, which can broadly be related to octane quality, is influenced by the amount of octane upgrading process needed. An example of the latter is that by decreasing the severity of the cat reformer to produce lower octane quality reformate results not only in an increase in overall yield but at the same time requires less energy.

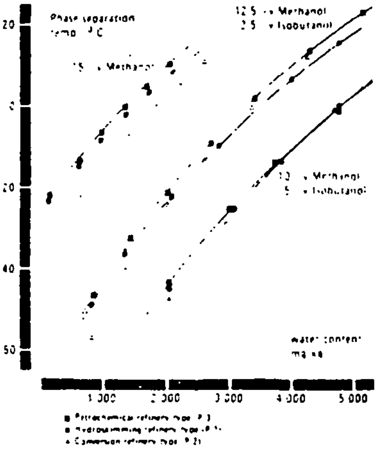


Fig. 12: Influence of isobutanol on phase separation temperature with increasing water content on the premium type fuels

In general the premium-type methanol fuels have been produced from components which are normally used for blending regular grade gasoline using the addition of methanol to improve the octane quality. An indication for the maximum possible cost saving might be the current differential manufacturing costs in Germany between premium and regular gasolines. The situation for a potential cost saving is different with regular gasolines as the price difference to chemical feedstock (naphtha) is only marginal. Virtually no cost advantage can be gained by blending regular-type methanol containing fuels.

The above comments relate only to the cost of components that are produced in current refineries in Germany. The premium and regular candidate methanol containing fuels have to be considered separately, because so far we have not been able to blend an economic premium-type methanol containing fuel and an economic regular-type methanol containing fuel from the single refineries working to the hydroskimming and conversion concept. The critical problem is how to produce economic regular-type fuels from the components available that will meet our fuel stability target e.g. it is necessary to use low molecular weight aromatic-containing components, which are high quality octane components and hence premium priced components and which have to be transported from other refineries. The low cost advantage when blending regular-type fuels which contain methanol would make this concept less attractive than the blending of premium-type fuels. Despite these facts in our studies pyrolysis gasoline component has been used to formulate regular-type fuels. However, as pointed out earlier it was even then necessary to use isobutanol to meet our fuel stability target. This type of blend represents only a small fraction of the total European gasoline output.

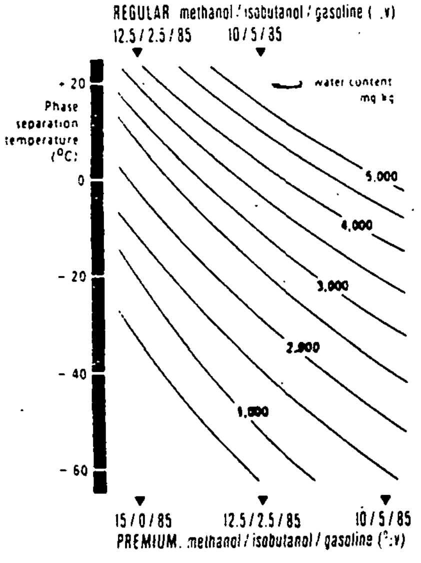


Fig. 13: Effect of substituting isobutanol for methanol on the phase separation temperature for both PREMIUM and REGULAR blends fuels

Two other overall refinery aspects must be considered when discussing economics. The first is that as a result of lowering the severity of the reformer, the refinery may become deficient in hydrogen which is used e.g. in de-sulphurization units. It may be necessary, in this case, to build an extra unit for the manufacture of hydrogen. Secondly, existing refinery facilities e.g. isomerization units, installed to manufacture high cost gasoline components which are necessary to meet current automotive specifications have a life of about 20 years. It has been necessary over the past five years to build such units in German refineries to produce low leaded premium gasolines. To start producing low octane quality base gasoline in the short-term for use with methanol would result in considerable loss of investment on these units.

In respect of economics it can be summarised that in a developing society, where new industrial concepts are set up, the potential octane pool of methanol could be built in beneficially, whereas in an established modernised refinery system, in a highly industrialised area, the benefits are difficult to establish from a manufacturers point of view. This is because of the integrated complex refinery production system.

5. Controlled Car Performance Tests

5.1 Road Antiknock Performance

Methanol containing fuels cause a greater temperature drop in the inlet manifold and in the combustion chamber than conventional gasolines. Consequently this phenomenon reduces the peak temperatures of the combustion cycle and will thus reduce the knocking tendencies of the air-fuel mixture. However this temperature decrease cannot take place in the laboratory CFR knock test engine as the air-fuel mixture, for the more critical Motor Octane Number, is heated to a constant temperature. It has therefore been suggested that the antiknock performance of gasoline-methanol blends in multi-cylinder car engines is better than is shown by the MON of the laboratory CFR engine.

To investigate this we have compared the road antiknock performance of about 24 fuels in two cars under high constant speed conditions. All gasolines had a lead concentration of 0.15 g/l and Research Octane Numbers between 96 and 102 and Motor Octane Numbers between 85 and 91. Half of the fuels were conventional gasolines, while the other half were gasoline blends containing 15 % by volume methanol. The range of RON and MON was nearly identical for the two fuel groups. With the measured Road Octane Numbers (RoON) and the RON and MON of the fuels tested a predicting equation of the following form was derived for each car

$$\text{RoON} = a + b\ \text{RON} + c\ \text{Sensitivity}$$

where RoON = Road Octane Number
RON = Research Octane Number
Sensitivity = Research Octane Number minus Motor Octane Number

To find whether methanol containing fuels performed better than conventional gasolines and better than expected from their RON and MON, the Road Octane Number of all fuels were calculated from the derived equation and the difference between observed RoON and calculated RoON were compared for the two fuel groups. It is shown in Figure 14 that in neither of the two test cars there exists a systematic difference between the conventional and the methanol containing fuels. It is concluded therefore that under constant speed conditions the suggested road antiknock bonus above RON and MON of methanol containing fuels does not exist. It is appreciated that using only two test cars a generalisation is somewhat difficult. It may be necessary, therefore, to validate this conclusion in other car models

5.2. Fuel Performance at Low Ambient Temperatures

It was described earlier that gasoline-methanol fuels may cause engine malfunctions under low temperature cold running conditions because of the larger temperature drop in the inlet system of the engine. Therefore it had to be investigated whether the developed gasoline-methanol blends would ensure acceptably smooth engine operation at cold running conditions. From the

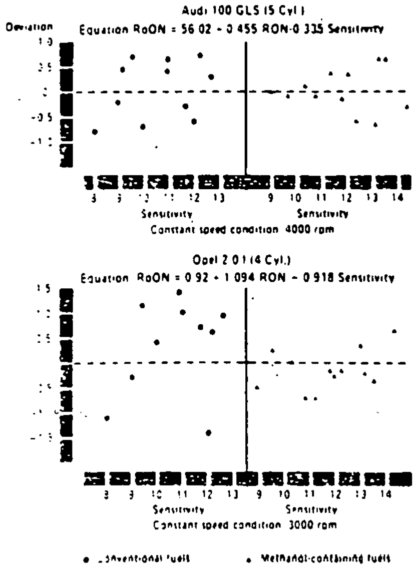


Fig. 14: Road antiknock performance of conventional and methanol containing fuels

five fuel blends (3 premium and 2 regular) four were tested at −5°C, a typical winter temperature for middle Europe, in three vehicles on the chassis dynamometer For comparison the CEC reference premium grade gasoline (RF 01 T 74) was included. The volatility of this fuel is in the middle range of the winter specification and will thus represent about the average performance of current conventional gasolines.

Previous tests have shown that the addition of methanol has little or no effect on cold starting performance. This means that to ensure adequate starting performance the percentage volume of fuel evaporated at 70°C (E70°C) of a methanol containing fuel has to be in the upper range or higher than permitted by the current DIN specification. The results on our test fuels are generally in line with this observation. Also in line with previous work[7] is the observation of relatively large differences between car types. Figure 15 shows the average ratings obtained for cold starting together with the volatility of the fuel. It appears from this work that for cold starting the E70°C of the base gasoline is the overriding factor.

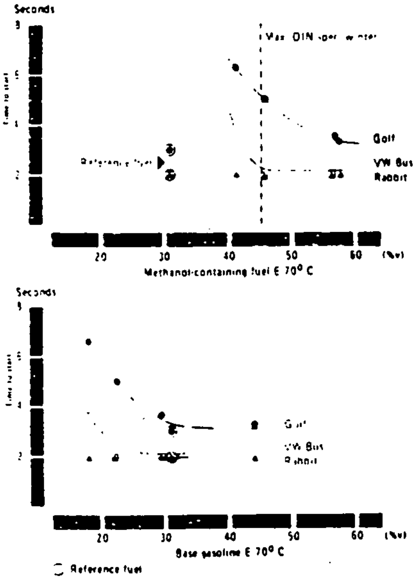
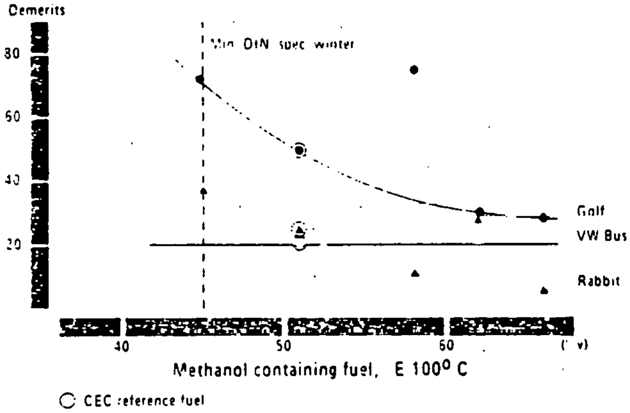


Fig. 15: Performance of test fuels at low ambient temperatures. Cold start performance

In contrast to the findings on cold starting, methanol as a blending component may deteriorate the driveability performance at low temperature. Again it was found that certain cars i.e. with fuel injection systems, are insensitive. It also appears that in those cars which are sensitive to fuel volatility, methanol containing fuels cause poor driveability if the percentage volume of fuel evaporated at 100°C (E100°C) is in the minimum range of the DIN specification. In contrast to the results on cold starting the „E100°C" of the methanol containing fuel, Figure 16, and not of the base gasoline seems to be the better parameter to describe driveability performance. However, more controlled tests would be necessary to substantiate these findings.

Fig. 16: Performance of test fuels at low ambient temperatures. Driveability performance



5.3 Fuel Performance at High Ambient Temperatures

A critical aspect of methanol as a fuel component is its low boiling point which may cause vapour lock problems in the car fuel system. To investigate this aspect a limited programme was carried out on a chassis dynamometer by Volkswagenwerk Research followed by a more extensive test on the road in the south of Spain. In both tests the standard test procedure was used, i.e. the temperatures of the fuel systems were stabilised while driving with 80 % of the max. speed or with a lower speed which was possible on the road This temperature stabilisation was followed by a hot soak with either engine stopped or engine idling. The three performance aspects, hot starting, hot idle and acceleration performance after soak are used to rate the fuels.

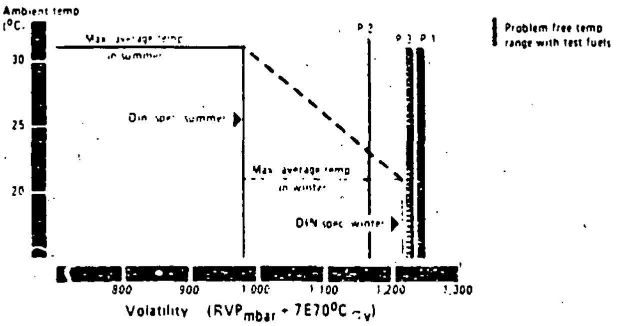
5.3.1 Vapour Lock Tests on the Chassis Dynamometer

The premium-type methanol containing fuels representing the three refinery systems have been tested in a Volkswagen Golf which had been prepared to use methanol containing fuels. As explained before the volatility is around the maximum for conventional winter fuels (expressed as the Reid Vapour Pressure + 7 times the percentage evaporated at 70°C, RVP + 7E70)[8]. The vapour lock performance of these fuels (Figure 17) was found to be safe up to the ambient temperatures of 31/32°C, which is about the maximum summer temperature in Germany It was shown by this experiment that providing special care is taken when designing the car fuel system, winter-type fuels can be used without malfunctions at high ambient summer temperatures. It should be mentioned however that fuels of high Reid Vapour Pressures may encounter problems when transported and when dispensed from service station pumps at high summer temperatures.

5.3.2. Vapour Lock Tests on the Road

In contrast with the chassis dynamometer test the road test was mainly carried out with normal production cars. It was jointly carried out by Aral, Shell, Veba and Volkswagen. The design and the results of this work will be explained in another paper at this symposium[3]. This present paper is concerned only with the blending of the fuels used in this test.

Fig. 17: Performance of test fuels at high ambient temperatures. Comparison with seasonal max. temperatures and volatility specifications

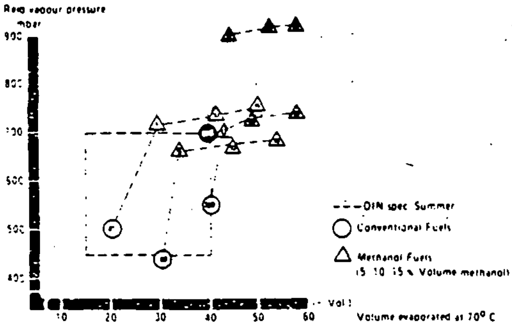


Three sets of fuels were used: hydrocarbon base fuels, methanol containing fuels and hydrocarbon fuels with similar volatility characteristics as the methanol containing fuels.

Four hydrocarbon base fuels were blended, one with low volatility (minimum DIN summer specification according to RVP and E70°C), one with high volatility (maximum DIN summer specification), and two intermediate volatility fuels. A wide range of refinery components were used to blend the base fuels.

The methanol containing fuels were prepared at the test site by blending appropriate hydrocarbon base fuel together with methanol at 5, 10 and 15 % by volume. The volatility effect that the methanol component has on the base hydrocarbon fuel is shown in Figure 18. Where technically possible the three experimental premium-type methanol containing fuels were also used

Fig. 18: Volatility characteristics of fuels used in summer test (hot fuel handling)



A third set of hydrocarbon fuels was prepared at the test site to match the volatility characteristics of the methanol containing fuels. This was achieved by blending butane and/or isopentane into an appropriate hydrocarbon base fuel.

6. Investigations on Meaningful Analytical Test Techniques

Engine performance i.e. cold starting ability, driveability and the avoidance to vapour lock, all depend on the volatility of the fuel. It is well known that methanol has unusual effects on the volatility of the gasoline blend which makes the prediction of engine performance difficult when using the conventional analytical test techniques. Experiments for improved interpretation of both the boiling and the vapour pressure characteristics have been studied.

6.1. Studies on the Boiling Characteristics

The boiling characteristics of a conventional gasoline changes considerably when methanol is added. The distillation curves determined according to DIN 51 751 are, in contrast to conventional curves, nearly horizontal in the boiling range from about 30 to 50 % evaporated volume, i.e. considerably more fuel components evaporate in this temperature range than in the case of conventional gasoline. This boiling behaviour is caused by the formation of azeotropes of methanol with certain hydrocarbons which distil below their own boiling point and even below the boiling point of pure methanol (65°C).

For conventional gasoline such an increase in volatility would generally cause an improved warm-up performance of a cold engine. However, such an interpretation of the boiling curves is not permissible with gasoline-methanol blends, as the distillation according to DIN 51 751 compensates for the higher heat of evaporation of methanol, which is about three times higher than that of gasoline (the heating rate is controlled automatically with the distillation apparatus to achieve the prescribed distillation rate).

In contrast to the distillation apparatus, the amount of heat available in the engine is limited, especially when the engine is still cold. Owing to the high heat of evaporation of the methanol, less fuel is evaporated and a higher temperature drop in the inlet manifold is brought about, which both have a negative effect on the mixture preparation. The problem involved is to show the higher heat of evaporation of gasoline-methanol blends analytically in such a way that a reasonable interpretation of the data obtained would be possible. As a first approach this was attempted by modifying the boiling analysis technique. The heating rate, which is normally variable within wide limits, was fixed in the form of a linear increasing pattern with time, and to characterise the gasoline, the distillation time was plotted instead of the fuel temperature. Although with this method the relatively higher heat of evaporation of the blended fuel could be represented, the reproducibility was found to be inadequate. As a second approach the standard distillation was used, but the heating voltage was measured as an indication of the heating rate. This again showed that there was a clearly higher energy input when evaporating the methanol containing fuel (Figure 19). It will be seen that the heating voltage is higher in the first phase of distillation. The steep rise at about 50 % of the evaporated volume is, however, partly brought about by the inertia of the apparatus, which is clearly discernible by the subsequent crossover of the heating voltage curve of the methanol fuel below the heating voltage curve of the base fuel.

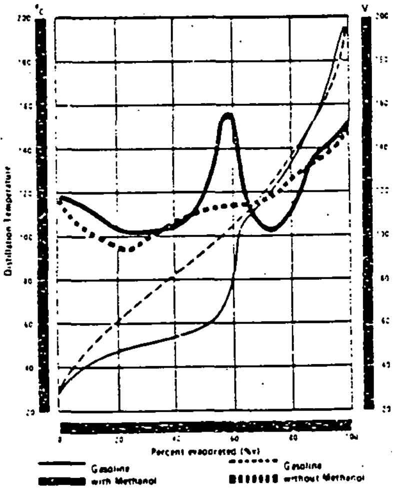


Fig. 19: Distillation and heating voltage curves for gasoline / methanol blends according to DIN 51 751

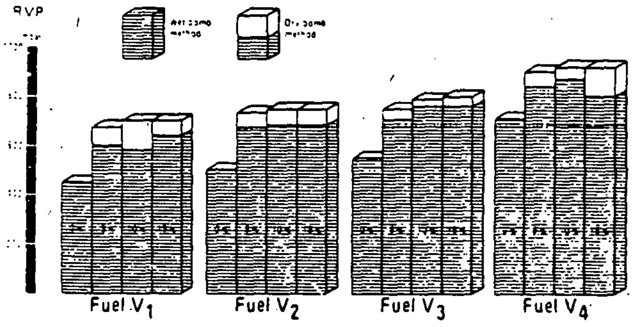
6.2. Study on the Vapour Pressure Characteristics

At 38°C pure methanol has a relatively low vapour pressure, 300 mbar, compared with current gasoline of about 450 to 900 mbar. However, when methanol is blended with gasoline a positive deviation from Raoult's Law for molar vapour pressure additivity results, i.e. the vapour pressure of the blend is higher than either component[10].

This is due to the fact that methanol is a polar molecule, whereas gasoline is essentially non-polar. The hydrogen bonding between methanol molecules (reason for it having a high boiling point) are less significant in gasoline-methanol blends. Consequently methanol tends to behave more like one would predict from its molecular weight, i.e. less than propane [11]. Hence, small additions of methanol to gasoline results in large increase in the vapour pressure as determined by the Reid method. It can be seen from Figure 20 that the increase in vapour pressure due to methanol is independant of base fuel volatility. The result of adding methanol above 15 % by volume is that the vapour pressure of the fuel decreases. This is due to hydrogen bonding recommencing between the methanol molecules and hence reducing the blends overall vapour pressure.

The above conclusions have been obtained from the dry bomb results. We consider it quite important that there be more general recognition of the fact, that the presence of traces of water, inherent in the normal Reid Vapour Pressure method, may give rise to phase separation within the bomb and hence result in low values as shown in Figure 20.

Fig. 20: Comparison of wet and dry bomb Reid vapour pressure methods for base gasolines and methanol-containing fuels



7. Summary

a) If in the long-term crude oil derived gasoline would be in short supply or no longer available, methanol is considered to be a rather attractive alternative proposition compared with other possible alternative contenders.

b) In contrast to previous work an attempt has been made to build in the advantages and overcome the disadvantages of methanol (15 % by volume) as a fuel component for refinery types, i.e. hydroskimming, conversion and petrochemical.

c) From laboratory studies and controlled road tests the following conclusions can be made:

- the increase in octane quality by use of methanol as a component is largest with low octane quality fuel components.
- the value of methanol as an octane blending component is greatest for the hydroskimming type of refinery and poorest for the conversion type of refinery. The value in the petrochemical refinery lies in between the two.
- with the components selected for the conversion and petrochemical refineries, the Motor Octane Number (MON) can not be raised above 88 with the use of methanol i.e. high speed knock performance could not be improved.
- there was no road antiknock bonus of methanol containing fuels compared with conventional fuels of the same Research and Motor Octane Number. This was indicated by testing 24 fuels in two cars.
- low molecular weight aromatics improve the fuel stability more than the high molecular weight aromatics.
- a useful equation has been developed which can predict the phase separation temperature from the water, low and high molecular weight aromatics, and olefinic contents. A further improvement to the predicting equation may be possible by taking into account the different types of olefins.
- the use of isobutanol improves fuel stability.
- cold starting performance is better predicted by the volatility of the base gasoline rather than by the finished methanol fuel, whereas the driveability performance is controlled by the volatility of the finished methanol containing fuel.
- to ensure acceptable starting and driveability, the front end volatility of the methanol containing fuel should be at the maximum or even higher than current DIN specification.
- vapour lock performance is one of the critical areas with methanol containing fuels. If special care is taken in designing the car fuel system, vapour lock problems with methanol containing fuels can be avoided.
- analytical test techniques could be altered to enable a better interpretation of the engine performance of methanol containing fuels taking into account the energy consumed in a distillation test, or using a dry bomb technique for the vapour pressure measurement.

d) The high octane quality of methanol makes it a useful motor fuel blending component. Assuming methanol would be available at the same or lower price than gasoline components, cost savings might be possible when blending premium-type fuels with methanol. These could be off-set in established modern refineries where certain octane upgrading facilities would no longer be needed, and transportation of components, required for the blending of economic regular-type methanol containing fuels would be necessary.

e) Possible future work has to be aimed at a better understanding/interpretation of analytically obtained data, and studies carried out of the potential problem areas with regards to storage and handling of methanol containing fuels. Additional investigations to quantify, in more detail, the implication on cost and energy savings with such fuels are needed.

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PART TWO

TABLE OF CONTENTS

B-1* CHAPTER I
ALCOHOLS - CHARACTERISTICS-FORMS-SOURCES

CHAPTER II
THE PREPARATION OF MASHES AND FERMENTATION

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* Denotes source document - see

PART TWO - continued

PART TWO - continued

CHAPTER VII
FORMULATED ALCOHOL FUELS

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PART TWO

Compilation of Facts from the State-of-the-Art on Alcohol Chemistry and in Alcohol Identification, Production, and Use.

Ethanol as "Spirit" and as Fuel.

Overview of Modern Evaluation of Alcohols as Motor Fuels.

Characteristics of Alcohol Fuels and Expectations.

CHAPTER I

ALCOHOLS - CHARACTERISTICS-FORMS-SOURCES

Introduction

Fossil-based liquid fuels, such as gasoline, diesel and kerosene, are a disorganized mixture of hydrocarbons. Their basic characteristics are only the average of a mixture of related factors, each factor being provided and controlled by different types of moleculars. Basically, the specifications of any liquid fossil fuel are defined by its average molecular behavior.

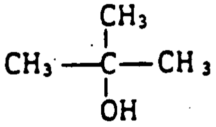
To the contrary, alcohols are well defined chemical substances. The characteristics of these substances are totally related to their molecular arrangement as well as to the physical and energy contributions of their atomic structure.

These well known and defined characteristics of alcohol, as a pure substance are of paramount importance in determining the expected behavior of biomass-based formulated fuels.

Preparation and Physical Properties

Structure

Alcohols are compounds of the general formula, ROH, where R is an alkyl or substituted alkyl group. The group may be primary, secondary, or tertiary; it may be openchained or cyclic; it may contain a double bond, a halogen atom, or an aromatic ring. For example:

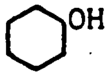


$CH_3-\overset{CH_3}{\underset{OH}{C}}-CH_3$

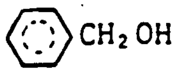
tert-Butyl alcohol

$H_2C=CH-CH_2OH$

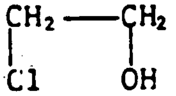
Allyl alcohol



Cyclobexanol

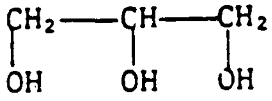


Benzyl alcohol



$\underset{Cl}{CH_2}-\underset{OH}{CH_2}$

Ethylene chlorohydrin
(ß-Chloroethyl alcohol)



$\underset{OH}{CH_2}-\underset{OH}{CH}-\underset{OH}{CH_2}$

Glycerol

All alcohols contain the hydroxyl (-OH) group, which, as the functional group, determines the properties and characteristic of this family. Variations in structure and the R group may affect the rate at which the alcohol undergoes certain reactions, and even, in a few cases, may affect the kind of reaction.

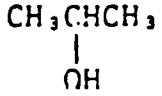
Nomenclature

Alcohols are named by three different systems.

For the simpler alcohols the common names are most often used. These consist simply of the name of the alkyl group followed by the word alcohol. For example:

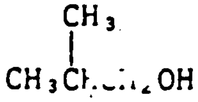
CH_3CH_2OH

Ethyl alcohol



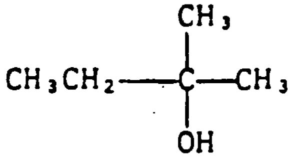
$CH_3CH(OH)CH_3$

Isopropyl alcohol



$CH_3CH(CH_3)CH_2OH$

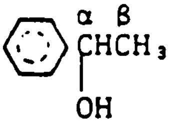
Isobutyl alcohol



$CH_3CH_2C(CH_3)(OH)CH_3$

tert-Pentyl alcohol

p-Nitrobenzyl alcohol

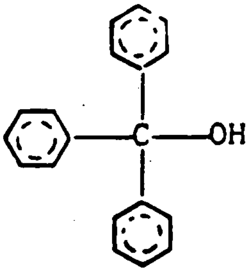


α-Phenylethyl alcohol

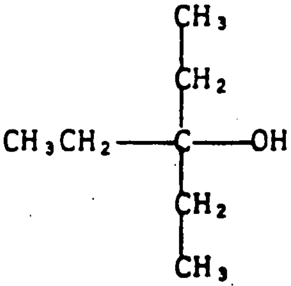
We should notice that similar names do not always mean the same classification; for example, isopropyl alcohol is a secondary alcohol, whereas isobutyl alcohol is a primary alcohol.

As mentioned before, compounds too complicated for common names may be given derived names. According to this system, alcohols are considered to be derived from methyl alcohol, CH_3OH, by the replacement of one or more hydrogen atoms by other groups. We simply name the groups attached to the carbon bearing the -OH and then add the suffix -carbinol to include the C-OH portion:

ALCOHOLS I

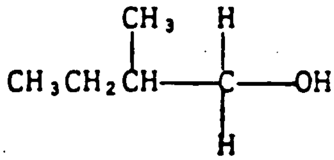


Triphenylcarbinol



$CH_3CH_2C(CH_2CH_3)_2OH$

Triethylcarbinol



$CH_3CH_2CH(CH_3)CH_2OH$

sec-Butylcarbinol

Finally, there is the most versatile system, the IUPAC. The rules are:

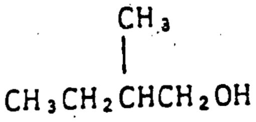
(1) Select as the parent structure the longest continuous carbon chain that contains the -OH group; then consider the compound to have been derived from this structure by replacement of hydrogen by various groups. The parent structure is known as ethanol, propanol, butanol, etc., depending upon the number of carbon atoms; each name is derived by replacing the terminal -e of the corresponding alkane name by -ol.

(2) Indicate by a number the position of the -OH group in the parent chain, generally using the lowest possible number for this purpose.

(3) Indicate by numbers the positions of other groups attached to the parent chain.

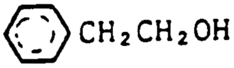
CH_3OH

Methanol

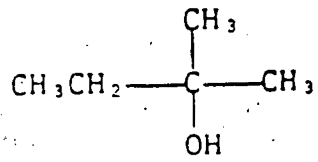


$CH_3CH_2\overset{\overset{CH_3}{|}}{CH}CH_2OH$

2-Methyl-1-butanol

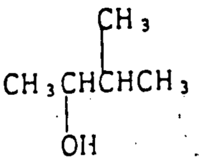


2-Phenylethanol



$CH_3CH_2-\underset{\underset{OH}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_3$

2-Methyl-2-butanol

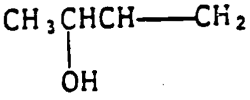


$CH_3\underset{\underset{OH}{|}}{CH}\overset{\overset{CH_3}{|}}{CH}CH_3$

3-Methyl-2-butanol

$ClCH_2CH_2OH$

2-Chloroethanol



$CH_3\underset{\underset{OH}{|}}{CH}CH=CH_2$

3-Buten-2-ol

Physical Properties

The compounds we have studied so far, the various hydrocarbons, have the physical properties that we might expect of such non-polar compounds: The relatively low melting points and boiling points that are characteristic of substances with weak intermolecular forces; solubility in non-polar solvents and insolubility in polar solvents like water. We shall find alcohols to be considerably different from hydrocarbons because of the presence in alcohol molecules of the very polar -OH group, and in particular because this polar group contains hydrogen.

A striking difference between alcohols and hydrocarbons is the miscibility of the lower alcohols with water. Because of the polar -OH group alcohols are held together by very much the same sort of intermolecular forces as those holding together water molecules. As a result there can be mixing of the two kinds of molecules, the energy required to break apart two water molecules or two alcohol molecules being supplied by formation of a similar bond between a water molecule and an alcohol molecule.

This is true, however, only for the lower alcohols, where the -OH groups constitutes a large portion of the molecule. A long aliphatic chain with a small -OH group at one end is mostly alkane, and its physical properties reflect this.

For practical purposes we consider that the borderline between solubility and insolubility in water occurs at about 4 to 5 carbon atoms for normal primary alcohols.

The boiling points show the usual increase with increasing carbon number, and the usual decrease with branching. The unusual thing about the boiling points of alcohols is that they are so much higher than those of the corresponding hydrocarbons.

Hydrogen Bonding - Association

Among hydrocarbons the factors that determine boiling point seem to be chiefly molecular weight and shape; this is reasonable for molecules that are held together chiefly by van der Waals forces.

Structure and Boiling Point

Name	Structure	Mol. Wt.	Dipole Moment, D	B.P., °C
n-Pentane	$Ch_3CH_2CH_2CH_2CH_2$	72	0	36
Ethyl ether	CH_3CH_2——o——CH_2CH_2	74	1.18	35
n-Propyl chloride	$CH_3CH_2CH_2C1$	79	2.10	47
n-Butyraldehyde	$CH_4CH_2CH_2CHO$	72	2.72	76
n-Butyl alcohol	$CH_3CH_2CH_2CH_2OH$	74	1.63	118

Table I

PHYSICAL PROPERTIES

ALCOHOLS

Name	Formula	M.p., °C	B.p., °C	Density at 20°C	Solub., g/100g H O
Methyl	CH_2OH	- 97	64.5	0.793	∞
Ethyl	CH_3CH_2OH	-115	78.3	.789	∞
n-Propyl	$CH_3CH_2CH_2OH$	-126	97	.804	∞
n-Butyl	$CH_3(CH_2)_2CH_2OH$	- 90	118	.810	7.9
n-Pentyl	$CH_3(CH_2)_3CH_2OH$	- 78.5	138	.817	2.3
n-Hexyl	$CH_3(CH_2)_4CH_2OH$	- 52	156.5	.819	0.6
n-Heptyl	$CH_3(CH_2)_6CH_2OH$	- 34	176	.822	0.2
n-Octyl	$CH_3(CH_2)_6CH_2OH$	- 15	195	.825	0.05
n-Decyl	$CH_3(CH_2)_8CH_2OH$	6	228	.829	
n-Dodecyl (Lauryl)	$CH_3(CH_2)_{10}CH_2OH$	24			
n-Tetradecyl (Myristyl)	$CH_3(CH_2)_{12}CH_2OH$	38			
n-Hexadecyl (Cetyl)	$CH_3(CH_2)_{14}CH_2OH$	49			
n-Octadecyl	$CH_3(CH_2)_{16}CH_2OH$	58.5			
Isopropyl	$CH_3CHOHCH_2$	- 86	82.5	.789	∞
Isobutyl	$(CH_3)_2CHCH_2OH$	-108	108	.802	10.0
sec-Butyl	$CH_3CH_2CHOHCH_3$	-114	99.5	.806	12.5
tert-Butyl	$(CH_3)_2COH$	25.5	83	.789	∞
Isopentyl	$(CH_3)_2CHCH_2CH_2OH$	-117	132	.813	2
active-Amyl [(-)-2-Methyl-1-butanol]	$CH_3CH_2CH(CH_3)CH_2OH$		128	.816	3.6
tert-Pentyl	$CH_3CH_2C(OH)(CH_3)_2$	- 12	102	.809	12.5
Cyclopentanol	cyclo-C_5H_9OH		140	.949	
Cyclohexanol	cyclo-$C_6H_{11}OH$	24	161.5	.962	
Allyl	$CH_2{=}CHCH_2OH$	-129	97	.855	∞
Crotyl	$CH_3CH{=}CHCH_2OH$		118	.853	6.6
Methylvinylcarbinol	$CH_2{=}CHCHOHCH_2$		97		
Benzyl	$C_6H_5CH_2OH$	- 15	205	1.046	4
α-Phenylethyl	$C_6H_6CHOHCH_2$		205	1.013	
β-Phenylethyl	$C_6H_6CH_2CH_2OH$	- 27	221	1.02	1.6
Diphenylcarbinol (Benzhydrol)	$(C_3H_6)_2CHOH$	69	298		0.05
Triphenylcarbinol	$(C_3H_6)_3COH$	162.5			
Cinnamyl	$C_6H_5CH{=}CHCH_2OH$	33	257.5		

Alcohols contain the strongly polar -OH group, and we might first consider that the difference in boiling point is due to the greater polarity of the alcohol molecule. This is undoubtedly a factor. The dipole moment of n-butyl alcohol (1.63) is larger than that of the ether (1.18) and much larger than the zero moment for n-pentane. The stronger intermolecular forces arising from dipole-dipole attractions are overcome, and boiling occurs, only at higher temperatures.

To account for these "abnormalities", and on the basis of evidence of many kinds, hydrogen bonding has been proposed: a hydrogen atom serves as a bridge between two electronegative atoms, holding one by a covalent bond and the other by purely electrostatic forces. This electrostatic bond has a strength of about 5 kcal/mole (compared with 50-100 kcal/mole for most covalent bonds). Liquids whose molecules are held together by hydrogen bonds are called associated liquids; their abnormally high boiling points are due to the greater energy required to break the hydrogen bonds.

Like water, alcohols are associated liquids, their abnormal boiling points arising from hydrogen bonding. Although ethers and aldehydes contain oxygen, they contain hydrogen that is bonded only to carbon; these hydrogens are not positive enough to bond appreciably with oxygen. The solubility of the lower alcohols in water is due to the hydrogen bond that can exist between a molecule of water and a molecule of alcohol, as well as between two molecules of alcohol or between two molecules of water.

Source of Alcohols

If an organic chemist were allowed to choose ten aliphatic compounds with which to be stranded on a desert island, he would almost certainly pick alcohols. From them he could make nearly every other kind of aliphatic compound: alkenes, alkyl halides, ethers, aldehydes, ketones, acids, esters, and a host of others. From the alkyl halides he could make Grignard reagents, and from the reaction between these and the aldehydes and ketones obtain more complicated alcohols not only as raw materials but frequently as the solvents in which reactions are carried out and from which products are recrystallized.

For alcohols to be such important starting materials in aliphatic chemistry, they must be not only versatile in their reactions but also available in large amounts and at low prices. There are two principal ways to get the simple alcohols that are the backbone of aliphatic organic synthesis: by hydration of alkenes obtained from the cracking of petroleum, and by fermentation of carbohydrates. In addition to these two chief methods, there are some others that have more limited application.

Hydration of Alkenes

Alkenes containing up to four or five carbon atoms can be separated from the mixture obtained from the cracking of petroleum. Alkenes are readily converted into alcohols either by direct addition of water, or by addition of sulfuric acid followed by hydrolysis. By this process there can be obtained only those alcohols whose formation is consistent with the application of Markovnikov's rule: for example, isopropyl but not n-propyl, sec-butyl but not n-butyl, tert-butyl but not isobutyl. Thus the only primary alcohol obtainable in this way is ethyl alcohol.

Fermentation of Carbohydrates

Fermentation of sugars by yeast, the oldest synthetic chemical used by man, is still of enormous importance for the preparation of ethyl alcohol and certain other alcohols. The sugars come from a variety of sources, mostly molasses from sugar cane or starch obtained from various grains; the name "grain alcohol" has been given to ethyl alcohol for this reason. In addition to ethyl alcohol there is obtained a smaller amount of a substance known as fusel oil, a mixture of primary alcohols: mostly isopentyl alcohol with smaller amounts of n-propyl alcohol, isobutyl alcohol, and 2-methyl-1-butanol, known as active amyl alcohol (amyl = pentyl).

Much newer is the Weizmann process for the bacterial fermentation of starch, which yields a mixture consisting of n-butyl alcohol (60%), ethyl alcohol (10%), and acetone (30%), CH_3COCH_3. Discovered at the time of World War I by Chaim Weizmann (then at the University of Manchester, and at his death in 1942 as the first President of Israel), this process was first important as a source of acetone, needed in the manufacture of smokeless powder; the butyl alcohol was considered a by-product and was simply stockpiled. After the war, the development of lacquers for the rapidly expanding automobile industry made butyl alcohol the more valuable product, and in a sense acetone became the by-product. Now both are important.

Synthesis of Methanol

As is very often the case for the smallest member of a family, methanol is prepared quite differently from the others: from simple inorganic compounds. At 350-400°, and in the presence of certain metallic oxides, carbon monoxide and hydrogen react to yield methanol.

$$CO + 2H_2 \xrightarrow{Cr_2O_3 + Z_nO,\ 350\text{-}400^o,\ 3000\ lb/in.^2} \underset{\text{Methanol}}{CH_3OH}$$

Methanol is poisonous: drinking it, breathing it for prolonged periods, or allowing it to remain long on the skin can lead to blindness or death.

Aldol Condensation

The methods just outlined yield comparatively simple alcohols. More complicated alcohols are prepared on an industrial scale from aldehydes and ketones by what is essentially an aldol condensation; this method, which is also used in the laboratory, is discussed later.

Oxo Process

Addition of carbon monoxide and hydrogen to alkenes (hydroformylation) in the presence of a catalyst yields aldehydes and ketones, which can be reduced to alcohols. This is the Oxo process, initially developed in Germany, and of growing importance in the chemical industry.

ETHANOL — Its Various Forms and Sources

Alcohol. (Fr., alcool; Fer., alkohol.) Formula, C_2H_6O.

Pure alcohol is a liquid substance, composed of carbon, hydrogen and oxygen, in the following proportions:

C.	52.17
H.	13.04
O.	34.79
	100.00

It is the most important member of an important series of organic compounds, all of which resemble each other closely, and possess many analogous properties. They are classed by the chemist under the generic title of "Alcohols."

Alcohol does not occur in nature; it is the product of the decomposition of sugar, or, more properly, of glucose, which, under the influence of certain organic, nitrogenous substances, called ferments is split up into alcohol and carbonic anhydride. The latter is evolved in the form of gas, alcohol remaining behind mixed with water, from which it is separated by distillation. The necessary purification is effected in a variety of ways.

Pure, absolute alcohol is a colorless, mobile, very volatile liquid, having a hot, burning taste, and a pungent and somewhat agreeable odor. It is very inflammable, burning in the air with a bluish-yellow flame, evolving much heat, leaving no residue, and forming varpors of carbonic anhydride and water. Its specific gravity at 0°C (32°F) is .8095, and at 15.51°C. (60°F.) .794; that of its vapor is 1.613. It boils at 78.4°C. (173°). The boiling point of its aqueous mixtures are raised in proportion to the quantity of water present. Mixtures of alcohol and water when boiled give off at first a vapor rich in alcohol, and containing but little aqueous vapor; if the ebullition be continued a point is ultimately reached when all the alcohol has been driven off and nothing but pure water remains. Thus, by repeated distillations alcohol may be obtained from its mixtures with water in an almost anhydrous state.

Table I - The Boiling Points of Alcoholic Liquors of Different Strengths, and the Proportions of Alcohol in the Vapors Given Off

Proportion of Alcohol in the boiling liquid in 100 vols	Temperature of the boiling liquid	Proportion of alcohol in the condensed vapor in 100 vols.	Proportion of alcohol in the boiling liquid in 100 vols.	Temperature of the boiling liquid.	Proportion of alcohol in the condensed vapor in 100 vols.
92	171.0F.	93	20	189.5F.	71
90	171.5F	92	18	191.6F	68
85	172.0F	91.5	15	194.0F	66
80	172.7F	90.5	12	196.1F	61
75	173.6F	90	10	198.5F	55
70	175.0F.	89	7	200.6F.	50
65	176.0F.	87	5	203.0F.	42
50	178.1F	85	3	205.1F.	36
40	180.5F.	82	2	207.5.F.	28
35	182.6F.	80	1	209.9F.	13
30	185.0F.	78	0	212.0F.	0
25	187.1F.	76			

Absolute alcohol has a strong affinity for water. It absorbs moisture from the air rapidly, and thereby becomes gradually weaker; it should therefore be kept in tightly-stoppered bottles. When brought into contact with animal tissues, it deprives them of the water necessary for their constitution, and acts in this way as an energetic poison. Considerable heat is disengaged when alcohol and water are brought together; if, however, ice be substituted for water, heat is absorbed, owing to the immediate and rapid conversion of the ice into the liquid state. When one part of snow is mixed with two parts of alcohol, a temperature as low as 5.8^{O}F. below zero is reached.

When alcohol and water are mixed together the resulting liquid occupies, after agitation, a less volume than the sum of the two original liquids. This contraction is greatest when the mixture is made in the proportion of 52.3 volumes of alcohol and 47.7 volumes of water, the result being, instead of 100 volumes, 96.35. A careful examination of the liquid when it is being agitated reveals a vast number of minute air-bubbles, which are discharged from every point of the mixture. This is due to the fact that gases which are held in solution by the alcohol and water separately are less soluble when the two are brought together; and the contraction described above is the natural result of the disengagement of such dissolved gases. The following table represents the contraction undergone by different mixtures of absolute alcohol and water.

Table II - 100 Volumes of Mixture at 59°F.

Alcohol	Contraction	Alcohol	Contraction	Alcohol	Contraction
100	0.00	65	3.61	30	2.72
95	1.18	60	3.73	25	2.24
90	1.94	55	3.77	20	1.72
85	2.47	50	3.74	15	1.20
80	2.87	45	3.64	10	0.72
75	3.19	40	3.44	5	0.31
70	3.44	35	3.14		

Alcohol is termed "absolute" when it has been deprived of every trace of water, and when its composition is exactly expressed by its chemical formula. To obtain it in this state it must be subjected to a series of delicate operations in the laboratory, which it would be impossible to perform on an industrial scale. In commerce it is known only in a state of greater or less dilution.

Alcohol possesses the power of dissolving a large number of substances insoluble in water and acids, such as many inorganic salts, phosphorus, sulphur, iodine, resins, essential oils, fats, coloring matters, etc. It precipitates albumen, gelatine, starch, gum, and other substances from their solutions. These properties render it an invaluable agent in the hands of the chemist.

Alcohol is found in, and may be obtained from, all substances—vegetable or other—which contain sugar. As stated above, it does not exist in these in the natural state, but is the product of the decomposition by fermentation of the saccharine principle contained therein; this decomposition yields the spirit in a very dilute state, but it is readily separated from the water with which it is mixed by processes of distillation, which will subsequently be described. The amount of alcohol which may be obtained from the different unfermented substances which yield it varies considerably, depending entirely upon the quantity of sugar which they contain.

Alcohol is produced either from raw materials containing starch, as potatoes, corn, barley, etc., or raw materials containing sugar, as grapes, beets, sugar cane, citrus, jerusalem artichokes, etc.

The following are some of the most important sources from which alcohol is obtained: Grapes, apricots, cherries, peaches, currents, gooseberries, raspberries, strawberries, figs, plums, bananas, and many tropical fruits, artichokes, potatoes, carrots, turnips, beet-root, sweet corn, rice and other grains. Sugar cane refuse, sorgum, molasses, wood, paper, and by a new French process from acetylene. On a large scale alcohol is usually obtained from sugar beets, molasses or the starch contained in potatoes, corn and other grains. The starch is converted into maltose by mixing with an infusion of malt. The maltose is then fermented by yeast. Sulphuric acid may be used to convert even woody fibre, paper, linen, etc., into glucose, which may in turn be converted into alcohol.

Table III - Principal Alcohols

Chemical Name	Source	Formula	Boiling Point °F.
1 Methyl Alcohol	Distillation of Wood	$C H_3OH$	150.8
2 Ethyl Alcohol	Fermentation of Sugar	C_2H_5OH	172.4
3 Propyl Alcohol	Fermentation of grapes	C_3H_7OH	206.6
4 Butyl Alcohol	Fermentation of beets	C_4H_9OH	242.6
5 Amyl Alcohol	Fermentation of potatoes	$C_5H_{11}OH$	278.6
6 Caproyl Alcohol	Fermentation of grapes	$C_6H_{13}OH$	314.6
7 Aenanthyl Alcohol	Distillation castor oil with potatoes	$C_7H_{15}OH$	347.
8 Capryl Alcohol	Essential oil hog weed	$C_8H_{17}OH$	375.8
9 Nonyl Alcohol	Nonane from petroleum	$C_9H_{19}OH$	
10 Rutyl Alcohol	Oil of Rue	$C_{10}H_{21}OH$	
11 Cytyl Alcohol	Spermaceti	$C_{16}H_{33}OH$	
12 Ceryl Alcohol	Chinese wax	$C_{26}H_{53}OH$	
13 Melisyl Alcohol	Bees' wax	$C_{30}H_{61}OH$	

Among a variety of other substances which have been and are still used for the production of alcohol in smaller quantities, are roots of many kinds, such as those of asphodel, madder, etc. Seeds and nuts have been made to yield it. It will thus be seen that the sources of this substance are practically innumerable; anything, in fact, which contains or can be converted into sugar is what is termed "alcoholisable."

Alcohol has become a substance of such prime necessity in the arts and manufacturereres, and in one form or another enter so largely into the composition of the common beverages consumed by all classes of people that its manufacture must, of necessity, rank among the most important industries of this and other lands.

Of the alcohols given in the above table only two concern the ordinary distiller, or producer of alcohol for general use in the arts. Methyl alcohol, the ordinary "wood alcohol," or wood naphtha, and Ethyl alcohol, which is produced by the fermentation of sugar and may therefore be made from anything which contains sugar.

CHAPTER II

THE PREPARATION OF MASHES AND FERMENTATION

Alcohol may be produced either from (1) farinacious materials, such as potatoes or grains, (2) from sacchariferous substances such as grapes, sugar beets, sugar cane, or the molasses produced in sugar manufacture.

The Preparation of Starchy Materials

Saccharification, Preparatory Mashing

With starchy materials it is first necessary to convert the starch into a sugar from which alcohol can be produced by the process of fermentation. This is called saccharification.

Gelatinizing

The first step in this process is gelatinizing the starch; that is, forming it into a paste by heating it with water, or into a liquid mass by steaming it under high pressure. The liquid or semi-liquid mass is then run into a preparatory mash vat and cooled.

Saccharifying

The disintegrated raw materials or gelatinized starch in the preparatory mash vat is now to be "saccharified" or converted into sugar. This is effected by allowing malt to act on the starch. This malt contains a certain chemical "ferment" or enzyme, called "diastase" ("I separate").

This is able under proper conditions to break up the gelatinized starch into simpler substances—the dextrins—and later into a fermentable sugar called maltose.

Production of Alcohol From Sacchariferous Substances

Substances such as grape juice, fruit juice, sugar beets, cane sugar and molasses already contain fermentable sugar. Saccharification is therefore not needed and juices or liquids from these matters are either directly fermented as in the case of sugar cane, or—as in the case of sugar beets—the sugar in juice is transferred by yeast into a fermentable sugar.

Fermentation

Fermentation is an obscure and seemingly spontaneous change or decomposition which takes place in most vegetable and animal substances when exposed at ordinary temperatures to air and moisture. While fermentation broadly covers decay or putrifaction, yet it is limited in ordinary use to the process for producing alcoholic liquors from sacchariferous mashes.

Fermentation is brought about by certain bodies called ferments—these are either organized, as vegetable ferments such as yeast, or unorganized as diastase—the enzyme of germinated malt. The last is used to convert starch into maltose, the first is used to convert maltose into fermentable sugar. The organized ferments are either to be found floating freely in the air under the name of wild yeast or are artifically produced. If a solution of pure sugar be allowed to stand so that it can be acted on by the organisms in the air, it will remain unaltered for a long time, but finally mold will appear upon it and it will become sour and dark-colored. If, however, a suitable ferment is added to it, such as yeast, it rapidly passes into a state of active fermentation by which the sugar is split up into alcohol and carbon dioxid, the process continuing from 48 hours to several weeks according to the temperature, the amount of sugar present, and the nature and quantity of the ferment. Fermentation cannot occur at a temperature much below 40°F., nor about 140°F. The limits of practical temperature, however, are 41° to 86°F. Brewer's yeast is chiefly employed in spirit manufacture.

The most striking phenomena of fermentation are the turbidity of the liquid, the rising of gas bubbles to the surface, and the increase in temperature, the disappearance of the sugar, the appearance of alcohol and the clearing of the liquid. At the end a slight scum is formed on the top of the liquid and a light colored deposit at the bottom. The deposit consists of yeast which is capable of exciting the vinous fermentation in other solutions of sugar. The lower the temperature the slower the process, which at a temperature above 86°F. the vinous fermentation is liable to pass into other forms of fermentation to be hereafter considered.

There are many theories of fermentation, of which the two most important are those of Pasteur and Buchner. The first teaches that fermentation is caused purely by the organic life of the yeast plant and is not a mere chemical action, whereas the second view most largely held today is that fermentation is a purely chemical change due to certain unorganized substances called "enzymes" present in the yeast.

The theory need not detain us. It is sufficient that the yeast plant in some manner acts to decompose the saccharified mash into alcohol and carbonic acid gas.

Yeast

Yeast is a fungus, a mono-cellular organism, which under proper conditions propogates itself to an enormous extent. There are many races or varieties of yeast each having its peculiar method of growth.

For our purposes we may divide the yeast races into two classes, wild yeast and cultivated yeast. Originally any of the yeast races were supposed to be good enough to effect fermentation but today every effort is made to procure and use only those races which have the greatest power to decompose sugar. It was for this reason that the old distiller kept portions of his yeast over from one fermentation to the next. This was yeast whose action they understood and whose abilities were proven. This yeast so kept was open, however, to the chance of contamination and yeast today is as carefully selected and bred as is a strain of horses, or dogs, or plants.

After getting a portion of selected pure yeast for breeding purposes, it may be sowed, that is, propagated very carefully in a yeast mash, in sterilizing apparatus, where all chance of contaimination by bacteria or wild yeast is avoided. From this bed of mother yeast, or start yeast for the successive yeast mashes is taken.

The preparation of the various varieties of yeast mashes is too lengthy to be set forth except in special treatises on the subject, but the ordinary method of yeasting is as follows.

The yeast mash we will assume is composed of equal parts of barley malt and rye meal. Hot water at 166°F. is first put into the mash tub. The rake or stirrers are then rotated and the meal run in slowly. The stirring is continued for twenty minutes after the meal is all in, during which the mash has become saccharified.

The mash is then allowed to stand for about twenty hours, and to grow sour by lactic fermentation. The lactic acid so produced protects the mother yeast from infection by suppressing wild yeast and bacteria. During this period great care is taken to prevent the temperature of the mash falling below 95°F. and consequent butyric and acetous fermentation following. After it has so stood the sour mash is cooled by circulating water in the coils and stirring until it is reduced to from 59° to 68°F. depending on whether the mash is thin or thick. Start yeast during the cooling of the mash when at about 86°F. is added and stirred in. For the next twelve hours the yeast ferments and when a temperature of 84°F. has been attained the mash is cooled to 65°F. at which temperature it is maintained until allowed to enter the fermenting tubs through the pipe leading thereto from the yeast tub.

There are four principal kinds of fermentation: alcoholic, acetous, lactic and viscous.

Alcoholic Fermentation

This may be briefly described as follows: The mash in the fermenting vat having been brought to the proper temperature, the ferment is thrown in, and the whole is well stirred together.

This is known as pitching.

The proper pitching temperature varies with the method of fermentation adopted, the length of the fermenting period, the materials of the mash, its thickness or attenuation. It must always be remembered that there is a great increase in the temperature of the "beer" during fermentation and that the temperature at its highest should never under any circumstances, become greater than 86°F. and with thick mashes that even a less heat is desirable. Therefore the pitching temperature should be such that the inevitable rise due to fermentation shall not carry the temperature to or beyond the maximum point desired for the particular mash being treated. It is to accurately control the pitching temperature and the fermenting temperature that the fermenting tanks are provided with cooling appliances.

In about three hours' time, the commencement of the fermentation is announced by small bubbles of gas which appear on the surface of the vat, and collect around the edges. As these increase in number, the whole contents are gradually thrown into a state of motion, resembling violent ebullition, by the tumultuous disengagement of carbonic anhydride. The liquor rises in temperature and becomes covered with froth. At this point, the vat must be covered tightly, the excess of gas finding an exit through holes in the lid; care must now be taken to prevent the temperature from rising too high, and also to prevent the action from becoming too energetic, thereby causing the contents of the vat to overflow. In about twenty-four hours the action begins to subside, and the temperature falls to that of the surrounding atmosphere. An hour or two later, the process is complete; the bubbles disappear, and the liquor, which now possesses the characteristic odor and taste of alcohol, settles out perfectly clear. The whole operation, as here described, usually occupies from forty-eight to seventy-two hours. The duration of the process is influenced, of course, by many circumstances, chiefly by the bulk of the liquor, its richness in sugar, the quality of the ferment, and the temperature.

Acetous Fermentation

This perplexing occurrence cannot be too carefully guarded against. It results when the fermenting liquor is exposed to the air. When this is the case, the liquor absorbs a portion of the oxygen, which unites with the alcohol, thus converting it into acetic acid as rapidly as it is formed. When acetous fermentation begins, the liquor becomes turbid, and a long, stringy substance appears, which after a time settles down to the bottom of the vat. It is then found that all the alcohol has been decomposed, and that an equivalent quantity of acetous acid remains instead. It has been discovered that the presence of a ferment and a temperature of 68° to 95°F. are indispensable to acetous fermentation, as well as contact with the atmosphere. Hence, in order to prevent its occurrence, it is necessary not only to exclude the air, but also to guard against too high a temperature and the use of too much ferment. The latter invariably tends to excite acetous fermentation. It should also be remarked that it is well to cleanse the vats and utensils carefully with lime water before using, in order to neutralize any acid which they may contain; for the least trace of acid in the vat has a tendency to accelerate the conversion of alcohol into vinegar. A variety of other circumstances are favorable to acetification, such as the use of a stagnant or impure water, and the foul odors which arise from the vats; stormy weather or thunder will also engender it.

Lactic Fermentation

Under the influence of lactic fermentation, sugar and starch are converted into lactic acid. When it has once begun, it develops rapidly, and soon decomposes a large quantity of glucose; but as it can proceed only in a neutral liquor, the presence of the acid itself speedily checks its own formation. Then, however, another ferment is liable to act upon the lactic acid already formed, converting it into butyric acid, which is easily recognized by its odor of rank butter. Carbonic anhydride and hydrogen are evolved by this reaction. The latter gas acts powerfully upon glucose, converting it into a species of gum called mannite, so that lactic fermentation—in itself an intolerable nuisance—becomes the source of a new and equally objectionable waste of sugar. It can be avoided only by keeping the vats thoroughly clean; they should be washed with water acidulated with five percent of sulphuric acid. An altered ferment, or the use of too small a quantity, will tend to bring it about.

The best preventives are through cleanliness, and the use of good, fresh yeast in the correct proportion.

Viscous Fermentation

This is usually the result of allowing the vats to stand too long before fermentation begins. It is characterized by the formation of viscous or mucilaginous matters, which render the liquor turbid, and by the evolution of carbonic anhydride and hydrogen gases the latter acting as in the case of lactic fermentation and converting the glucose into mannite. Viscous fermentation may generally be attributed to the too feeble action of the ferment. It occurs principally in the fermentation of white wines, beer, and beet juice, or of other liquors containing much nitrogenous matter. It may be avoided by the same precautions as are indicated for the prevention of lactic fermentation.

Periods of Fermentation

The operation of fermentation may be conveniently divided into three equal periods.

The first or pre-fermentation period is that when the yeast mixed into the mash is growing; the temperature should then be kept at about 63 to 68°F. during which time the yeast is propagated. The growth of the yeast is manifested by the development of carbonic acid gas and by a slight motion of the mash. When alcohol is produced to an extent of say five percent, the growth of the yeast stops.

The second period of chief ferementation then begins. Carbonic acid is freely developed and the sugar is converted into alcohol. The temperature at this time should not exceed 81.5°F. The second period of fermentation continues about 12 hours, when the last period commences.

During the third period or after fermentation there is a lessening of the formation of carbonic acid and a lowering of the temperature. In this stage the mash is kept at a temperature of 77° to 81°F.

In order to conveniently regulate the temperature of the mash the vat may be provided with a copper worm at the bottom thereof, through which cold water is forced. This, however, need only to used for thick mashes. There are also various kinds of movable coolers used for this purpose.

There are a number of different forms which fermentation may take. The insoluble constituents of the mash in the process of fermentation are forced to the surface, and form what may be termed a cover. If the carbonic acid gas bubbles seldom break this cover it indicates that the conversion of the sugar into alcohol and carbonic acid is proceeding very slowly and imperfectly. If, however, the cover is swirling and seething, and particularly if the cover is rising and falling with every now and then a discharge of gas, it is an indication that the conversion is properly proceeding. Foaming of the mash is to be prevented, as the froth or foam flows over the mash tank and considerable loss is sustained. It may be prevented by pouring a little hot lard into the vat, or petroleum, provided its odor will not interfere with the use of the alcohol when distilled.

Water is added in small quantities near the termination of the second period of fermentation. This dilutes the alcohol, in the mash and lessens its percentage, and thus the further growth of the yeast is permitted.

After fermentation the mash takes either the form of a thick diluted pulp or of a thin liquor. Again the reader is reminded that the mash after fermentation contains alcohol mixed with water—and that the next step in the process—distillation is necessary merely to separate the alcohol from the water.

There is always some loss in the process of fermentation; in other words, the actual production is below the theoretical amount due. Theoretically one pound of starch should yield 11.45 fluid ounces of alcohol. With a good result 88.3 percent of this theoretical yield is obtained; with an average result of 80.2 percent and with a bad result only about 72.6 percent or less.

Fermenting Apparatus

It remains now to describe briefly the vessels or vats employed in the processes of fermentation. They are made of oak or cypress, firmly bound together with iron bands, and they should be somewhat deeper than wide, and slightly conical, so as to present as small a surface as possible to the action of the air. Their dimensions vary, of course, with the nature and quantity of the liquor to be fermented. Circular vats are preferable to square ones, as being better adapted to retain the heat of their contents. The lid should close securely, and a portion of it should be made to open without uncovering the whole. For the purpose of heating or cooling the contents when necessary, it is of great advantage of have a copper coil at the bottom of the vat, connected with two pipes, one supplying steam and the other cold water.

Iron vats have also been used, having a jacketed space around them, into which hot or cold water may be introduced. As wooden vats are porous and hence uncleanly they have to be constantly scrubbed and disinfected. It is advisable to cover the interior with linseed oil, varnish or with a shellac varnish. The diameter of the coil varies according to the size of the vat.

The room in which the vats are placed should be made as free from draughts as possible by dispensing with superfluous doors and windows; it should not be too high and should be enclosed by thick walls in order to keep in the heat. As uniformity of temperature is highly desirable, a thermometer should be kept in the room, and there should be stoves for supplying heat in case it be required. The temperature should be kept between 64°F and 68°F.

Every precaution must be taken to ensure the most absolute cleanliness; the floors should be swept or washed with water daily, and the vats, as pointed out above, must be cleaned out as soon as the contents are removed. For washing the vats, lime-water should be used when the fermentation has been too energetic or has shown a tendency to become acid; water acidulated with sulphuric acid is used when the action has been feeble and the fermented liquor contains a small quantity of undecomposed sugar. Care must be taken to get rid of carbonic anhydride formed during the operation. Buckets of lime-water are sometimes placed about the room for the purpose of absorbing this gas; but the best way of getting rid of it is to have a number of holes, three or four inches square, in the floor, through which the gas escapes by reason of its weight. The dangerous action of this gas and its effects upon animal life when unmixed with air are too well known to necessitate any further enforcement of these precautions.

The beer obtained by mashing and fermenting consist essentialy of volatile substances, such as water, alcohol, essential oils and a little acetic acid, and of non-volatile substances, such as cellulose, dextrine, unaltered sugar and starch, mineral matters, lactic acid, etc.

The volatile constituents of the liquor possess widely different degrees of volatility; the alcohol has the lowest boiling point, water the next, then acetic acid, and last the essential oils. It will thus be seen that the separation of the volatile and non-volatile constituents by evaporation and condensation of the vapors given off is very easily effected, and that also by the same process, which is termed distillation, the volatile substances may be separated from one another. As the acetic acid and essential oils are present only in very small quantities, they will not require much consideration.

The aim of distillation is to separate as completely as possible the alcohol from the water which dilutes it. Table I shows the amount of alcohol contained in the vapors given off from alcoholic liquids of different strength, and also their boiling points.

A glance at this table shows to what an extent an alcoholic liquor may be strengthened by distillation, and how the quantity of spirit in the distillate increases inproportion as that contained in the original liquor diminishes. It will also be seen that successive distillations of spirituous liquors will ultimately yield a spirit of very high strength.

As an example, suppose that a liquid containing five percent of alcohol is to be distilled. Its vapor condensed gives a distillate containing 42 percent of alcohol which, if re-distilled, affords another containing 82 percent. This, subjected against to distillation, yields alcohol of over 90 percent in strength. Thus, three successive distillations have strengthened the liquor from five percent to 90 percent.

It will thus be clear that the richness in alcohol of the vapors given off from boiling alcoholic liquids is not a constant quantity, but that it necessarily diminishes as the ebullition is continued. For example a liquor containing seven percent of alcohol yields, on boiling, a vapor containing 50 percent. The first portion of the distillate will, therefore, be of this strength. But as the vapor is proportionally richer in alcohol, the boiling liquor must become gradually weaker, and, in consequence, must yield weaker vapors. Thus, when the proportion of alcohol in the boiling liquid has sunk to five percent, the vapors condensed at that time will contain only 40 percent; at two percent of alcohol in the liquor, the vapors yield only 28 percent, and at one percent, they will be found when condensed to contain only 13 percent. From this it will be understood that if the distillation be stopped at any given point before the complete volatilization of all the alcohol the distillate obtained will be considerably stronger than if the process had been carried on to the end. Moreover, another advantage derived from checking the process before the end, and keeping the last portions of the distillate separate from the rest, besides that of obtaining a stronger spirit, is that a much purer one is obtained also. The volatile, essential oils, mentioned above, are soluble only in strong alcohol, and insoluble in its aqueous solutions. They distill also at a much higher temperature than alcohol, and so are found only among the last products of the distillation, which results from raising the temperature of the boiling liquid. This system of checking the distillation and removing the products at different points is frequently employed in the practice of rectification.

Continuous Alcoholic Fermentation

Continuous alcoholic fermentations are shown to be preferably one stage processes. It was found that the specific yield of ethanol (based upon the fermented sugar) can be about 98% of the theoretical value compared to about 93% yield in normal batch processes. Continuous fermentation of enzymatically saccharified starch containing raw materials is limited by the saccharification rate and takes about 40 hours fermentation time. Fermentation of clarified beet or cane juices only needs 6 hours fermentation time. Scale-up is no problem. The process don't need sterile conditions because bacteria don't have a chance for considerable growth and because of selective conditions for growing and fermenting yeast.

Alcoholic fermentation is used since thousands of years to produce beverages like beer, wine and champagne. The industrial production of ethanol by fermentation and distillation started about a hundred years ago. The technical process requires at least three stages:

1. Producing of fermentable substrate solutions
2. Fermentation
3. Separation of ethanol

This paper deals with alcoholic fermentation and gives notes on some problems of substrate solutions.

The fermenting yeasts (e.g. saccharomycas strains) catalyze the disproportionation of sugars to ethanol and carbon dioxide. This is an exothermic reaction where about 4% of the combustion energy of sugar are released. The biochemical equation is

$$C_6H_{12}O_6 + 2ADP + P \quad 2C_2H_6O + 2CO_2 + 2ATP \quad (A)$$

Yeast is able to use the anaerobically born energy bounded in ATP for anabolic metabolism resulting in yeast growth. Thus, in solutions containing sugar as the only carbon source, consequently the ethanol yield must be a little bit lower than the stoichiometric (theoretical) value cited in equation (A) above. In practice a 94% yeild, based upon the fermented sugar, is thought to be the optimum (1).

Most of the characteristic properties which are necessary to be known for carrying-out technical fermentation processes are well known. Optimum temperatures are 25 to 40°C, pH-values of 3 to 7 are allowed, ethanol concentration may reach up to 15% (v./v.).

Although extensive research is done since more than one hundred years, alcoholic fermentations on a technical scale are batch processes until now except some sterile beer fermentations. Many scientists are convinced that continuous fermentations are impossible on a technical scale because of the large problems of infections. Because of the longer generation time of yeast with respect to bacteria, it is understood that a sterile culture isn't possible on a simple way. We can expect e.g. lactobacilli which are ubiquitous in non-sterile sugar solutions. Therefore the total process can only be maintained during a longer time if we are successful in choosing fermentation conditions selective for yeast but not for bacteria.

We believe that the biotechnological production of ethanol as a fuel must be carried out by continuous processes because of economical reasons (3). If in the future ethanol should be produced in large factories there is need of a continuous fermentation process, which is insensible against unavoidable troubles in practice and which, on the other hand, can be automatically controlled to avoid yield losses.

There are a lot of proposals for continuous alcoholic fermentation processes (5-14). Because of the fact, that the produced ethanol inhibits fermentation rate and yeast growth, all continuous fermentation processes proposed in scientific literature are multistage processes: the first stages with a low ethanol concentration serving for proliferation of yeast cells, the following stages serving for the bulk alcohol production.

Oxygen is known to be an essential growth factor for fermenting yeast. Although yeast growth is possible in strict anaerobic substrate solutions which contain some growth factors, e.g. biotin, pantothenate, inosite, thiamine, nicothinic acid and pyridoxine (2), as well as sterines (15) and unsatturated lipid acids (16), there is only need of biotin, pantothenate and inosite in aerobic fermentations (2). Thus continuous alcoholic fermentations are carried out in the presence of oxygen in catalytic amounts (17-24). Molecular oxygen is an important factor in regulation of mitochondrial and plasmatic enzyme synthesis (25, 26).

Oxygen demand in alcoholic fermentation at temperatures of 30-35°C and 7-10% (v./v.) ethanol as claimed for distillery practice is at least 0.2 mg O_2/g yeast x h (27, 28) and is higher than in beer fermentation.

Before discussing experimental data of our continuous alcoholic fermentation process, we would like to give a description by the help of brain experiments.

Looking at normal batch fermentations, we know, that a considerable growth of bacteria occurs only after the exponential growth phase of yeast. This is an indication that bacterial growth is reduced if there is a high yeast growth rate. Assuming a multistage continuous fermentation process, it will hardly be possible to maintain high yeast growth rates in all stages. Complete inhibition of bacterial growth doesn't occur at ethanol concentrations below 9% etOH (v./v.) (4). Thus we can expect an increased growth of bacteria in all stages characterized in a low yeast growth rate. Increased number of bacteria consequently results in yield losses. These thoughts lead our notion on a one stage process.

What will happen in the first stage of a multistage process? Assuming a positive result, we can expect, that on a long term basis there will be a selection of yeast cells, which have higher specific fermentation rates and are less inhibited by the produced ethanol. This would result in a slow increase of ethanol concentration in this stage. In the ideal case we would get yeast cells which are able to ferment all sugar in the first stage.

What will happen at troubles in a multistage process (e.g. interruption of sugar dosage)? As long as sugar is available, the yeast will ferment it and ethanol concentration increases. When sugar dosage later on is continued, the yeast can't ferment the same amount of sugar in the first stages (because of ethanol inhibition of fermentation rate). This will result in yield losses.

Compared to a multistage process, there will be no increase of ethanol in a one stage process at dosage interruptions because of the low sugar concentration. Consequently after continuation of dosage the yeast will be able to ferment at the prior rate.

As a result of this brain experiment we were searching for a yeast, which is able to grow and ferment at ethanol concentrations gained in distilleries, that means 7 to 10% (v./v.).

CHAPTER III

ALCOHOLOMETRY

Alcoholmetry is the name given to a variety of methods of determining the quantity of absolute alcohol contained in spirituous liquors. It will readily be seen that a quick and accurate method of making such determinations is of the very utmost importance to those who are engaged in the liquor traffic, since the value of spirit depends entirely upon the percentage of alcohol which it contains. When alcoholic liquors consist of simple mixtures of alcohol and water, the test is a simple one, the exact percentage being readily deducible from the specific gravity of the liquor, because to a definite specific gravity belongs a definite content of alcohol; this is obtained either by means of the specific gravity bottle, or of hydrometers of various kinds, specially constructed.

All hydrometers comprise essentially a graduated stem of uniform diameter, a bulb forming a float and a counterpoise or ballast. The hydrometers may either be provided with a scale indicated on the neck or else with weights added to sink the hydrometer to a certain mark. The first instruments are called hydrometers of "constant immersion," the others, of "variable immersion."

At the latter end of the last century, a series of arduous experiments were conducted by Sir C. Blagden, at the instance of the British government, with a view to establishing a fixed proportion between the specific gravity of spirituous liquors and the quantity of absolute alcohol contained in them. The result of these experiments, after being carefully verified, led to the construction of a series of tables, reference to which gives at once the percentage of alcohol for any given number of degrees registered by the hydrometer; these tables are invariably sold with the instrument. They are also constructed to show the number of degrees over- or under-proof, corresponding to he hydrometric degrees. Other tables are obtainable which give the specific gravity corresponding to these numbers.

The measurement of the percentage of absolute alcohol in spirituous liquors is almost invariably expressed in volume rather than weight, owing to the fact that such liquors are always sold by volume. Nevertheless, the tables referred to above show the percentage of spirit both by volume and weight.

In the United States the standard liquor, known as proof spirit, contains 92.3 percent by weight and 94.9 percent by volume, of absolute alcohol; it has a specific gravity of .9186 at 60°F. A proof gallon contains by measurement 100 parts of alcohol and 81.5 parts of water. The strength and therefore the value of spirituous liquors is estimated according to the quantity by volume of anhydrous spirit contained in the liquor with reference to this standard. Thus the expression "20 percent overproof," "20 percent underproof," means that the liquor contains 20 volumes of water for every volumes over or under this fixed quantity, and that in order to reduce the spirit to proof, 20 percent of water by volume, must be subtracted or added, as the case may be. Any hydrometer constructed for the measurement of liquids of less density than water may be employed. That known as "Syke's" is most commonly used for alcoholometric purposes. It is shown in Figure 11 and consists of a spherical brass ball A, to which is fixed two stems; the upper one B is also of brass, flat, and about 3 1/2 inches in length; it is divided into ten parts, each being subdivided into five, and the whole being numbered as shown in the figure. The lower stem C is conical, and slightly more than an inch long; it terminates in a weighted bulb D. A series of circular weights, of the form shown in the figure, accompany the instrument; these are slipped upon the top of the lower stem C, and allowed to slip down until they rest upon the bulb D. The instrument is used in the following way: It is submerged in the liquor to be tested until the whole of the upper stem is under the surface, and an idea is thus gained of the weight that will be required to partly submerge the stem. This weight is added, and the hydrometer again placed in the liquor. The figure on the scale to which the instrument has sunk when at rest is now observed, and added to the number on the weight used, the sum giving, by reference to the tables, the percentage by volume of absolute alcohol above or below the standard quantity.

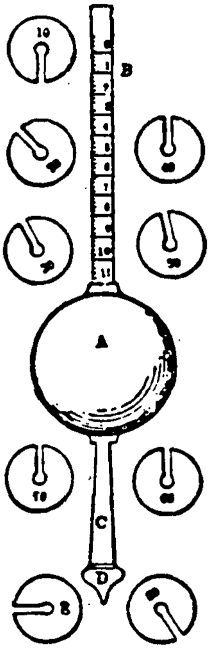


Figure 11., SYKE'S HYDROMETER

In exact estimations, the temperature of the liquor tested must be carefully registered, and the necessary corrections made. In Jones' hydrometer, which is an improvement upon Skye's, a small spirit thermometer is attached to the bulb, and by noting the temperature of the liquor at the time of the experiment, and referring to the tables accompanying the instrument, the strength is found at once without the need of calculation.

Dica's hydrometer is very similar to Jones' instrument above described. It is of copper, has a stem fitted to receive brass poises, a thermometer, a graduated scale etc.

In Europe, Gay-Lussac's hydrometer and tables are chiefly used for alcoholmetric testing. This instrument is precisely similar in construction to those of Twaddle and Baume. On the scale, zero is obtained by placing it in pure distilled water at 59°F., and the highest mark, or 100, by placing it in pure alcohol at the same temperature, the intermediate space being divided into 100 equal divisions, each representing one percent of absolute alcohol. The correction for temperature, as in the above cases, is included in the reference tables.

Another hydrometer, used in France for alcoholmetric determinations, is Cartier's. In form it is precisely similar to Baume's hydrometer. Zero is the same in both instruments, but the point marked 30° in Cartier's is marked 32° in Baume's, the degrees of the latter being thus diminished in the proportion of 15 or 16. Cartier's hydrometer is only used for liquids lighter than water.

The alcoholmeter of Tralles is the official instrument for testing alcoholic liquors in the U.S. but the instrument which is most generally used both here and abroad is that of Beume. There are two instruments bearing Beaume's name, one for liquids lighter than water, the other for those which are heavier. All hydrometers, alcoholmeters and saccharometers work on the same principle, though they are each differently graduated for the particular work to be done and the details of the measuring process are slightly different. All these instruments are provided with tables whereby their readings may be corrected and the specific gravity of the liquid determined.

The above hydrometric methods can be safely employed only when the spirit tested contains a very small amount of solid matter, since, when such matter is contained in the liquor in quantity, the density alone cannot possible afford a correct indication of its richness in alcohol. Many methods have been proposed for the estimation of alcohol in liquor, containing saccharine coloring and extractive matters, either in solution or suspension. Undoubtedly the most accurate of these, though at the same time the most tedious, is to subject the liquor to a process of distillation by which a mixture of pure alcohol and water is obtained as the distillate. This mixture is carefully tested with the hydrometer, and the percentage of alcohol in it determined by reference to the tables as above described; from this quantity and the volume of the original liquor employed the percentage by volume of alcohol in that liquor is readily found. The condensing arrangement must be kept perfectly cool, if possible in a refrigerator, as the alcohol in the distillate is very liable to be lost by re-evaporation. When great accuracy is desired, and time is at the operator's disposal, the above method is preferable to all others.

It is performed in the following manner: Three hundred parts of the liquor to be examined are placed in a small still, or retort, and exactly one-third of this quantity is distilled over. A graduated glass tube is used as the receiver, in order that the correct volume may be drawn over without error. The alcoholic richness of the distillate is then determined by any of the above methods, and the result is divided by three, which gives at once the percentage of alcohol in the original liquor. The strength at proof may be calculated from this in the ordinary way.

If the liquor be acid, it must be neutralized with carbonate of soda before being submitted to distillation. From eight to ten percent of common salt must be added, in order to raise the boiling point, so that the whole of the spirit may pass over before it has reached the required measure. In the case of the stronger wines it is advisable to distill over 150 parts and divide by two instead of three. If the liquor be stronger than 25 percent by volume of alcohol, or above 52 to 54 percent under-proof, an equal volume of water should be added to the liquid in the still, and a quantity distilled over equal to that of the sample tested, when the alcoholic strength of the distillate gives, without calculation, the correct strength required. If the liquor be stronger than 48 to 50 percent under-proof, three times its volume of water must be added, and the process must be continued until the volume of the distillate is twice that of the sample originally taken. In each case the proportionate quantity of common salt must be added.

For the estimation of alcohol in wines, liquors, etc., the following method may be employed: A measuring flask is filled up to a mark on its neck with the liquor under examination, which is then transferred to a retort; the flask must be carefully rinsed out with distilled water, and the rinsings added to the liquor in the retort. About two-thirds are then drawn over into the same measuring flask, and made up to its previous bulk with distilled water, at the same temperature as that of the sample before distillation. The strength is then determined by means of Syke's hydrometer, and this, if under-proof, deducted from 100, gives the true percentage of proof-spirit in the wine.

A quick, if not always very exact, method consists in determining the point at which the liquor boils. The boiling point of absolute alcohol being once determined, it is obvious that the more it is diluted with water the nearer will the boiling point of the mixture approach that of water; moreover, it has been proved that the presence of saccharine and other solid matters has but an almost inappreciable effect upon this point. Field's alcoholometer, since improved by Ure, is based upon this principle. It is shown in Figure 12, and consists, roughly speaking, of a cylindrical vessel A, to contain the spirit; this vessel is heated from beneath by a spirit lamp, which fits into the case B. A delicate thermometer C, the bulb of which is introduced into the spirit, is attached to a scale divided into 100 divisions, of which each represents one degree over-or under-proof. This method is liable to several small sources of error, but when a great many determinations have to be made, and speed is an object rather than extreme accuracy, this instrument becomes exceedingly useful. It does not answer well with spirits above proof, because the variation in their boiling points are so slight as not to be easily observed with accuracy. But for liquors under-proof, and especially for wines, beer, and other fermented liquors, it gives results closely approximating to those obtained by distillation, and quite accurate enough for all ordinary purposes. Strong liquors should therefore be tested with twice their bulk, and commercial spirits with an equal bulk, of water, the result obtained being multiplied by two or three, as the case may be.

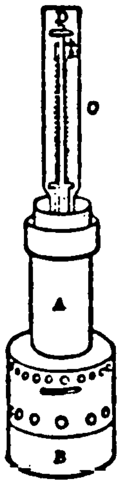


Figure 12. FIELD'S ALCOHOLOMETER

Another very expeditious, but somewhat rough, method was invented by Geisler. It consists in measuring the tension of the vapor of the spirit, by causing it to raise a column of mercury in a closed tube. The very simple apparatur is shown in Figure 13. A is a small glass bulb, fitted with a narrow tube and stopcock. This vessel is completely filled with the spirit, and is then screwed upon a long, narrow tube B, bent at one end and containing mercury. This tube is attached to a graduated scale showing the percentage of absolute alcohol above or below proof. To make the test the cock is opened, and the bulb, together with the lower part of the tube, is immersed in boiling water, which gradually raises the spirit to its boiling-point. When this is reached, the vapor forces the mercury up the tube, and, when stationary, the degree on the scale to which it has ascended gives directly the percentage of alcohol.

Another method, which is not be relied on for very weak liquors, but which answers well for cordials, wines, and strong ales, is that known as Brande's method. The liquor is poured into a long, narrow glass tube, graduated centesimally, until it is half-filled. About 12 or 15 percent of subacetate of lead, or finely powered litharge, is then added, and the whole is shaken until all the color is destroyed. Powered anhydrous carbonate of potash is next added until it sinks undissolved in the tube, even after prolonged agitation. The tube is then allowed to rest, when the alcohol is observed to float upon the surface of the water in a well-defined layer. The quantity read off on the scale of the tube and doubled, gives the percentage by volume of alcohol in the original liquid. The whole operation may be performed in about five minutes, and furnishes reliable approximative results. In many cases it is necessary to add the lead salt for the purpose of decolorizing the liquid.

For the investigation of the amount of sugar in, or the concentration of the mash, or beer, a specially scaled hydrometer is used which is termed a saccharometer. Sugar possesses a higher degree of specific gravity than water, and hence it follows that the greater the amount of sugar in the mash the higher will be the specific gravity. The less the hydrometer sinks into the fluid the greater the amount of sugar present. Saccharometers are provided with thermometers whereby the reading may be corrected to a standard temperature, usually 59°F. The saccharometer is correct for solutions containing sugar alone but it is only approximately correct for mash liquor which contains a variety of other matters in variable quantities.

It is a prime necessity that the distiller should be able to determine if the mash has been completely saccharified by the malt. For this purpose a solution of iodine is used. Iodine gives to starch a blue color. If the starch however, has been completely changed into sugar there will either be no discoloration or the filtered mash liquid which is at first a yellowish red becomes blue then violet, and at last red.

Determination of the Purity of Alcohols. While the knowledge of the amount of alcohol contained in a liquid is of great practical utility, this does not give any idea of the impurities present.

An alcohol of 100 degrees or an absolute alcohol, may contain numerous impurities which may greatly affect its quality. It is therefore necessary in addition to analyze the purity of the alcohol.

In commercial practice there are certain simple processes which will give a basis by which to determine the impurities left after distillation and rectification. These processes are largely empirical. They are based on the perception of the senses and are consequently of an entirely relative degree of precision. Nevertheless, when made by a practical expert, the operation may give very useful preliminary indications.

This test is made in a glass of special shape broad at the bottom and narrowing at the top in order to concentrate the aroma of the product. Ordinary brandies are tested undiluted. Commercial alcohols, of about 95 degrees must be diluted with water to a maximum of 30 degrees. Otherwise the burning tang of the alcohol would preclude any delicacy of perception and allow impurities to pass unnoticed.

For the examination by sense of taste, the operator rinses his mouth for a moment with the liquid itself. The taste of ethyl alcohol is fairly transient; it disappears quickly allowing the taste of the accompanying foreign matter to be perceived almost immediately afterward. With a little practice this test enables one to distinguish by their flavor the primal origin of alcohols and to judge of their purity. Some professionals succeed by training in arriving at high degree of skill in the art of tasting alcohol as it should be done.

In order to determine the purity of alcohol there are besides chemical tests used by the trade. These tests, which consist in characterizing and measuring separately the impurities which alcohol may contain, such as acids, ethers, aldehydes, bases, etc., belong exclusively to analytical chemistry; they are extremely delicate and complicated. We will not venture to touch upon them here.

One of the simplest tests for purity is that of Barbet. This is based upon the time taken to discolor a solution of permanganate of potash under the action of the tested alcohol. It is not only very rapid but in general more practical than other tests. It allows the aggregate of the impurities contained in an alcohol to be ascertained in a single operation.

The permanganate solution used is very weak (0. gr. 200 of salt), and of a violet-red color. The technique of the proceeding is as follows: 50 cubic centimeters of the alcohol to be tested are placed in a glass vessel the temperature of which is maintained at 64.40°F. 2 cubic centimeters of the permanganate solution are abruptly added and the time noted to within a second. Discoloration is awaited and as soon as it takes place the time is again noted. The total discoloration of the permanganate is not very marked and passes through intermediate stages; therefore it is preferable not to await complete discoloration but to stop at a pale salmon tint, which tint may be comparatively fixed by a sample of colored liquid (say a solution of fuchsine and chromate of potash).

The comparative times of discoloration obtained by M. Barbet with various commercial alcohols, are as follows:

Pure alcohol	43 min. 30 sec.
Extra fine alcohol	5 min. 30 sec.
Semi fine alcohol	5 min. 10 sec.
Medium flavor alcohol (first running)	5 min. 5 sec.
Mediocre alcohol	5 min. 11 sec.
Medium flavor alcohol (last running)	2 min. 12 sec.

CHAPTER IV

A STANDARD PROCESS OF PRODUCING ALCOHOL FROM AGRICULTURAL PRODUCTS

Alcohol from Potatoes

In certain countries, as for instance Germany and France, potatoes form the greatest source of alcohol, particularly for industrial purposes. With the possible exception of corn and beets they will probably be most used in America.

The best potatoes for distilling are those which are most farinaceous when boiled. In other words, those which are "mealy" and most appetizing. These give the largest yield of alcohol per bushel. The best season of the year in which to use potatoes is from October to March, when they germinate.

The potatoes should be kept in dry cellars, and at even temperatures, warm enough to prevent freezing and not so warm that they will rot or sprout. Diseased potatoes may however be used, if they have not been attacked by dry rot, though they are not so easily worked. Frosted potatoes may be also used, but they must not have been completely frozen.

Before being steamed, the potatoes should be washed, either by hand or by a machine, care being taken to remove all stones, clods of earth, and other foreign substances which might impede the subsequent operations.

There are three main methods of saccharifying the fecula or starch of the potato. The first and most important by reducing the tubers to a pulp, and malting the entire mass. The second and third, by rasping the potatoes and so separating the fecula or starch grains from the mass, and then making a thin liquor or wash containing this fecula.

Originally, in the first process, the washed potatoes were submitted to the action of boiling water, but later cooking by steam at a temperature of 212°F. was used, as being much more convenient to handle and more effective in action. The object of steaming is to break the coating and reduce the contents thereof to a pasty condition, wherein the starch is more effectively acted on by the malt and yeast. Ordinary steaming does not, however, render the pulp sufficiently pasty; some of the starch remains undissolved and is lost, hence in the modern practice, steam is turned into the steaming vat under a pressure of three or four atmosphere (45 to 60 lbs. to the square inch).

High pressure steaming will be later described but the simple and older method of mashing and apparatus therefor, used prior to 1870, was as follows:

Figure 14 shows a section of a steaming vat. This consists of a conical wooden tub H provided at its top with a suitable cover O having a trap or door P for putting in the potatoes. This as shown, consists of a hinged lid, having a button p or other fastening means. This lid and cover should be of course steam tight, and it would be better to have it clamped down by a screw clamp than held by a button.

Somewhat above the bottom of the vat, a steam inlet pipe I enters, connected at its other end by a coupling i with a suitable steam generator (see Figure 16). Preferably the outlet of this pipe is screened by a perforated plate M so that it may not be clogged by the pulp. It is also best that a filling piece be placed at the junction of the bottom with the sides in order that there be no sharp corner from which the pulp may not be easily cleaned out.

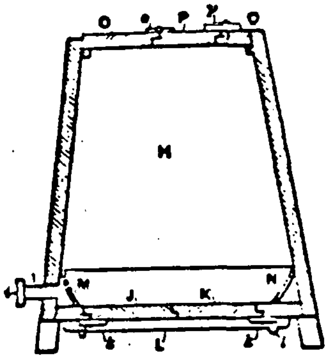


Figure 14. STEAMING VAT FOR POTATOES

The bottom of the vat may either have a discharge door at the side as in Figure 17 or at the bottom, as in Figure 14.

An under side view of the latter construction is shown in Figure 15. The bottom of the vat is made in two parts or doors J K. These are held closely by a transverse bar L inserted at its end into a stirrup 1^1 and supported at its other end by a button 1, or other means.

While various forms of steam generators may be used, Figure 16 shows a simple construction well adapted to the needs of a small distillery. D designates the brick work of a furnace, and A the boiler. This is so set that an annular space E surrounds the sides of the boiler, through which the products of combustion must pass.

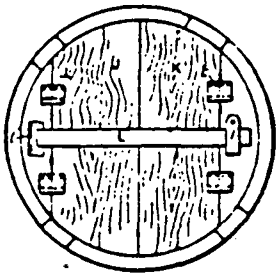


Figure 15. BOTTOM OF STEAMING VAT

The head of the boiler is connected by a pipe B and collar b to the steam inlet pipe I of the steaming vat, heretofore described, as by the collars b i.

A filling tube C enters the boiler and projects nearly to the bottom, and the water outlet-pipe F with cock f leads off from the upper water line. The tube C forms also a safety valve, for if the steam pressure becomes too great in the boiler and connected vat, it will force water up and out through the tube. If, however, the water falls below the level of the lower end of the tube, steam will issue and warn the attendant that water is too low. It would be best however, to provide a steam gauge, whereby the pressure of steam in the boiler and vat could be accurately indicated.

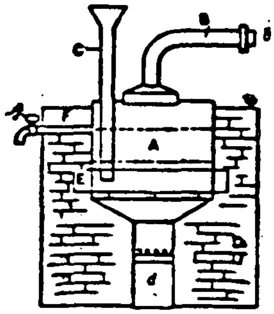


Figure 16. STEAM GENERATOR

It is to be noted that when steamed the potatoes will swell and occupy more space and that the steam vat should therefore not be much more than two-thirds filled with potatoes.

With the steaming vat above shown, the potatoes are delivered mixed with a considerable quantity of water, but a better plan is to have a perforated false bottom to the tub, whereby the condensed water may be carried away, the steamed potatoes remaining behind.

Two hours of steaming should reduce the potatoes to proper condition, which may be tested by introducing a pointed iron rod through a suitable aperture, normally kept closed. If the rod passes freely inward, the potatoes are done and may be discharged into the crusher, shown in Figure 17. In this Figure the steaming vat A is shown mounted above the crusher. A pipe B with cock b leads to the steam generator. The steamed potatoes are shoveled out through the door a, which is usually held closed by means of the clamps or buttons a' a".

The crusher consists of a hopper C whose bottom fits closely against two adjacent smooth faced rools H I or iron. These are driven by gears D E. The shafts of these gears have cranks d d whereby it may be operated. These gears are unequal so that the rolls shall move at different speeds, and thus one will have a grinding action against the face of the other. A counter weighted scraper e bears against the face of the roll.

The crushed potato pulp passes between the rolls and into a bin beneath, having adjustable walls made of boards F, sliding in suitable guides f, from which the pulp may be shoveled into the mashing tank or "back." The crusher might, however, be arranged to deliver immediately into the mashing tank, if the latter is provided with means for stirring the delivered pulp.

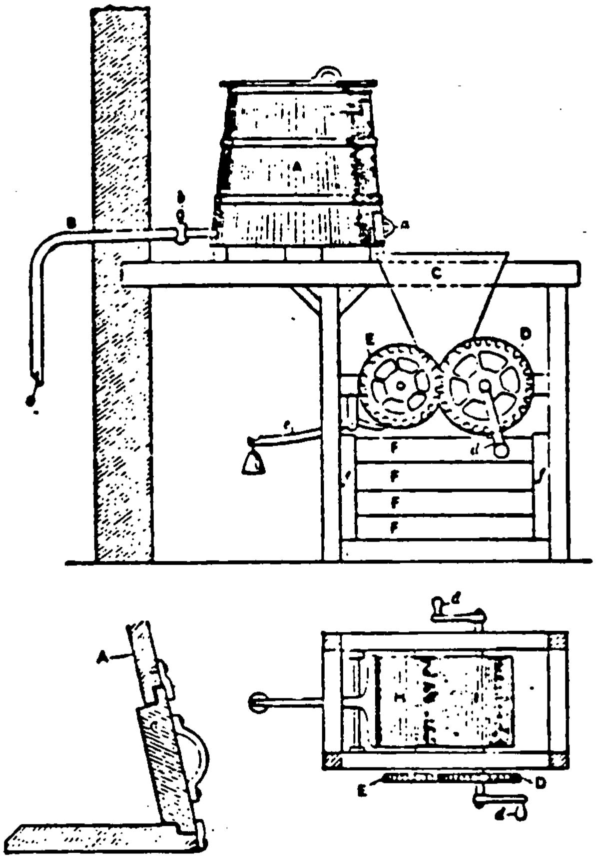


Figure 17. POTATO STEAMER AND CRUSHER

The pulp or paste thus made is now placed in a vat, holding about 650 to 850 gals., in which the saccharification takes place. About 2200 lbs. of the crushed potatoes and 155 lbs. of broken malt are introduced, and immediately afterwards water is run in at a temperature of about 97°F to 104°F., the contents being well stirred with a fork meanwhile. The vat is then carefully closed for half an hour, after which boiling water is added until the temperature reaches 140°F., when the whole is left for three or four hours. The process of fermentation is conducted in the same vat. Alternate doses of cold and boiling water are run in upon the mixture, until the quantity is made up to 700 or 775 gallons, according to the size of the vat, and so as finally to bring the temperature to 75°F. or 79°F. Five and half to six gallons of liquid brewer's yeast are then added, and fermentation speedily sets in. This process complete, the fermented pulp is distilled in an apparatus devised for distilling materials of a pasty nature; the product has a very unpleasant odor and taste.

The process above described is the old method of pulping the potatoes by using steam. Under the modern method, however, and with modern apparatus, in preparing potatoes for distillation in large quantities, the steaming of the material is accomplished at one time and under a high steam pressure. The apparatus is also used for the preparation of corn, potatoes and other starch-containing substances.

There are many apparatuses which have been devised for the purpose, but the principle on which they work is practically the same in all cases. They comprise a closed tank, fitted with stirrers, agitators, or other means for mixing and comminuting the contents, means for admitting steam under pressure, means for cooling the mixture to the proper mashing temperatures, and means for forcing the steamed material out of the tank.

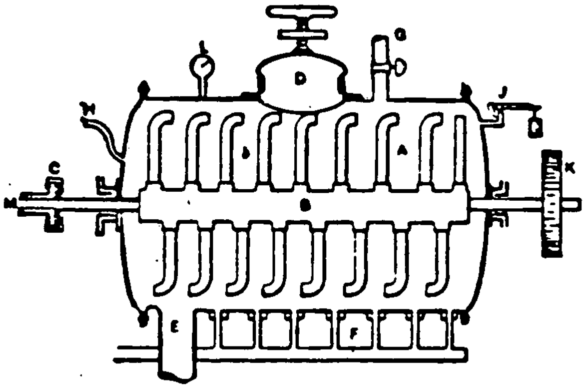


Figure 18. BOHN'S STEAMER AND CRUSHER

The Steamer. One of the earliest forms of steamer was that of Hallefreund devised in 1871, and adapted for working on a large scale. A modified form of the apparatus known as Bohn's steamer and masher is illustrated in Figure 18. This comprises a steaming cylinder A, having a securely closed opening D for the introduction of the potatoes. Centrally through the cylinder passes a hollow shaft B, which is rotated by the power pulley K. Hollow arms b project radially from the shaft B. These act as mixers of the mash and as coolers. The shaft B at one end is connected to a cold water supply pipe M as by a coupling C, the supply pipe being provided with a cock. E designates a discharge opening for the mash. A pipe F provides for the entrance of steam into the cylinder. G is a pipe through which malt is put in to be mixed with the pulp. L is a steam gauge and J is a safety valve. H designates a water pipe.

In operation the potatoes are placed in the cylinder A and submitted to the action of steam at about 46 lbs. to the square inch, and at a temperature of from 266°F. to 275°F.

When disintegrated, the steam is blown off, and the potatoes crushed by rotating the stirring shaft. As the pulp must be reduced from 275°F. to 149°F., the mashing temperature, cold water is forced into the stirrer which chills the blades and quickly cools the mass.

In the vacuum mash cooker the steaming cylinder is partly filled with hot water at 140°F. to 150°F. The potatoes to be mashed are fed into the cylinder whole. The steamer is then closed and steam admitted while the mash is stirred until a pressure of 65 pounds is reached, when the dissolution of the starch is complete. The steam is then exhausted and the temperature reduced to 212°F. To reduce this temperature to the proper saccharifying point of 145°F., the hot air is exhausted.

Barley malt meal in the proportion of 6 to 10 percent is used. This has been previously mixed with cold water in the small grain masher. The malt is admitted to the cylinder and thoroughly mixed with the potato, when the mixture is withdrawn into a drop tub, where it is still further stirred. It is then cooled and then fermented.

While the crushed potatoes are being cooled and stirred, a mixture of green malt with water is prepared in an adjacent vat, and when the pulp in the cylinder has been reduced to 149°F. the malt mixture is introduced into the cylinder through the pipe G and thoroughly mixed with the crushed potatoes. The mass is now left to saccharify; the stirrer being operated at intervals throughout this period. This machine might be readily modified so that the steam should enter through the stirrers, by tubes attached to the arms, then the steam may be shut off and cold water sent into the arms themselves to cool the mash.

A variety of steamer used in various forms and modifications in all the larger distilleries, is known as the Henze steamer. In this, there are no stirrers. The cylinder is conical, and has steam pipes leading to the interior. At the end of its cone-shaped bottom it terminates in a blow-off tube, having in it a grate formed of sharp-edged bars. In operation, steam is introduced at a pressure of one to two atmospheres until the potatoes are cooked. More steam is then suddenly admitted at high pressure and the softened potatoes forced through the grating at the bottom and into the mashing apparatus in a finely divided state.

In steaming under pressure it is best that the safety valve be so regulated that the steam will constantly blow off as this action keeps the potatoes in motion and facilitates disintegration. Care should also be taken to see that everything about the apparatus is in good condition, as in working under the high pressures used in the last apparatus there is liability of explosion. Rust should be particularly guarded against.

With this apparatus a preparatory mash vat is used into which the contents of the steamers are blown out, malt and water to form milk having been previously let into the mash vat. Blowing out is accomplished in 45 or 50 minutes at 130°F. and about one-sixth of the charge in the steamer is retained in the steamer. The mash in the vat is stirred and cooled and the remainder of the mash blown in raising the temperature to 145°F. when the mash is left to stand from half an hour to an hour. With heavy mashes, rich in sugar, even higher temperatures than 145°F. can be used for saccharifying.

The processes of crushing and saccharifying, above referred to, which are almost entirely used today, requie steam. The following methods provide for the isolation of the fecula or starch, without steam and the production of a wash of a more watery consistency, therefore easier to handle in ordinary stills, and with less liability to burn.

Two operations are necessary by this method: First, rasping, or reducing the potatoes to a finely crushed and pulpy condition by means of a machine described in the chapter on Beet Mashing; and second, the separation of the fecula.

To this latter end the potato pulp is placed on a sieve, having side walls and net work of horse-hair, which is placed over a suitable tub. Water is run gradually through the pulp and sieve, while the pulp is rubbed up by hand. When the water comes through clear, then all the fecula of the pulp has been washed out, and the refuse left in the sieve can be thrown aside or used as a food for cattle.

For a mashing tub of say about 32 bushels capacity, the fecula from about 800 lbs. of potatoes is used. This is deposited in the mash tub with sufficient cold water to form a fairly clear paste. About twice as much water as fecula will bring the paste to proper consistency. This mixture should be constantly stirred as otherwise the fecula will sink to the bottom. About 40 gallons of boiling water are then added gradually. The mixture has at first a milky appearance, but at the last becomes entirely clear.

This liquid is mashed with about 45 lbs. of malted barley or Indian corn, ground into coarse flour. In ten minutes the mixture will be completely fluidified. It is then left to subside for three or four hours when it will have acquired a sweetish taste and be what is termed as "sweet mash." The fluid is then further diluted by the addition of sufficient water to give about 290 gallons of wash. Two or three pints of good yeast will bring this mixture to a ferment.

A less laborious method of accomplishing the same result is that at one time used in English distilleries. In this a double bottom tub is used, something like that shown in Figure 14, the upper bottom of which is perforated, and raised above the solid lower bottom. A draw-off cock opens out from the space between the two bottoms.

Assuming that the tub is of 220 gallons capacity, the from 2 to 20 lbs. of chaff are spread over the perforated bottom and pulp from 800 lbs. of raw potatoes placed on that. This is thoroughly drained for half an hour, through the draw-off cock. The pulp is then stirred while from 90 to 100 gallons of boiling water are added gradually. The mass then thickens into a paste. The paste is mashed with about 65 lbs. of well steeped malt, and the liquid left to subside for three or four hours. It is then drained off through the perforated bottom into a fermenting back or tub. For this amount of material the back should be of about 300 gallons capacity.

The leavings left in the preparatory tub still contain considerable starch, and after they are well drained they should be mixed with from 50 to 55 gallons of boiling water. The mixture is then agitated and drained off into the fermenting back. The sediment left is again sprinkled with water, this time cold, which is drained off into the back. This completely exhausts the husks left on the upper bottom. By this process 200 lbs. of potatoes should produce something over 12 1/2 gallons of spirit.

The objection to the last method described is that the spirit so obtained is unpleasant to taste and smell, but this would probably not be an objection for industrial uses.

The only means of obtaining alcohol of good quality from potatoes is to extract the starch separately and then convert it into sugar. This saccharification of the starch may be accomplished by sulphuric acid or by the action of diastase.

By the first of these methods the potatoes are disintegrated in such an apparatus as the Bohn steamer. A mixture is made of one-third potatoes, two-thirds water, and one-tenth part of sulphuric acid. The mixture is steamed for six or eight hours under pressure. The mash is then cooled and the acid neutralized by milk of lime. It is then fermented.

By the second and preferable method, dry or wet potato starch is used, which is malted, and the saccharine solution fermented with yeast. The proportions and method for a vat of say 800 gallons capacity are as follows:

Two hundred and sixty-five gallons of water are mixed with 1100 lbs. of dry or 1650 lbs. of moist starch. This mixture is well agitated, and 450 gallons of boiling water run in, together with 165 lbs. of malt. The whole is then stirred energetically and left to saccharify for three or four hours. The saccharine solution thus formed must be brought to 6° or 7° Baume, at a temperature of from 71° to 75°F. To this is then added 1 1/100 lbs. of dry yeast for every 220 gallons of "must." Fermentation is soon established and usually occupies about 36 hours. After remaining at rest for 24 hours the "must" is distilled. From each 220 lbs. of starch there should be a yield of about nine gallons of alcohol, at 90°F.

The fermentation of the potato mash is carried on as described in Chapter II.

Alcohol from Grain-Corn, Wheat, Rice, and Other Cereals

The different cereals constitute a very important source of alcohol in all countries, particularly of course for use in the manufacture of whiskey and gin.

All cereals contain an abundance of starchy substance which under the influence of diastase—that is, malt—is converted into fermentible sugar. The quantity of sugar and hence the yield of alcohol differs widely. The following table shows the results obtainable by good workmanship.

220 lbs Wheat	gives 7.0 gallons pure alcohol
220 lbs Rye	gives 6.16 gallons pure alcohol
220 lbs Barley	gives 5.5 gallons pure alcohol
220 lbs Oats	gives 4.8 gallons pure alcohol
220 lbs Buckwheat	gives 5.5 gallons pure alcohol
220 lbs Corn (Indian)	gives 5.5 gallons pure alcohol
220 lbs Rice	gives 7.7 gallons pure alcohol

In addition to these there are other raw materials containing starch which are sometimes used, as millet (55 percent starch), chestnuts (28 percent), and horse chestnuts (40 percent). The last is very difficult to work however.

Rice, wheat, rye, barley and corn are more frequently employed than other grains. Wheat gives a malt which is as rich in diastase as barley. Barley and buckwheat are added to these in some proportions. Oats, owing to their high price, are rarely used. Rice, of all the grain is the most productive to the distillers, but on account of its value as a food is not much used for the production of alcohol, unless damaged. Corn is the cereal most largely used for the production of industrial alcohol.

Great care should be exercised in making choice of grain for fermentation where the best results are desired. Wheat should be farinaceous, heavy and dry. Barley should be free from chaff, quite fresh and in large uniform grains of a bright color.

Rice should be dull white in color, slightly transparent, without odor, and of a fresh, farinaceous taste.

The flour or farinaceous part of grain is composed of starch, gluten, albumen, mucilage, and some sugar. The following table gives the proportions of these substances in the commonest grains.

Under certain conditions the albumen or gluten in the grain has the power of converting starch into saccharine matter. This is better effected by an acid such as sulphuric acid, or by a diastase. This latter substance is a principle developed during the germination of all cereals but especially of barley. it has the property of reacting upon starchy matters, converting them first into a gummy substance called dextrine, and then into glucose or grape sugar, see Chapter II.

The action of diastase upon starch or flour made into a paste is remarkable, 50 grains of diastase being sufficient to convert 220 lbs. (100 kilogrammes) of starch into glucose. The rapidity of this change depends on the quantity of water employed, and the degree of heat adopted in the operation.

Table IV - Proportions of Starch, Gluten, Etc., in Principal Grains

Grains	Starch	Glutens and other Azotized Substances	Dextrine, Glucose, and similar substances	Fatty Matter	Cellulose	Inorganic Salts, (Silica, Phosphates, & c.)
Wheat (average of five varieties)	65.99	18.03	7.63	2.16	3.50	2.69
Rye	65.65	13.50	12.00	2.15	4.10	2.60
Barley	65.43	13.96	10.00	2.76	4.75	3.10
Oats	60.59	14.39	9.25	5.50	7.06	3.25
Indian Corn	67.55	12.50	4.00	8.80	5.90	1.25
Rice	89.15	7.05	1.00	0.80	1.10	0.90

Inasmuch as barley germinates very readily, and develops a larger proportion of diastase than any other grain, except wheat, it is generally used as a producer of diastase.

There are many methods of preparing grain for fermentation, but all use at least two of the following operations: grinding, gelatinizing, steeping, or steaming, mashing saccharifying.

Grinding. Where cookers or the Henze steamers are not used every form of grain should be crushed or ground into a coarse flour. This is in order that the starchy interior may be easily acted on by the diastase. If the grain is not to be mixed with malt later it must be ground more finely so that it may be thoroughly penetrated by the water. The grains should not be ground except as required, as ground grain is liable to heating and consequent loss of fermentability, and is also liable to become musty, in which condition it loses much of its fermentability.

Steeping. This operation is best carried on in vats or tanks of iron or cement, for the reason that wood absorbs impurities which are communicated to the grain, thus lessening its germinative power. Wooden vats should be thoroughly scrubbed after use, and be kept continually whitewashed. The steeping tub should hold about two-thirds more than the amount of ground grain to be steeped.

Steeping is affected by pouring on to the crushed grain hot and cold water in such quantity that after 10 minutes or so of brewing the mixture will have a temperature of 75° to 95°F.

This warmth makes the water more penetrating. The water should not be poured in all at once, but a little at a time, until the grain is covered to a depth of three or four inches. Care should be taken not to let the temperature get too high, not above 95°F., as a temperature above that point kills the germinating power.

The mixture of crushed grain and water is now stirred for 10 minutes and then left to subside for half an hour. It is then stirred again and the mixture left to steep for 30 or 40 hours, depending on the temperature of the atmosphere, the dryness of the grain, and the character of the water. In very warm weather the water should be changed every few hours by running it off through a hole in the bottom of the tub and running in fresh at the top. This prevents fermentation setting in prematurely.

When the grain swells, and yields readily between the fingers it has been sufficiently steeped, and the water is run off. This is an old method of gelatinizing grain, but a better way is by the use of cookers or high pressure steamers as described for potatoes.

Mashing. This consists in mixing the coarse flour with malt and then by means of certain operations and mechanisms bringing it to a condition most favorable to fermentation through the action of yeast. The mixing of the raw flour with barley or other malt effects the conversion of the starch of the grain into maltose. The yeast afterwards converts this maltose into sugar.

Saccharifying. To effect the action of the diastase of the malt on the grain, in the old methods, boiling water must be poured into the vat until the temperature of the mass reaches about 140° to 168°F., the whole being well stirred meanwhile; when this temperature has been reached, the vat is again covered and left to stand for four hours, during which time the temperature should, if possible, be maintained at 140°F., and on no account suffered to fall below 122°F., in order to avoid the inevitable loss of alcohol consequent upon the acidity always produced by so low a temperature. In cold weather the heat should of course be considerably greater than in hot. It should be also remarked that the greater the quantity of water employed, the more complete will be the saccharification, and the shorter the time occupied by the process.

Having undergone all the above processes, the wash is next drawn from the mash tub into a cistern, and from this it is pumped into the coolers. When the wash has acquired the correct temperature, viz., from 68° to 78°F., according to the bulk operated upon, it is run down again into the fermenting vats situated on the floor beneath. Ten to twelve pints of liquid or 5 1/2 to 6 1/2 lbs. of dry brewer's yeast are then added for every 220 lbs. of grain; the vat is securely covered, and the contents are left to ferment. The process is complete at the end of four or five days, and if conducted under favorable conditions there should be a yield of about 6 1/6 gallons of pure alcohol to every 220 lbs. of grain employed.

There are a number of different methods of mashing, having each its advantages, and applicable to particular varieties of grain.

We will first consider the mashing of the steeped grain in general by one of the older and simpler processes.

The grain to be mashed, which has been ground and steeped as before described, is mixed with malt in the proportion of four to one, or even eight to one. In addiion, three or four pounds of chaff to every hundred or so pounds of steeped grain should be used.

Mash. Water is then run into the mash tub in the proportion of about 600 gallons to each 60 bushels of grain. Its temperature should be between 120° and 150°F. During the entrance of water, the mass is well stirred so as to cause the whole of the grain to be thoroughly soaked and to prevent the formation of lumps. It is best to add the grain to the water gradually and to stir thoroughly.

To this mass about 400 gallons of boiling water is gradually added to keep the temperature at about 145°F. During the addition of the boiling water the mash should be continually stirred so that the action of the water shall be uniform. This operation should last about two and one half hours. The vat should be then covered and left to stand from three-quarters to one hour for saccharification.

Another method of saccharifying is to turn boiling water gradually into the mash tank until the mixture has acquired a temperature of from 140° to 180°F. The mass is thoroughly stirred, and the tub is covered and left to subside for from two to four hours, during which time the temperature should not be allowed to fall below 120°F. A small tub needs more heat than a larger tub, and more heat is required in winter than in summer.

A convenient method of regulating the temperature of the mash tank, would be by a coil of pipes on the bottom. This would be connected by a two-way cock to a steam boiler and to a source of cold water. Heat should never be carried over 180°F., and the best temperature is from 145° to 165°F.

The greatest effect of the diastase of the malt upon the gelatinized starch is at 131°F. For ungelatinized starch this is not great enough, hence the greater part of the mashing is carried on at the lower temperature and only towards the end should the temperature be raised to the maximum 150°F.

Every distiller uses his own judgment as to the amount of the mashing water used, its temperature, the length of time during which the mash rests, and the length of time for saccharification.

Saccharification may be recognized by the following signs: The mash loses its first white mealy look and changes to dark brown. It also becomes thin and easily stirred. The taste is sweet and its odor is like that of fresh bread.

Corn and other grain may be mashed conveniently in an apparatus as used for potatoes, the steam being introduced under pressure.

The water is first placed in the steamer. Steam is introduced into the water and it is brough to a boil. The corn is then introduced gradually, the steam pressure increased to its maximum, and the mass blow out.

The corn or grain not previously crushed or ground is introduced into a steamer in the proportion of 200 lbs. of corn to 40 gallons of water. The steamer should have about 100 gallons of steam space for this amount.

The mashes described above are thick, more or less troublesome to distil, and only simple stills can be used. By the following method a clear saccharine fluid or wort can be obtained.

A mash vat is used having a double bottom. The upper bottom is perforated and between the two bottoms is a draw-off pipe and a pipe for the inlet of water.

Upon the upper perforated bottom is first placed a layer of between two and three pounds of chaff. Upon this is turned in a mixture of 400 lbs. corn and malt in the proportions of 1/5 malt to 4/5 grain. Eighty-seven gallons of water at a temperature of from 85° to 105°F is then let in to the bottom, while the mixture is thoroughly agitated for 10 minutes. It is then left to subside for half an hour.

After this steeping process, the mass is again agitated while 175 gallons of water at 190°F are let into the tub while the mass is continually and thoroughly stirred by mechanical stirrers. Brewing lasts for half an hour, and the liquid is then left to stand for seven hours.

At the end of this period the grain is covered by clear liquid which is drained off through the draw-off cock into the fermenting back.

To the contents left in the steeping tank 135 gallons of boiling water are added as before and the liquid therefrom drawn into the fermenting back.

It usually requires three infusions to extract the whole of the saccharine and fermentiscible matters contained in the grain. In some places, it is customary to boil down the liquors from the three mashings until they have acquired a specific gravity of about 1.05, the liquor from a fourth mashing being used to bring the whole to the correct degree for fermentation, the liquors from the third and fourth being boiled down to the same density and then added to the rest. In a large Glasgow distillery, the charge for the mash tubs is 29,120 lbs. of grain together with the proper proportion of malt. Two mashings are employed, about 28,300 gallons of water being required; the first mashing has a temperature of 140°F., and the second that of 176°F. In Dublin the proportion of malt employed is only about one-eighth of the entire charge. One mashing is employed, and the temperature of the water is kept at about 143°F. The subsequent mashings are kept for the next day's brewing.

By this process the grain is entirely deprived of all fermentible substances which have been carried away in a state of liquid sugar.

The whole operation of preparing and saccharifying grain is today carried on in steamers; or in the Henze high pressure steamers and preparatory mash vats described in Chapter II.

In steaming grain without pressure, the finely crushed grain is poured slowly into a vat previously nearly filled with water at a temperature of about 140 degrees F. A little less than half a gallon of water is used for each pound of grain. Care must be taken to stir the mass constantly to prevent lumping. When all the corn is mixed in, steam is allowed to enter and the temperature raised to about 200 degrees F. It should be left at this temperature for an hour or an hour and a half, when the temperature is reduced to 140°F. when about 10 percent of crushed malt is added and the temperature reduced to 68°F. by means of suitable cooling devices.

When steam cookers are used, the cylindrical boiler is first filled to the proper degree with water at a temperature of 140°F. The meal is then let in gradually being constantly stirred the while. The boiler is then closed and steam gradually let in while the mass is stirred until a pressure of 60 pounds and a temperature of 300°F has been reached. The starch then becomes entirely gelatinized, the pressure is relieved, and the temperature reduced to 212°F. and then rapidly brought to 145°F. The malt is added mixed with cold water, at such a stage before the saccharifying temperature is reached that the cold malt and water will bring it to 145°F. The malt is stirred and mixed with the mash for five or ten minutes and the mixed mass let into a drop tub when saccharification is completed. It is then cooled as described.

When the Henze steamers are used the grain may be treated in either the whole grain or crushed, as the high pressure to which it is subjected and the "blowing out" act to entirely disintegrate it. In this mode of operation, water is first let into the steamer and brought to a boil by the admission of steam. The grain is then slowly let into the apparatus. The water and grain should fill the steamer about two thirds full. The steamer is left open and steam circulated through the grain and water for about an hour, but without any raising of pressure. This acts to thoroughly cook and soften the grain.

When sufficiently softened the steam escape cock in the upper part of the steamer is regulated to allow a partial flow of steam through it and a greater flow of steam is admitted through the lower inlet. This keeps the grain in constant ebullition under a pressure of 30 lbs. of so. After another period of an hour the pressure in the steamer is raised to 60 lbs. at which point it is kept for half an hour, when the maximum steam pressure is applied, and the greater portion of the disintegrated mass blown out into a preparatory mass tub, into which malt has been placed mixed with water. The blowing out should be so performed that the temperature in the mass in the tubs shall not exceed 130°F. The mass is stirred and cooled and then the remainder of the mass in the steamer admitted to the tub which should bring the temperature of the mass up to 145°F. It is kept at this temperature for a period varying from half an hour to one and one-half hours and is then cooled to the proper fermenting temperature.

Another method of softening corn so that its starch is easily acted upon by the diastase of the malt is to steep it in a sulphurous acid solution at the temperature of about 120°F. for from fifteen to twenty hours. The mass is then diluted to form a semi-liquid pulp and heated to about 190°F. for an hour or two during which the mass is constantly stirred. The malt is then added. the mass is saccharified, cooled and then fermented.

Another method is to place mixed grain and hot water in a cooker of the Bohn variety (Figure 18). After half an hour of stirring and cooking under ordinary pressure, the steam pressure is raised to 45 lbs. This is kept up for from two to three hours when the grain is reduced to a paste. Concentrated muriatic acid equal to 2 1/2 percent of the weight of grain is then forced in, under steam pressure. In half an hour the grain will be entirely saccharified and ready for fermenting.

Alcohol from Beets

Cultivation. The beetroot (Beta vulgaris), indigenous to Europe, is cultivated in France, Germany, Belgium, Holland, Scandinavia, Austria, Russia, and to a very small extent in England and New Zealand, and to a very large extent in the United States and Canada. There are many varieties. The most important to the sugar-maker is the white Silesian, sometimes regarded as a distinct species (B. alba); it shows very little above ground, and penetrates about 12 in.; it has a white flesh, the two chief forms being distinguished by one having a rose-colored skin and purple-ribbed leaves, the other a white skin and green leaves. Both are frequently grown together, and exhibit no marked difference in sugar-yielding qualities.

Good sugar-beets possess the following broad characteristics: (1) Regular pear-shaped form and smooth skin; long, tapering, carrot-like roots are considered inferior; (2) white and firm flesh, delicate and uniform structure, and clean sugary flavor; thick-skinned roots are spongy and watery; those with large leaves are generally richer; (3) average weight 1 1/2 to 2 1/2 lbs., neither very large nor very small roots being profitable to the sugar-manufacturer; as a rule, beets weighing more than 3 1/2 lbs. are watery, and poor in sugar; and roots weighing less than 3/4 lb. are either unripe or too woody, and in either case yield comparatively little sugar; the sp. gr. of the expressed juice, usually 1.06 to 1.07, even reaching 1.078 in English-grown roots, indicating over 14 percent of crystallizable sugar, is the best proof of quality; juice poor in sugar has a density below 1.060; (4) in well-cultivated soil, the roots grow entirely in the ground, and throw up leaves of moderate size.

Composition of the Roots. Internally the root is built up of small cells, each filled with a juice consisting of a watery solution of many bodies besides sugar. These include several crystallized salts (mostly of which are present in minute tracesonly), such as the phosphates, oxalates, malates, and chlorides of potassium, sodium, and calcium, the salts of potash being by far the most important; and several colloid bodies (albuminous (nitrogenous) and pectinous compounds); as well as a substance which rapidly blackens on exposure to the air.

The greater part of the sugar in ripe beets is crystallizable, and, when perfectly pure, is identical in composition and properties with crystallized cane-sugar; but it is more difficult to refine this sugar so as to free it from the potash salts, and commerical samples have not nearly so great sweetening power as ordinary cane-sugar. Beets contain no uncrystallizable sugar; the molasses produced in beet-sugar manufactories is the result of changes which cannot be entirely avoided in extracting the crystallizable sugar.

Soil. The best soil for beets contains a fair proportion of organic matter, is neither too stiff nor too light, and crumbles down into a nice friable loam; it must be capable of being cultivated to a depth of at least 16 in. The subsoil should be thoroughly well drained, and rendered friable by autumn-cultivation and free admission of air. A deep friable turnip-loam, containing fair proportions of clay and lime, appears to be the most eligible land for sugar-beets. Lime is a very desirable element. Well-worked clay-soils, especially calcareous clays, are well adapted, if properly drained and of sufficient depth. Peaty soils and moorlands are quite unsuitable, as well as lands which are too dry, like the thin gravelly soils resting on siliceous gravel subsoils, or too wet and cold, like many of the thin soils above impervious chalk marl.

Speaking generally, the best soils for sugar-beet are precisely those on which other root-crops can be grown to perfection, that is, land which is neither too heavy nor too light, which has a good depth, is readily penetrated by the roots, and naturally contains lime, potash, clay, and sand, as well as organic matter, is such proportions as in good friable clay-loams. An analysis of the soil should be made previous to planting it with the sugar-beet, as the salts presented in solution in the soil will pass into the juice, and greatly interfere with the processes of sugar manufacture. Certain soils may be at once indicated as unsuitable; they are clover-land, recent sheep-pastures, forest-land grugged during the preceding 15 years, the neighborhood of salt works, volcanic and saline soils of all kinds. The beet requires a certain supply of potash and soda salts in the soil, but if these are present in excess, as in recent forest-land, the juice does not work well, nor give its proper yield of sugar.

Sowing. The best time for sowing beetroot is the beginning or middle of April. If sown too early, the young plants may be partially injured by frost; if later than the first week in May, the crop may require to be taken up in autumn, before it has had time to get ripe. About 10 to 12 lbs. of seed is required per acre. As regards the width between the plants, generally speaking, the distance between the rows and from plant to plant should not be less than 12 nor greater than 18 in. Should the young plants be caught by a night's frost, and suffer every so little, it is best to plough them up at once and re-sow, for they are certain to run to seed, and are then practically useless for the manufacture of sugar. Sugar-beets require to be frequently horse- and hand-hoed. As long as the young plants are not injured, the application of the hoe from time to time is attended with great benefit to the crop. It is advisable to gather up the soil round each plant, in order that the head may be completely covered with soil. Champonnois' researches point to the advantage of planting in ridges, by which the supply of air to the roots is greatly facilitated.

The conditions best calculated to ensure the roots possessing the characters most desirable from a sugar-maker's point of view are chiefly as follows: (1) Not to sow on freshly-manured land; it is eminently preferable not to manure for the beet crop, but to manure heavily for wheat in the preceding year; (2) not to employ forcing manures, nor to apply manure during growth; (3) to use seed from a variety rich in sugar; (4) to sow early, in lines 16 in. apart, at most, the plants being 10 to 11 in. from each other; there will then be 38,000 beets on an acre, weighing 21 to 28 ounces each, or 52,800 to 70,400 lbs. per acre; (5) to weed the fields as soon as the plants are above ground, to thin out as early as possible, and to weed and hoe often, till the soil is covered with the leaves of the plants; (6) never to remove the leaves during growth; (7) finally, not to take up the roots, if it can be avoided, before they are ripe, the period of which will depend upon the season.

Good seed may be raised by the following means: The best roots, which show least above ground, are taken up, replanted in good soil, and allowed to run to seed. This seed is already good; but it may be further improved by sowing it in a well prepared plot possessing all the most favorable conditions; the resulting plants are sorted, set out in autumn, put into a cellar, and in the spring, before transplanting, those of the greatest density, and which will give seeds of the best quality, are separated. These are transplanted at 20 ins. between the rows and 13 in. between the feet, which are covered with about 1 1/2 in. of earth. Finally they are watered with water containing molasses and superphosphate of lime, as recommended by Corenwinder.

Harvesting. Sugar-beets must be taken up before frost sets in. When the leaves begin to turn yellow and flabby, they have arrived at maturity, and the crop should be watched, that it may not get over-ripe. If the autumn is cold and dry, the crop may be safely left in the ground for seven to ten days longer than is needful, but should the autumn be mild and wet, if the roots are left in the soil, they are apt to throw up fresh leaves, and nothing does so much injury. In watching the ripening of the crop, a good plan is to test the sp. gr. of the expressed juice. A root or two may be taken up at intervals, and reduced to pulp on an ordinary hand-grater, the juice obtained by pressing the pulp through calico, and the density observed by a hydrometer. As long as the gravity of the juice continues to increase, the crop should be left in the land. Good sugar-yielding juice has a sp. gr. of about 1.065, rising to about 1.070. Immature roots, cut across, rapidly change color on the exposed surface, turning red, then brown, and finally almost black. If newly-cut slices turn color on exposure, the ripening is not complete; but if they remain some time unaltered, or turn only slightly reddish, they are sufficiently ripe to be taken up. The crop should be harvested in fine, dry weather. In order that the roots may part with as much moisture as possible, they are left exposed to the air on the ground before being stacked, but not for longer than a few days, and they need to be guarded against direct sunlight. Perhaps the best plan is to cover them loosely with their tops in the field for a couple of days, then trim them, and at once stack them.

Storing. For storing roots, special care should be taken to prevent their germinating and throwing out fresh tops, which is best done by selecting a dry place for the storage ground. They may be piled in pyramidal stacks, about six feet broad at base, and seven feet high. At first, the stacks should be thinly covered with earth, that the moisture may readily evaporate; subsequently, when frosty weather sets in, another layer of earth, not exceeding one foot in thickness, may be added. This is essentially the method generally adopted for storing potatoes and beets.

In continental Europe and Canada, extra precaution is necessitated by the rigorous climate. In S. Russia, the plan shown in Figure 19 is sometimes used.

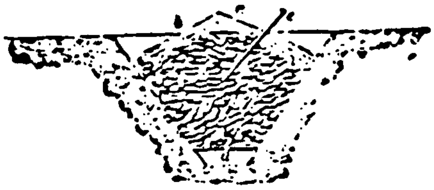


Figure 19. STACK FOR STORING BEETS

The beets are disposed completely below the surface of the soil, in a trench dug with sharply sloping sides. At about 15 in. from the bottom, is an openwork floor of reeds, on which the beets are piled to within a few inches of the level of the exterior soil. On the top, and following the apex of the heap, is laid a triangular ridgepiece a, for the purpose of facilitating evaporation. The whole is covered with a layer b of straw and fine earth, the thickness of which is varied according to the indivations of the thermometer c placed in the center of the mass. Between the floor of the trench and the openwork floor is a space d, communicating with two vertical channels leading to the outer air, thus providing ventilation. The outlets of the channels can be opened and closed at will. The Russians also often employ regular cellars, as shown in Figure 20. The structure consists of two stories, covered with a bed of earth, each furnished with a floor of hurdles or open planking, on which the beets are piled to the depth of about one yard. Lateral passages facilitate ventilation, and openings in the roof permit the heated air to escape. The cost of erecting these cellars is heavy, but there is great saving of labor in storing the beets, as it suffices to simply pile them up on the floors. Moreover, the arrangement permits the examination of the contents beyond the indications of a thermometer; and enables any portion to be removed, even during snowy weather.

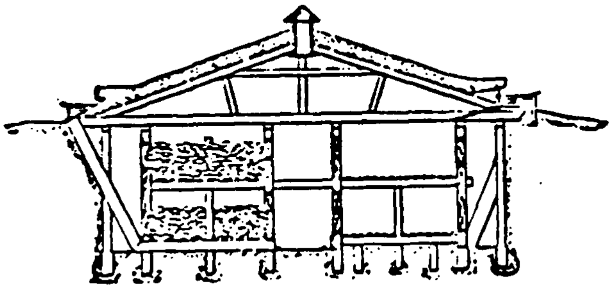


Figure 20. STORAGE CELLAR FOR BEETS

Alcohol from Beets. Beets contain 85 percent of water, and about 10 percent of cane sugar, the remainder being woody fibre and albumen; cane sugar not being in itself fermentible—as is grape sugar—it has to be converted into "inverted sugar" by a ferment as yeast. Either the sugar beets may be mashed or the molasses which remains from the manufacture of beet sugar. The conversion of the sugar into alcohol is effected in several different ways, of which the following are the principal:

- By rasping the roots and submitting them to pressure, and fermenting the expressed juice.
- By maceration with water and heat.
- By direct distillation of the roots.

The first two methods are the best as by them the woody fibre of the plant which is non-fermentible is separated from the fermentible juice. In both the first and second processes the beets must first be entirely cleaned of adhering dirt, trash and clods of earth, and then rasped, pulped or sliced by certain machinery.

Cleaning. Care must be taken in this operation that the beets shall be freed from small stones and adhering hard lumps of earth which would otherwise get into the rasping machinery to the damage and stoppage of the mechanism.

There are many forms of cleaners but all are alike in this, that the beets shall be subjected to the action of water while traveling through or over a perforated casing. The simplest machine, and one easily constructed by any carpenter, comprises an elongated cylinder formed of lathes or strips spaced apart such distance as will allow dirt and stones to pass between them. This is mounted on a central shaft and revolved in a tank of water. It should be slightly inclined so that the potatoes or beets to be washed may beed downward from the open upper end-disk or wheel, to the lower end where they are thrown out. At the upper end is a hopper and at the lower, the end disk has inwardly projecting lips, which as the cylinder revolves lifts the beets up and tumbles them out on to an incline which carries them to the rasping machine.

Another form of machine comprises a perforated cylinder of sheet iron, revolving in a tank of water. A better form of cleaner than either of those consists of an inclined trough in which a spiral feeding screw of sheet iron rotates. The beets are fed into the trough at its lower end and are carried upward, slowly, by the feeding screw. About the trough is a water pipe having a number of outlets by which water may fall on to the beets and into the trough. The water rushing down the inclined trough carries with it all dirt and stones, and by the time the beets have reached the upper end they are entirely cleaned and ready for slicing or rasping.

For pressing out the juice, the beets are mashed into a pulp, while for diffusion the beets are sliced.

Rasping. Figure 21 shows one form of rasping machine. On a suitable supporting frame is mounted a cylinder a having a diameter of about 24 inches. The cylinder is formed of alternate saw blades and wooden washers holding them a slight distance apart. The saws or teeth are so set on the cylinder as not to slice the beets but to shred them up into a fine pulp. The cylinder rotates at a speed of 800 to 1000 revolutions a minute in front of an inclined table, having a jigger whereby the beets are fed downward against the toothed cylinder. The teeth carry the pulp downward and it falls into a receptacle beneath.

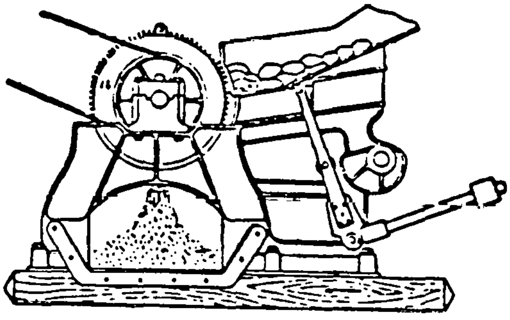


Figure 21. BEET AND POTATO RASP

It is best to add to this pulp a small portion of sulphuric acid, say two-tenths of one percent. This prevents by fermentations.

Pressing. The pulp obtained from the raspers has now to be expressed. This is either done by platen presses or by roller pressers. With platen presses the first pressing may be done by screws, but the final pressing should be accomplished by hydraulic presses.

For the hydraulic press, the pulp is placed in wooden sacks, containing 10 to 12 lbs., superposed in the press with their mouths doubled under, a separated by iron plates; about 25 are collected, and the pile is put into a screw-press, called a "preparatory" press, which exracts about 45 to 50 percent of the juice. These pressed sacks are piled anew on the movable plate of a powerful hydraulic press, which takes 50 at a charge. Each preparatory press can supply four hydraulic presses, which are ranged around it, so that of the four presses there will be one charging, one commencing to press, one in full pressure, and one discharging, at the same moment. Motion is communicated to the four hydraulic presses by four pumps mounted on the same bed, and tended by the same workman who directs the pressing. An improvement upon the general form of hydraulic press is that devised by Lalouette, which enables two workmen and one boy to work five presses. These presses turn out about 34,200 lbs. per 24 hours in the first pressing, and 68,400 lbs. in the second. Hydraulic presses are rapidly falling into disuse in the beet-sugar industry, by reason of the superior merits of continuous presses, and the extended adoption of the diffusion system.

Continuous presses for beet were suggested by the roller-mills used in the cane-sugar industry. But the conditions in the two cases are widely different; the begass of the cane is solid, and rapidly parts from the juice; whereas the pulp and juice of the beet have a strong tendency to combine, and the foller-surface must therefore be permeable only by the juice. In Poizot et Druelle's press, the pulp passes between two cylinders, carried by endless cloths. The object is to unite the best features of the hydraulic press. To this end, a first gentel pressing is produced against the first cylinder by the elasticity of the principal cloth on which it is borne. Then, encountering a series of four little rollers, performing the functions of the preparatory press, it is next seized between the second and first cylinders, and deprived of the maximum quantity of juice.

Dujardin's roll press is shown in Figure 22, which is a vertical section of the machine, the side plate being removed. The pulp is forced upward through a pipe under high pressure. This has a regulating slide valve D. The rolls B B revolve towards and nearly in contact with each other, and they are perforated so that the expressed juice may run off through the rolls. These perforations are conical in form with the apex of the cone outward. The cylinders are also covered with a webbing of cloth or horse hair. Below the rolls is block C', which with the outer walls of the chamber, form diverging passages which extend upward, as shown, on either side of the rolls and then downward along the lower faces of the rolls to the point when they contact. The pulp is compressed with great force against and between the rolls, the juice is forced through the perforations and the residue passes upward and outward under the presser bar E in the form of a ribbon which is guided away by the trough F. The pressure of the bar E is regulated by screws and the tighter said bar is pressed against the rolls the greater will be the pressure of the pulp behind the bar and against the rolls, and the greater the juice expressed.

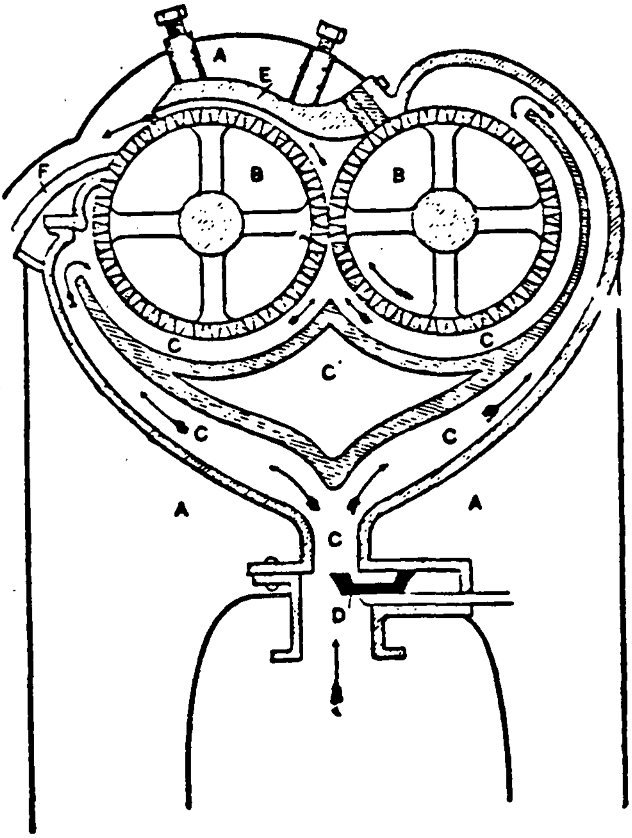


Figure 22. DUJARDIN'S ROLL PRESS

The rolls revolve very slowly only about seven or eight times a minute but the capacity of the machine is very great, it being capable of pressing the pulp of from 85,000 to 175,000 lbs. of beets daily. The residue from the first pressing should be submitted to a further pressing after being macerated with spent wash. This residue may be fed to cattle. The utmost cleanliness is essential to these processes; all the utensils employed should be washed daily with lime-water to counteract acidity.

Extraction by Maceration and Diffusion. The object to this process is to extract from the beets the means of water or spent liquor all the sugar which they contain, without the aid of rasping or pressure. Spirit is thus produced at considerably less expense, although it is not of so high a quality as that yielded by the former process. The operation consists in slicing up the beets in a specially constructed slicing machine, into slices of regular thickness, and then allowing the slices to macerate in a series of vats at stated temperatures. It is essential that the knives by which the roots are cut should be so arranged that the roots are divided into slices having a width of 4/10 of an inch and a thickness of 4/100 of an inch, and a variable length; the roots are, of course, well washed before being placed in the hopper of the cutter.

When cut, the beets are covered with boiling water in a macerator of wood or iron for one hour, the water should contain 4.4 of sulphuric acid to every 2200 lbs. of beets. After this, the water is drawn off into a second vat in which are placed more beets, and allowed to macerate again for an hour. This is repeated a third time in another vat, and the juice, which has now acquired a density equal to that obtained by rasping, is run off into the fermenting vat. When the first vat is empty it is immediately refilled with boiling water and fresh beets; the juice from this operation is run into the second vat, when the contents of that one are run into the third. To continue the operation, the beets are completely exhausted by being macerated for an hour with a third charge of boiling water (acidulated as in the former case). The exhausted pulp is removed to make room for fresh slices; and the first vat is then charged with juice which has already passed through the second and third vats. After macerating the fresh beets for one hour, the charge is ready for fermentation. In ordinary weather, the juice should now be at the right heat for this process, viz., about 71.1° or 75.2°F., but in very cold weather it may require some reheating.

In Figure 22 is shown a series of vats for the extraction of the sugar from beets such as is termed a "diffusion battery."

The vessels, 1, 2, 3, and 4 are of wood or sheet iron. Each vessel has a bottom sieve and a top sieve between which the beet slices are to be placed. From the bottom of each vessel below the sieve a pipe D runs to the top of the vessel next in order. From the bottom of the last vessel 4 of the series a pipe C runs back to the top fo the one first used. Pipes A and B are connected to each vessel for the admission of water and spent respectively. A discharge pipe E leads from each vessel to a collecting vat 5.

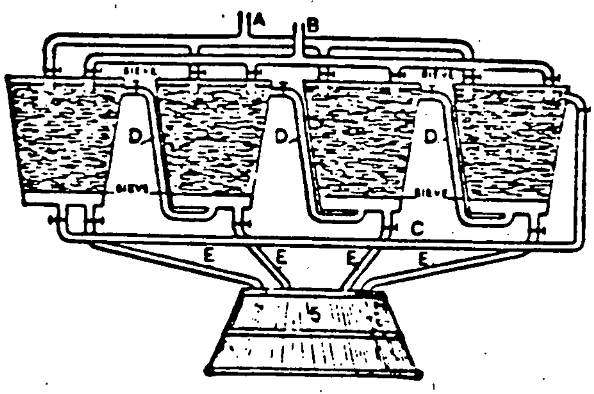


Figure 23. DIFFUSION BATTERY

Maceration and diffusion is accomplished as follows: The sliced beets are placed between the sieves in vessel 1 and water or spent wash at a temperature of 185°F. is let in and the beets allowed to macerate for three-quarters of an hour, meanwhile tub 2 is charged with sliced beets. The cock or pipe D between the vessels is opened when the time, three quarters of an hour, has elapsed; hot water or spent wash is admitted by pipes A or B to the vessel 1, which forces the sugar solution therein into vessel 2. When the required amount of fluid has been passed into 2 from 1, the inlet of water into 1 is stopped, and the vessel heated to 185°F.

Vessel 3 is charged with beet slices and in three-quarters of an hour vessels 1, 2, and 3 are connected and water or wash admitted into 1, which forces the solution in 1 into 2 and that in 2 into 3 when it is again raised to 185°F.

The same operation is repeated as to vessel 4 and in three-quarters of an hour all the vessels are connected, hot water or spent wash is admitted to 1 and the sugar solution drawn off from 4 into the vat.

The beets in tub 1 having now been exhausted, the fluid in that vessel is drawn off and the exhausted beets thrown away. 1 is now recharged with beets and the pipe between it and 4 opened. The former operation is repeated except that now vessel 4 becomes 1, and 1 becomes 4. These successive chargings and dischargings are continued; vessel 3 becomes 1 in its turn and so on.

Fermentation. Before fermentation the juice procured as has been described is brought to about 82°F.; at this temperature it is run off into the fermenting vats. Here it is necessary, as before noted, to add to the juice a small quantity of concentrated sulphuric acid, for the purpose of neutralizing the alkaline salts which it contains, and of rendering it slightly acid in order to hasten the process; this quantity must not exceed 5 1/2 lbs. to every 1220 gallons of juice, or the establishment of fermentation would be hindered instead of promoted. The addition of this acid tends also to prevent the viscous fermentation to which the juice obtained by rasping and pressure is so liable. Although the beet contains albumen, which is in itself a ferment, it is necessary, in order to develop the process, to have recourse to artificial means. A small quantity of brewer's yeast—about 1 3/4 gallons of juice—is sufficient for this; the yeast must previously be mixed with a little water. An external temperature of about 68° to 78°F. must be carefully maintained. Fermentation lasts for from four to five hours.

The fermentation of acidulated beet-juice sets in speedily. The chief obstacle to the process is the mass of thick scum which forms upon the surface of the liquor. This difficulty is sometimes obviated by using several vats and mixing the juice, while in full fermentation, with a fresh quantity. Thus, when three vats are employed, one is set to ferment; at the end of four or six hours, half its contents are run into the second vat and here mixed with fresh juice. The process is arrested, but soon starts again in both vats simultaneously; the first is now allowed to ferment completely, which is effected with much less difficulty than would have been the case had the vat not been divided. Meanwhile the second vat, as soon as the action is at its height, is divided in the same manner, one-half of its contents being run into the third. When this method is employed, it is necessary to add a little yeast from time to time when the action becomes sluggish.

Direct Distillation of the Roots. This process, commonly called "Leplay's method," consists in fermenting the sugar in the slices themselves. The operation is conducted in huge vats, holding as large a quantity of matter as possible, in order that the fermentation may be established more easily. They usually contain about 750 gallons, and a single charge consists of 2200 lbs. of the sliced roots. The slices are placed in porous bags in the vats, containing already about 440 gallons of water acidulated with a little sulphuric acid; and they are kept submerged by means of a perforated cover, which permits the passage of the liquor and of the carbonic acid evolved; the temperature of the mixture should be maintained at about 77° or 80°F. A little yeast is added, and fermentation speedily sets in; it is complete in about 24 hours or more, when the bags are taken out and replaced by fresh ones; fermentation declares itself again almost immediately, and without any addition of yeast. New bags may, indeed, be placed in the same liquor for three or four successive fermentations without adding further yeast or juice.

The slices of beets charged with alcohol are now placed in a distilling apparatus of a very simple nature. It consists of a cylindrical column of wood or iron, fitted with a tight cover, which is connected with a coil or worm, kept cool in a vessel or cold water. Inside this column are arranged a row of perforated diaphragms or partitions. The space between the lowest one and the bottom of the cylinder is kept emply to receive the condensed water formed by the steam, which is blown into the bottom of the cylinder in order to heat the contents. Vapors of alcohol are thus disengaged from the undermost slices, and these vapors as they rise through the cylinder vaporize the remaining alcohol, and finally pass out of the top at a considerable strength and are condensed in the worm. When all the contents of the still have been completely exhausted of spirit, the remainder consists of a cooked pulp, which contains all the nutritive constituents of the beet except the sugar.

Alcohol from Molasses and Sugar Cane

Another common source of alcohol is molasses. Molasses is the uncrystallizable syrup which constitutes the residiuum of the manufacture and refining of cane and beet sugar. It is a dense, viscous liquid, varying in color from light yellow to almost black, according to the source from which it is obtained; it tests usually about 40° by Baume's hydrometer. The molasses employed as a source of alcohol must be carefully chosen; the lightest in color is the best, containing most uncrystallized sugar. The manufacture is extensively carried on in France, where the molasses from the beet sugar refineries is chiefly used on account of its low price that obtained from the cane sugar factories being considerably dearer. The latter is, however, must to be preferred to the former variety as it contains more sugar. Molasses from the beet sugar refineries yields a larger quantity and better quality of spirit than that which comes from the factories. Molasses contains about 50 percent of saccharine matter, 24 percent of other organic matter, and about 10 percent of inorganic salts, chiefly of potash. It is thus a substance rich in matters favorable to fermentation. When the density of molasses has been lowered by dilution with water, fermentation sets in rapidly, more especially if it has been previously rendered acid. As, however, molasses from beet generally exhibits an alkaline reaction, it is found necessary to acidify it after dilution; for this purpose sulphuric acid is employed, in the proportion of about 4 1/2 lbs. of the concentrated acid to 22 gallons of molasses, previously diluted with eight or ten volumes of water. Three processes are thus employed in obtaining alcohol from molasses; dilution, acidification, and fermentation. The latter is hastened by the addition of a natural ferment, such as brewer's yeast. It begins in about eight or ten hours, and lasts upwards of 60.

About three gallons of alcohol may be obtained from one hundred pounds of molasses.

Beet Sugar Molasses. The first step in the process of rendering the molasses fermentable is to mix the molasses with water, to a certain dilution, in the proportion of two parts of water to one of molasses. This may be done by hand, but preferably it is performed in a vat provided with stirring or agitating mechanism, such as will effectually mix the water with the viscid syrup, and whereby also the wash may be thoroughly agitated and aerated.

There are numerous forms of mixing vats, all working however, on the principle shown in Figure 24. In this, the vat A is provided with a central shaft C carrying radial mixing blades E. This shaft is driven by bevel gears D, F. As the rotation of these blades would merely tend to create a rotary current of molasses and water, and not to mix them, some means should be used for impeding and breaking up this current. To that end the cover is provided with downwardly projecting rods I which create counter currents, and thoroughly intermingle the two liquids. Another and even better form of mixer consists of a tank into the lower portion of which enters a perforated pipe of relatively large diameter. This is provided at the end with an air entrance and a steam injector. The injected steam draws in air and the steam and air are forced under pressure into the vat, thus diluting the contained molasses, agitating it and thoroughly aerating it.

The molasses as it comes from the sugar house may contain anywhere from 30 to 45 percent of sugar, and this should be diluted with water to a concentration of 16 to 18 percent of sugar.

The density of the wash after "setting up" is 1.060. It is to be noted that though with improved apparatus a wash as concentrated at 12° of 15° Baume may be worked; yet where simple apparatus is used six degrees or eight degrees is better and much more favorable to rapid and complete fermentation.

After setting up, one gallon of strong sulphuric acid and 10 lbs. of sulphate of ammonia are added for each 1000 gallons of wash. This neutralizes the alkaline carbonates in the beet juice which would otherwise retard fermentation, and it assists the yeast to invert the cane sugar as formerly described. The addition of ammonia is in order to give food to the yeast and obtain a vigorous fermentation.

The yeast used for fermenting molasses is prepared either from malt or grain and is used as concentrated as possible, and in the proportion of about 2 percent.

The "pitching" temperature of a molasses wash varies with the concentration of the wash, being higher for strongly concentrated solutions than for weak ones. When the wash tests as high as 12° Baume, fermentation begins at about 77°F. and is raised during fermentation to 85° or 90°F. A temperature around 82°F. is best on the average as this is most conducive to the growth of yeast.

Where the vats are large and the syrup considerably diluted the temperature rises very quickly and must be moderated by passing a current of cold water through a coil of pipe on the bottom of the vat.

In the making of molasses mashes it must be remembered that every gallon of molasses will be diluted with about five gallons of water or other fermented liquid matter, and therefore 50 gallons of molasses wash will require a still capable of working up about 300 gallons. It is possible to distill four or five charges during the day of 12 hours and hence a still of 60 gallons will be capable of distilling the beer or wash made with 50 gallons of molasses. A still with a capacity of 100 gallons operating on wash having a strength of one gallon of molasses to five of water, will produce about 10 gallons of proof spirit from each charge; thus a 100 gallon still will make from 40 to 80 gallons of spirit in a day. With unskilled labor, however, it is impossible to get this rate of production and the best that can be done will be about four charges a day.

It may be suggested that in getting estimates on stills it is best to accompany the request with a statement of the character of the mash intended to be treated, the amount of raw materials intended to be used up, the charging capacity required, number of gallons of mash desired to be worked up every 12 hours.

Fermenting Raw Sugar. This is accomplished by dissolving the sugar in hot water, then diluting it, and then adding a ferment, fermentation being aided by adding sulphuric acid to the diluted molasses, in the proportion of one half to one pound of acid to every hundred pounds of pure sugar used.

The wash is pitched with compressed yeast in the proportion of 2 1/2 to 8 percent of the weight of the sugar used. The pitching temperature is from 77° to 79°F.,. and the period of fermentation is 48 hours.

Cane Sugar Molasses. Besides the molasses of the French beet sugar refineries, large quantities result from the manufacture of cane sugar in Jamaica and the West Indies. This is entirely employed for the distillation of rum. As the pure spirit of Jamaica is never made from sugar, but always from molasses and skimmings, it is advisable to notice these two products, and, together with them, the exhausted wash commonly called dunder.

The molasses proceeding from the West Indian cane sugar contains crystallizable and uncrystallizable sugar, gluten, or albumen, and other organic matters which have escaped separation during the process of defecation and evaportion, together with saline matters and water. It therefore contains in itself all the elements necessary for fermentation, i.e., sugar, water, and gluten, which latter substance, acting the part of a ferment, speedily establishes the process under certain conditions. Skimmings comprise the matters separated from the cane juice during the processes of defecation and evaporation. The scum of the clarifiers, precipitators, and evaporators, and the precipitates in both clarifiers and precipitators, together with a proportion of cane sugar mixed with the various scums and precipitates, and the "sweet-liquor" resulting from the washing of the boiler pans, etc., all become mixed together in the skimming-receiver and are fermented under the name of "skimmings." They also contain the elements necessary for fermentation, and accordingly they very rapidly pass into a state of fermentation when left to themselves; but, in consequence of the glutinous matters being in excess of the sugar, this latter is speedily decomposed, and the second, or acetous fermentation, commences very frequently before the first is far advanced. Dunder is the fermented wash after it has undergone distillation, by which it has been deprived of the alcohol it contained. To be good, it should be light, clear, and slightly bitter; it should be quite free from acidity, and is always best when fresh. As it is discharged from the still, it is pumped up when cool into the upper receivers, where it clarifies, and is then drawn down into the fermenting cisterns as required. Well-clarified dunder will keep for six weeks without any injury. Good dunder may be considered to be the liquor, or "wash," as it is termed, deprived by distillation of its alcohol, and much concentrated by the coiling it has been subjected to; whereby the substances it contains, as gluten, gum, oils, etc., have become, from repeated boilings, so concentrated as to render the liquid mass a highly aromatic compound. In this state it contains at least two of the elements necessary for fermentation, so that, on the addition of the third, vis., sugar, that process speedily commences.

The first operation is to clarify the mixture of molasses and skimmings previous to fermenting it. This is performed in a leaden receiver holding about 300 to 400 gallons. When the clarification is complete, the clear liquor is run into the fermenting vat, and there mixed with 100 or 200 gallons of water (hot, if possible), and well stirred. The mixture is then left to ferment. The great object that the distiller has in view in conducting the fermentation is to obtain the largest possible amount of spirit that the sugar employed will yield, and to take care that the loss by evaporation or acetification is reduced to a minimum. In order to ensure this, the following course should be adopted. The room in which the process is carried on must be kept as cool as it is possible in a tropical climate; say, 75° to 80°F.

Supposing that the fermenting vat has a capacity of 1000 gallons, the proportions of the different liquors run in would be 200 gallons of well-clarified skimmings, 50 gallons of molasses, and 100 gallons of clear dunder; they should be well mixed together. Fermentation speedily sets in, and 50 more gallons of molasses are then to be added, together with 200 gallons of water. When fermentation is thoroughly established, a further 400 gallons of dunder may be run in, and the whole well stirred up. Any scum thrown up during the process is immediately skimmed off. The temperature of the mass rises gradually until about 4° or 5° above that of the room itself. Should it rise too high, the next vat must be set up with more dunder and less water; if it keeps very low, and the action is sluggish, less must be used next time. No fermenting principle besides the gluten contained in the wash is required. The process usually occupies eight or ten days, but it may last much longer. The liquid now becomes clear, and should be immediately subjected to distillation to prevent acetous fermentation.

Sugar planters are accustomed to expect one gallon of proof rum for every gallon of molasses employed. On the supposition that ordinary molasses contains 65 parts of sugar, 32 parts of water, and three parts of organic matter and salts, and that, by careful fermentation and distillation, 33 parts of absolute alcohol may be obtained, we may then reckon upon 33 lbs. of spirit, or about four gallons, which is a yield of about 5 2/3 gallons of rum, 30 percent over-proof, from 100 lbs. of such molasses.

The following process is described in Deerr's work on "Sugar and Sugar Cane."

"In Mauritius a more complicated process is used; a barrel of about 50 gallons capacity is partly filled with molasses and water of density 1.10 and allowed to spontaneously ferment; sometimes a handful of oats or rice is placed in this preliminary fermentation. When attenuation is nearly complete more molasses is added until the contents of the cask are again of density 1.10 and again allowed to ferment. This process is repeated a third time; the contents of the barrel are then distributed between three or four tanks holding each about 500 gallons of wash of density 1.10 and 12 hours after fermentation has started here, one of these is used to pitch a tank of about 8,000 gallons capacity; a few gallons are left in the pitching tanks which are again filled up with wash of density 1.10 and the process repeated until the attenuations fall off, when a fresh start is made. This process is very similar to what obtains in modern distilleries save that the initial fermentation is adventitious.

"In Java and the East generally, a very different procedure is followed. In the first place a material known as Java, or Chinese, yeast is prepared from native formulae; in Java, pieces of sugar cane are crushed along with certain aromatic herbs, amongst which galanga and garlic are always present, and the resulting extract made into a paste with rice meal; the paste is formed into strips, allowed to dry in the sun and then macerated with water and lemon juice; the pulpy mass obtained after standing for three days is separated from the water and made into small balls, rolled in rice straw and allowed to dry; these balls are known as Raggi or Java yeast. In the next step rice is boiled and spread out in a layer on plantain leaves and sprinkled over with Raggi, then packed in earthenware pots and left to stand for two days, at the end of which period the rice is converted into a semi-liquid mass; this material is termed Tapej and is used to excite fermentation in molasses wash. The wash is set up at a density of 25° Balling and afterwards the process is as usual. In this proceeding the starch in the rice is converted by means of certain micro-organisms Chlamydomucor oryzae into sugar and then forms a suitable habitat for the reproduction of yeasts which are probably present in the Raggi but may find their way into the Tapej from other sources. About 100 lbs. of rice are used to pitch 1,000 gallons of wash."

Direct Processing of Sugar Cane into Ethanol

Translation

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In order to be able to avoid the use of roller mills for the direct processing of sugar cane into ethanol, a process has been developed that liberates the sugar by the influence of elevated temperature. The size-reduced cane is heated by the introduction of steam, subsequently fermentation can take place as well without separation of solids and solution, as can the sugar also be washed out practically completely by a much-simplified extraction process. The sterile sugar solution that is so obtained is fermented without further treatment.

As has been shown by laboratory- and technical experiments, the process promises savings of investment and operating costs, it also permits the use of polyglucosides that may be present or formed in unripe, overripe cane or in cane that has been damaged by infection, frost or other influences for ethanol formation. Alternatively or simultaneously sorghum can also be processed as well as molasses, starches that had been converted into sugars, since sugar cane processing will only require a part of the produced bagasse for energy production.

While in the past, ethanol was only one, though important by-product in the processing of sugar cane, there will, in the future, be major installations in rising numbers whose only final product from sugar cane processing will be ethenol, without providing a simultaneous or alternative sugar production. The technology that will be required for such installations, should not base itself only on the well-known and tested technologies of sugar production, rather, new and independent processes and methods should be developed, since the aims of the two productions deviate markedly from each other:

1) While in sugar production, it is most important to pro duce as large a quantity of crystallized sugar from the incoming cane as possible, it will be the goal of an ethanol installation to produce, with a minimum of effort of applied energy to produce energy of a higher value in the form of ethanol. This shift in the production goal can lead to the possible acceptance of a reduction of the amount of yield, if this is connected to reduced specific energy consumption.

2) In the case of sugar production all process steps must be avoided and all accompanying materials removed that could make the crystallisation of sugar more difficult or could inhibit it. If, on the other hand, ethanol is to be produced, it is only necessary to see to it that the fermentation is not disturbed by prior operations. A partial or even complete inversion of the cane sugar and an acid reaction of the solution to be fermented can be acceptable, neutralization and clarification of the juice is not necessarily required.

3) If, along with the sugar other soluble materials get into the juice from the cane, this is of little consequence to ethanol production as long as these substances do not interfere with fermentation. Such materials can possibly even contribute to a quicker fermentation and to a rise of the alcohol yield. For this reason, the sugar cane can be exposed during processing to entirely higher temperatures than this would be permissible in sugar production.

4) A solution that is as sterile as possible should be brought to fermentation so that the yeast that is applied can be recycled. This leads not only to reduced operating costs and higher yields, but it is also a prerequisite for a continuous course of fermentation that is desirable.

5) It should be endeavored to also use such sugar cane for alcohol production that has become less valuable or worthless for conventional sugar production because of its degree of ripeness, extended storage or because of damage by frost or insects. Along with this, the ethanol installation should also offer the possibility to process other sugar-containing plants, such as, for example, sorghum.

6) It is to be examined, whether it is necessary in every case, to separate the sugar-containing solution from the insoluble plant parts, or if it is not possible to ferment prior to such a separation. Subsequently, no longer the sugar, but the more easily volatilized alcohol would have to be separated.

Ballweg Gastechnik has prepared a study at the request of the German Society for Technical Cooperation, in which a process for the direct processing of sugar cane into alcohol has been worked out, taking into consideration the above mentioned points, on the basis of laboratory- and technical- experiments.

The idea upon which this process is based, starts with the inexpensive initial size reduction of the sugar cane and its subsequent exposure to the influence of higher temperatures in order to attain a rapid and effective destruction of the cell-walls and liberation of the sugar. At the same time, by means of thermic decomposition, the connection between marrow cells and fiber is dissolved to the extent that only short paths will have to be covered in the diffusion of the sugar from the interior of the destroyed cells into the free, surrounding solution. The sugar can then easily be extracted from the hot plant material.

Such thermic processes are used, among others, in the cellulose industry in order to decompose the size-reduced wood, to dissolve the connection between lignin and cellulose and to soften the first to such an extent as to make it easily removable in the further course of the processing.

The type and degree of the initial size reduction is of great importance to the further processing of the sugar cane after the thermic decomposition. With increasing size-reduction and shredding, on the one hand, the speed for the exsolution of the sugar increases, on the other hand the pour density of the material drops off considerably. If the cane is size reduced only into a sort of hogged chips, as they are known from the paper and cellulose industry, the pour density reaches a maximal value with about 550 to 600 kg/m^3. At this sort of size reduction a water addition of about 1:1 suffices for the complete covering of the material and a direct fermentation. Our experiments have shown that, under these cane, can be converted into ethanol in 48 hours with baker's yeast, a further size reduction does not provide any appreciable increase in fermentation speed. The alcohol-containing solution can be separated from the wood and then distilled. The remaining alcohol contents can be driven from the wood by bowing in steam and can thus be obtained. This process has, in all of its simplicity, also a series of disadvantages. The cutting machines that are required for such a size reduction of the cane are expensive, have only limited outputs and the wear periods of their knives are short. Because of the additional water required for the complete covering of the material, the sugar- and, therefore the attainable alcohol-concentration is much reduced, so that a greater expenditura of energy is required for distillation. In addition, only a part of the applied yeast can be recovered, which leads to reduction of yields.

A considerably less expensive and, at the same time, more progressive for of size reduction, that is also connected with a shredding of the cane, can be obtained by the application of a hammer mill. Prior shortening of the canes can be eliminated, one obtains a uniformly and finely size-reduced material in one work-step. This, however only shows a pour weight between 350 and 450 kg/m^3 and, because of the still higher addition of water that is required, a fermentation prior to separation of the insoluble plant parts is no longer useful. From the shredded cane, however, the sugar can be extracted in few steps completely after thermic decomposition. In this way, one will obtain a clear, slightly colored and sterile solution that can be fermented without any further processing. In the technical investigations, we were able to obtain sugar concentrations in solutions of that type, that were only slightly below the sugar concentrations of the original cane.

No adverse effect on the fermentation process or the fermentation speed caused by substances that were dissolved from the cane along with the sugar, could be determined by us, the gas chromatographic analysis of the volatile materials after fermentation showed that these are present to more than 99% in the form of ethanol, the remainder containing small amounts of methanol.

It should be especially noted that, in this manner, sugar cane that was partially spoilt as well a such cane, whose dry-content had risen, by transport and storage to above 40 wt%, could also be processed. While from this material only little or no sugar-containing juice could be expressed, we could extract, after the thermic decomposition, the total amount of sugar that was present in the cane. In part, even, the amount of sugar that could be extracted was significantly above the sugar content of the undecomposed cane, as determined by standard methods, something that we feel is based at least in part on a partial hydrolysis of the polyglucosides that were formed from the saccharose decomposition during the thermic decomposition.

The combination: pre-size reduction in a hammer mill, thermic decomposition and subsequent extraction promises, according to the results of our experiments, a not inconsiderable savings in investment costs in comparison to a conventional sugar mill. Along with the relatively small mechanical energy for the drive of the hammer mill and the pumps, the thermic decomposition and distillation only require low pressure steam, the entire energy requirement can be covered by the combustion of about 2/3 of the produced bagasse. The excess of bagasse can be otherwise used, or utilized for the energy requirements in the processing of corresponding amounts of molasses or starch-containing materials. Because of the thermic decomposition, such cane can also be used that is no longer useful in sugar production, by means of this and by the utilization of other sugar-containing plants, such as sorghum, it would appear that a cost reduction of the sugar supply costs can be reduced. Since a clear, sterile solution goes to fermentation, it is entirely possible to work with yeast recycling. A continuous operation is possible as well. Within the framework of a pilot plant that will begin operation in the middle of the coming year, the process that has been described is to be further developed and tested. In this connection it is also intended to investigate, whether or not, under certain conditions a processing of the entire cane, including leaves and top, is possible and useful.

Economical and Technical Aspects of Ethanol Production from Maniok

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The use of solar energy for the production of alcohol fuels by agricultural and biotechnological conversion processes, is in the first place a question of economy. Using fresh maniok and the common technology of today, only a small net-yield of energy can be attained.

The aspects of an ethanol-plant, to be be built in Mato Grosso, Brasil, are discussed. Continuous process techniques are proposed and some alternative solutions for economizing "waste" treatment are given.

Agricultural aspects

A particularly important property of the manioc plant is its tolerance to a wide range of climatic and soil conditions. Easy cultivation and good crop yields, a good resistance against plant diseases and last not least easier transportation and storage with respect to sugar cane, favour maniok. Also the possible use of shoots and leaves as an animal feedstuff is important. Because of the non-mechanized styles of farming maniok cultivation is predestinated for family farms.

From the experiences of the European agriculture we feel that care must be taken first and foremost on mellowness of the soil. This may be done by manuring (from animals fed with the leaves and vinasse) or by sprinkling of anaerobically digested vinasse or bushes.

Burning of the bushes is a dangerous procedure and may result in desert formation. This is well known even from wet-climate countries.

Thus recycling of components, which have not been converted to ethanol, and which are in a state meliorating the soil, is an essential factor for the whole alcohol program.

We can assume that one family farm of at least 0.15 km^2 agricultural fields produces 5-6 tons of maniok per week (4). About 1.200 farmers in a 600 km^2 cross-sectional area are necessary for the ethanol plant. - If in the future the specific crop yield will be doubled (1), this will only be possible with crop rotation, resulting in an increased production of various products, like corn, soya-bean, wheat etc.

Aspects of sweet mash production

Before fermenting, starch has to be hydrolyzed to sugars usable for yeast. This is the major disadvantage of starch containing raw materials with respect to sugar cane or beet juice. Hydrolysation may be done by heating and acidification or application of enzymes. The latter process seems to have more advantages. Pre-requisite for an economical saccharification process is a continuous thermal starch-liquefying process taking care of reusing most of the energy. Such a process was described by Tegge (5): The washed, crushed and with warm water diluted raw materials are mixed with steam in a special jet. Resulting temperature is less than 110° C to avoid caramel formation. After some seconds the hot paste is cooled in an expansion chamber. Temperature in this stage depends on the properties of the amylase which is dosed before steam treatment or into the partially cooled paste. Starch hydrolysation to oligosaccharides occurs within about one hour. The mash is cooled to fermentation temperature and at less than 60°C a glucoamylase is dosed. This enzyme hydrolyses oligo- and polysaccharides to glucose which can be fermented by yeast.

100 m^3 paste need about 10 tons of steam. Only 80 - 90 % of this thermal energy can be recovered by the use of vacuum evaporators. Cooling of the sweet mash from about 60°C to 30°C will be effected by heat exchangers.

Aspects of fermentation

Classical alcoholic fermentation is a batch process: Steamsterilized vessels of up to 200 m^3 are filled with fresh mash, i.e. sweet mash substituted with pressed yeast (1 kg pressed yeast/m^3 of sweet mash) or 5 % fermented mash which was acidified to kill bacteria. Normal fermentation time is about 60 hours. Because of the exothermic fermentation reaction (about 950 kJ/l ethanol) the fermenting mash is cooled with water by heat exchangers or by sprinkling the water upon the wall of the vessel. After fermentation the vessel is completely emptied, cleaned, sterilized and refilled with fresh mash.

Enlargement of the vessels isn't possible without problems if no mixing devices are installed.

If a 200-m^3-ethanol plant would be equipped with 200-m^3-fermenters, every two hours a new vessel would have to be filled with fresh mash and a total of about 35 vessels would be necessary.

It is quite obvious that a continuous fermentation process with only one fermenter simplifies the automatic control.

Basic data of such a process are described in a different paper (6). Main advantages of this process are the high specific ethanol yield, the insensibility against infections and the flexibility against unavoidable fluctuations of operation.

This continuous fermentation process is a synthesis from scientific research upon saccharification and yeast metabolism on the one hand and from specific know-how about mixing of large volumed liquids with high solid matter content on the other hand. One of the characteristic process techniques is a continuous circulation of the fermenting mash in such a way, that the sweet mash (without yeast) is diluted by the factor 1:1000 or more. The second characteristic principle of the process is the change of anaerobic and aerobic conditions for the fermenting yeast on a short time basis. Thus, the oxygen demand for assimilation and anabolic metabolism can be supplied without the disadvantages of the Pasteur effect. Furthermore the process is characterized by a comparable low pH value which is the result of a coexistence between yeast and lactobacilli.

It shall be mentioned that the existence of bacteria doesn't decrease the ethanol yield: Just the opposite occurs, the ethanol yield is higher than in the classical batch fermentation (6).

Technical implementation of the process is done by the use of air-lift shafts. The large pumping efficiency of such devices allows dimensions of the fermenter not known until now except biological sewage treatment plants. - There will be no problems to construct fermenters for a daily production of 1000 m^3 ethanol and more.

Aspects of vinasse treatment

Protein content of fresh maniok is less than 1%. Taking into account a dilution in the range of 1:1, the vinasse will contain less than 0,5 % of raw protein. On a dry matter basis raw protein of vinasse is about 10 %. There is not much in it for use as a forage on distant cattle farms.

There are two possibilities to use vinasse on an economizing way:

First, the anaerobic digestion and methane formation: BOD of dissolved organic compounds of vinasse (which was produced by continuous fermentation) is about 40 tons/200 m^3 of produced ethanol. Additional 35 tons of fibres and 10 tons of yeast give a total of 85 tons of BOD. While dissolved compounds and yeast may be digested by 90 %, the fibres will be digested by half of it. The sum of digested BOD will be about 60 tons, the produced marsh gas (conteining about 60 % methane) will be 36.000 m^3 representing a combustion energy of 9 x 10^{11}J, which is equal to about 20 % of the produced ethanol or to about 30 % of the energy used for steam production.

Methane fermentation is a very slow running process and, on the basis of maniok vinasse, the fermentation time will be in the range of 10 days (7,8,9). Fermenter volume will be over 20.000 m^3 and needs constructions and equipments to make the process attractive and not to make it too expensive at the beginning because of the enormous fermenter costs. - Methane fermentation is a mesophilic reaction. The vinasse comes from the distilling column at high temperatures and waste heat reuse is hardly possible.

Thus the methane fermenter may be constructed without insulation against loss of heat, that will result in lower costs.

After-treatment of the digested vinasse may be done in ponds. There is a lot of know-how upon facultative anaerobic ponds equipped with aerators revolving water only near the surface and providing odours. Because of additional oxygenation by algae, the energy demand of such a pond system is less than 30 KW.

Fibres and particles, non digested in the methane fermenter, settle in the ponds. The average sludge increase will be in the range of 250 m^3/d with 5 % solids dry matter. Pond area will be chosen so that sludge removal can be done after years and with big machines. - On a long term basis the produced sludge takes about 10-15 % of the maniok transport volume.

By the use of more revolving energy it is possible to produce aerobic conditions in the ponds. We believe that this will be the optimum way of treatment because of intensified algal bloomes and because of a simultaneous warm water fish cultivation. Especially carp is known to bring excellent yields under those conditions (10).

The second way of vinasse utilisation is the production of single cell biomass and the feeding of the protein enriched material to animals. The non-treated vinasse is a useful forage only for ruminates. About 50.000 bulls are necessery for the use of fresh vinasse. -

About two thirds of the dissolved carbon compounds of vinasse may be incorporated by yeasts like candida. Thus, raw protein (RP) content of vinasse can be increased to about 1,2 %, i.w. about 25 % RP in the dry matter. If mixed populations of bacteria are used for fermentation, RP content of the product may be increased to about 30 % and drying will be possible on an economical basis. Fodder production then is about 0,55 kg dry matter / 1 ethanol. When feeding with 50 % vinasse in the forage, a total of about 20.000 bulls or 120.000 pigs may be supplied by the ethanol plant.

Nutrients for single cell biomass production preferably come from liquid manure (11).

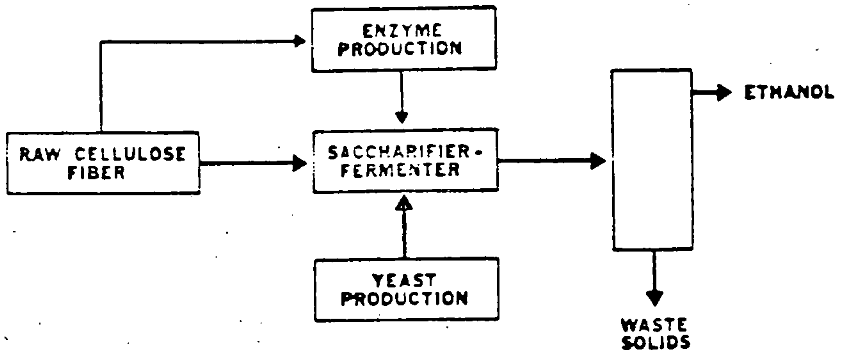
Thus, only the solid manure compounds have to be transported to the maniok farms, to close the circulation of nutrients. Continuous fermentation using mixed populations of bacteria are preferably carried out by adhesive fermentation (12), resulting in a simple operation and increased specific yields of biomass.

Aspects of energy

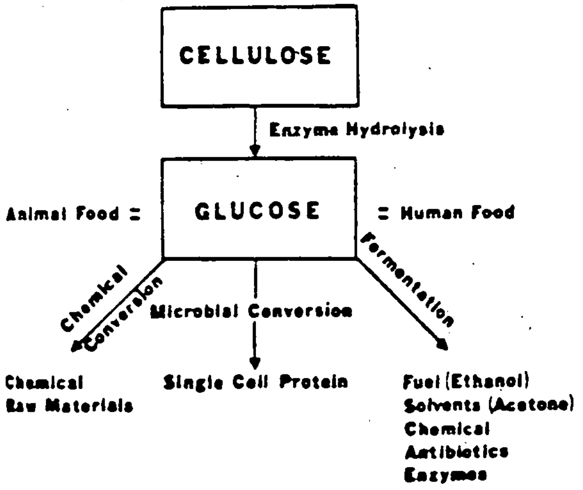
Combustion energy of the produced ethanol corresponds to about 50 MW. The total energy demand for ethanol production is about 35 MW, not included the energy for maniok farming and transport, for vinasse treatment and for survival of the men working for ethanol production. Net yield of thermal energy is about 30 % based on the produced ethanol. Including methane fermentation of vinasse net yield may be increased to about 60 %. The energy demand for transports and for men is estimated less than 10 % of the produced ethanol.

CELLULOSE

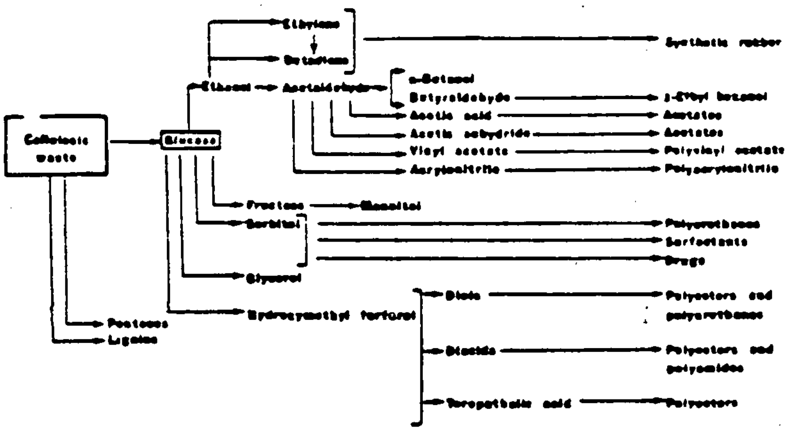
DIRECT ETHANOL PROCESS

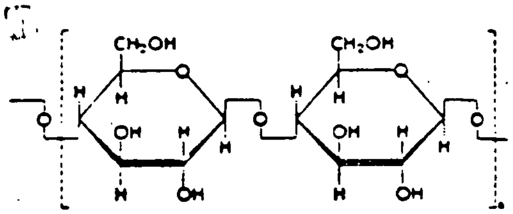


A CHEMICAL AND ENERGY RESOURCE

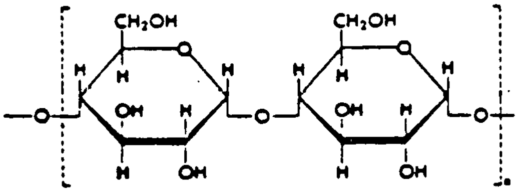


ROUTES FROM CELLULOSE TO PETROCHEMICALS ARE MANY AND VARIED





CELLULOSE



STARCH

- MOST ABUNDANT NATURAL MATERIAL
- ANNUALLY RENEWABLE
- NOT DIRECTLY USEFUL AS A FOODSTUFF

THREE CLASSES OF CELLULOSE FEEDSTOCKS

AGRICULTURAL BY-PRODUCTS

INDUSTRIAL & MUNICIPAL WASTE

SPECIAL CROPS

DIRECT ETHANOL PROCESS

GULF OIL CHEMICALS COMPANY
BIOCHEMICAL TECHNOLOGY

IN 1971 GULF OIL CHEMICALS COMPANY CONCEPTUALIZED THE NEED FOR ALTERNATE SOURCES OF CARBON/CARBON BONDS OTHER THAN FOSSIL FUELS. THEIR SEARCH LED THEM TO RECOGNIZE THAT RENEWABLE RESOURCES IN THE FORM OF HYDROCARBONS OR CARBOHYDRATES WOULD BE AN EXCELLENT FUTURE SOURCE FOR CHEMICALS.

THESE CARBON/CARBON BONDS ARE FORMED THROUGH A UNIQUE PROCESS CALLED PHOTOSYNTHESIS WHEREBY SOLAR ENERGY IS CONVERTED THROUGH THE ACTION OF PLANTS, ALONG WITH CARBON DIOXIDE, WATER AND INORGANIC NUTRIENTS TO CHEMICAL ENERGY.

THE TWO MAJOR FORMS OF CARBOHYDRATE CHEMICAL ENERGY ARE THOSE REPRESENTED BY THE MOLECULES, CELLULOSE AND STARCH. STARCH IS FOUND IN CORN, SUGAR CANE, POTATOES, ETC. AND IS CHARACTERIZED BY A UNIQUE LINKAGE BETWEEN GLUCOSE MOLECULES CALLED AN α-1,4 LINKAGE. THIS LINKAGE IS READILY BROKEN BY ENZYME SYSTEMS FOUND IN MAN AND ALMOST EVERY OTHER FORM OF LIFE. ITS COUNTERPART, CELLULOSE, DIFFERS ONLY IN THE CONFIGURATION OF THE BONDING BETWEEN THE TWO GLUCOSE MOLECULES CALLED A β-1,4 LINKAGE. NOT AS MANY LIFE FORMS HAVE THE ENZYME SYSTEM NECESSARY TO BREAK DOWN THIS BOND. THUS, THIS MATERIAL IS READILY AVAILABLE IN NATURE. BACTERIAL SYSTEMS, FUNGAL SYSTEMS AND SOME INVERTEBRATE SYSTEMS HAVE THE ENZYME SYSTEMS NECESSARY.

STARCH, BEING EASILY DEGRADABLE BY MAN AND OTHER ANIMALS IS A FOODSTUFF WHEREBY CELLULOSE, NOT BEING DEGRADABLE IN MAN OR OTHER ANIMALS CONSUMED BY MAN, IS NOT CONSIDERED A FOODSTUFF. IT IS ONLY NECESSARY BECAUSE OF ITS FIBROUS NATURE WITH RESPECT TO CERTAIN PHYSIOLOGICAL MOVEMENTS IN THE DIGESTIVE SYSTEMS OF THESE ANIMALS.

CELLULOSE IS THE MOST ABUNDANT NATURAL MATERIAL. IT IS ANNUALLY RENEWABLE AND NOT DIRECTLY USEFUL AS A FOODSTUFF.

CHAPTER V

DISTILLATION

Every distillation consists of two operations: The conversion of liquid into vapor, and the reconversion of the vapor into liquid. Hence perfect equilibrium should be established between the vaporizing heat and the condensing cold. The quantity of vapor must not be greater or less than can be condensed. If fire is too violent the vapors will pass out of the worm uncondensed. If the fire is too low the pressure of the vapor is not great enough to prevent the entrance of air, which obstructs distillation. As a means of indicating the proper regulation of the fire, the simple little device shown in Figure 1 may be used.

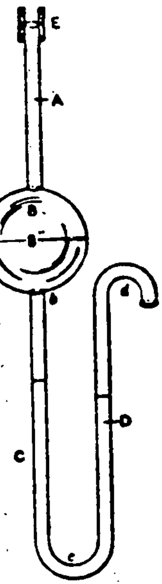


Figure 1. INDICATOR FOR REGULATING THE DISTILLING FIRE

This consists of a tube of copper or glass having a ball B eight inches in diameter. The upper end E of the tube is attached to the condensing worm. The lower end of the tube is bent in U-shape; the length of the two bends from b to outlet is four feet. The ball has a capacity slightly greater than the two legs of the bend.

Normally the liquid in the two legs will stand at a level. If, however, the fire is too brisk the vapor will enter the tube and drive out the liquor at d, and thus the level in the leg C will be less than in the leg D. If, however, the fire is low, the pressure of vapor in the worm will decrease and the pressure of the outside air will force down the liquid in leg D and up leg C into the ball.

A more perfected device but operating on the same principle is shown in Figure 11.

It is obviously impossible to present in the small compass of this manual a description of all the varieties of stills used, but these which have been described illustrate the principles on which all stills are constructed and were chosen for their simplicity of construction and clearness of their operation. The principle of their operation is exactly the same as the more modern forms now to be described.

The Apparatus employed in the process of distillation is called a still, and is of almost infinite variety. A still may be any vessel which will hold and permit fermentated "wash" or "beer" to be boiled therein, and which will collect the vapors arising from the surface of the boiling liquid and transmit them to a condenser. The still may be either heated by the direct application of fire, or the liquid in the still raised to the boiling point by the injection of steam. The steam of vapor rising from the boiling liquid must be cooled and condensed. This is done by leading it into tubes surrounded by cold water or the "cold mash."

The very simplest form of still is shown is Figure 2, and consists of two essential parts, the still, or boiler A, made of tinned copper, the condenser C which may be made of metal or wood and the worm B made of a coil of tinner copper pipe.

The liquor is boiled in A and the vapors pass off into the worm B, which is surrounded by the cold water of the condenser, the distillate being drawn off at f.

The heated vapors passing through the worm B will soonheat up the water in C thereby retarding perfect condensation. To prevent this, a cold water supply pipe may be connected to the bottom of C making a connection at the top of C for an overflow of the warmed up water. By this means the lowest part of the worm will be kept sufficiently cool to make a rapid condensation of the vapors.

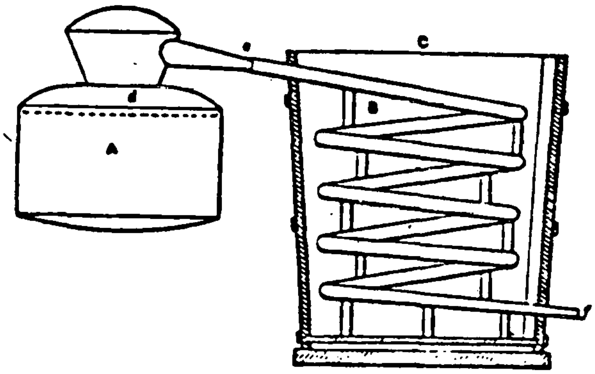


Figure 2. A SIMPLE STILL

The boiler A can be made in two parts: the upper part fitting into the lower part snugly at d. The pipe from the upper part fitting the worm snugly at e. This will enable the operator to thoroughly cleanse the boiler before puttingin a new lot of liquor. The joints at e and d should be luted with dough formed by mixing the flour with a small portion of salt and moistening with water. This is thoroughly packed at the junctions of the parts to prevent the escape of steam or vapor.

In an apparatus of this kind, the vapors of alcohol and water are condensed together. But if instead of filling the condenser C with cold water, it is kept at a temperature of 176°F. the greater part of the water-vapor will be condensed while the alcohol, which boils at 172.4°F. passes through the coil uncondensed. If therefore, the water be condensed and collected separately in this manner, and the alcoholic vapors be conducted into another cooler kept at temperature below 172.4°., the alcohol will be obtained in a much higher state of concentration than it would be by a process of simple distillation.

Supposing, again, that vapors containing but a small quantity of alcohol are brought into contact with an alcoholic liquid of lower temperature than the vapors themselves, and in very small quantity, the vapor of water will be partly condensed, so that the remainder will be richer in alcohol than it was previously. But the water, in condensing, converts into vapor a portion of the spirit contained in the liquid interposed, so that the uncondensed vapors passing away are still further enriched by this means. Here, then, are the results obtained; the alcoholic vapors are strengthened, firstly, by the removal of a portion of the water wherewith they were mixed; and then by the admixture with them of the vaporized spirit placed in the condenser. By the employment of some such method as this, a very satisfactory yield of spirit may be obtained, both with regard to quality, as it is extremely concentrated, and to the cost of production, since the simple condensation of the water is made use of to convert the spirit into vapor without the necessity of having recourse to fuel. The construction of every variety of distilling apparatus now in use is based upon the above principles.

A sectional view of another simple form of still is shown in Figure 3; V is a wooden vat having a tight fitting cover a, through the center of which a hole has been cut. The wide end of a goose neck of copper pipe g is securely fitted over this aperture, the smaller end of this pipe passes through the cover of the retort R extending nearly to the bottom; f is the steam supply pipe from boiler; M the rectifier consisting of a cylindrical copper vessel containing a number of small vertical pipes surrounded by a cold water jacket; o the inlet for the cold water which circulates around these small pipes, discharging at n; the pipes in M have a common connection to a pipe p, which connects the rectifier with coil in cooler C; s is a pipe to the receptacle for receiving the distillate; u cold water supply pipe to cooler, and W discharge for warmed-up water; k discharge for refuse wash in vat V.

The operation is as follows: The vat V is nearly filled with fermented mash and retort R with weak distillate from a previous operation. Steam is then turned into the pipe f discharging near the bottom of the vat V and working up through the mash. This heats up the mash and the vapors escape up g over into R where they warm up the weak distillate. The vapors thus enriched rise into M, where a good percentage of the water vapor is distilled, that is, condensed by the cold water surrounding the small pipes. The vapor then passes over through p into the coil, where it is liquified and from whence it passes by pipe s into the receiver. The cold water for cooling both M and C can be turned on as soon as the apparatus has become thoroughly heated up.

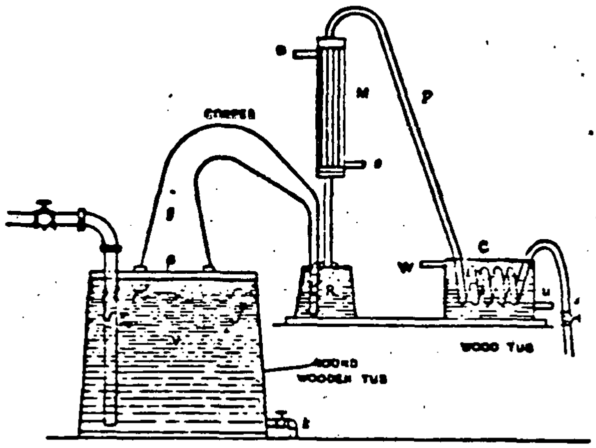


Figure 3. SIMPLE STILL, WITH RECTIFIER

The stills in use today in many parts of the South for the production of whiskey are quite as simple as those above described, and some for the making of "moonshine" liquor are more so.

The first distilling apparatus for the production of strong alcohol on an industrial scale was invented by Edward Adam, in the year 1801. The arrangement is shown in Figure 4; in which A is a still to contain the liquor placed over a suitable heater. The vapors were conducted by a tube into the eggshaped vessel B, the tube reaching nearly to the bottom; they then passed out by another tube into a second egg C; then, in some cases, into a third, not shown in the figure, and finally into the worm D, and through a cock at G into the receiver. The liquor condensed in the first egg is stronger than that in the still, while that found in the second and third is stronger than either. The spirit which is condensed at the bottom of the worm is of a very high degree of strength. At the bottom of each of the eggs, there is a tube connected with the sitll, by which the concentrated liquors may be run back into A for redistillation after the refuse liquor from the first distil has been run off.

In the tube is a stop-cock a, by regulating which, enough liquor could be kept in the eggs to cover the lower ends of the entrance pipes, so that the alcoholic vapors were not only deprived of water by the cooling which they underwent in passing through the eggs, but were also mixed with fresh spirit obtained from the vaporization of the liquid remaining in the bottom of the eggs, in the manner already described.

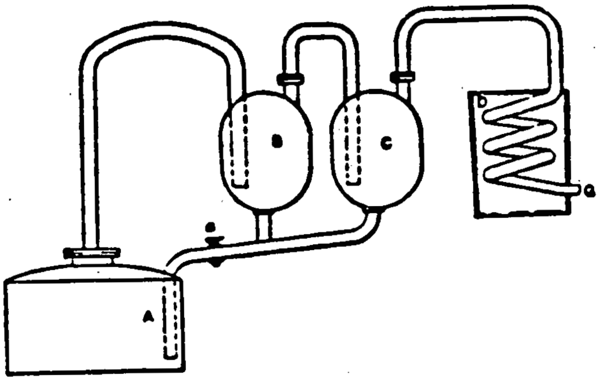


Figure 4. ADAM'S STILL

Compound Distillation. Where stills of the from shown in Figures 2 and 3 are used the alcohol obtained is weak. Hence it is necessary that the distillate be again itself distilled, the operation being repeated a number of times. In the better class of still, however, compound distillation is performed the mash is heated by the hot vapors rising from the still and the vapors are condensed and run back into the still greatly enriched.

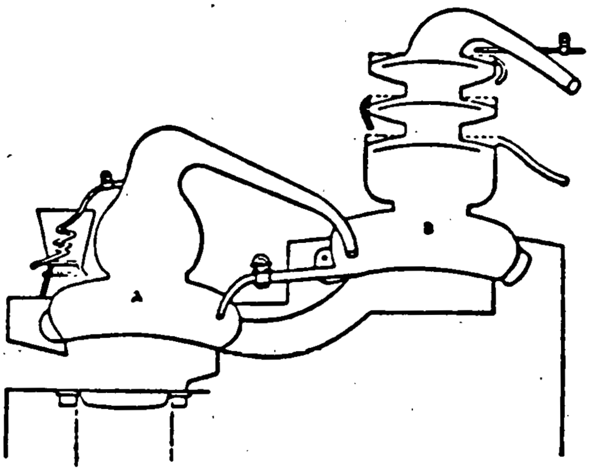
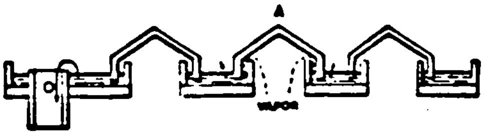


Figure 5. DOUBLE STILL

Modern Distilling Apparatus

All modern distilling apparatus for the production of a high grade of alcohol is based upon the principle set forth in the description of the Coffey still; that is, upon using a distilling column and a concentrating column, wherein the "wash" or mash fermented as described, passes over a series of plates or other obstructions in contact with an ascending column of heated vapor. This heated vapor extracts the alcohol from the wash, or from the low wines of the concentrator, and is continually strengthened during its journey until it passes off to a condenser as a vapor very rich in alcohol. The converse of this is true with the wash, which in its downward course is gradually deprived of its alcohol until it finally passes off at the bottom of the column.

Figure 7 is illustrative of the general form and arrangement of such a column and its adjuncts; the details, however, will vary with each make of still. In this the "column" consists of a casing really continuous but divided into two portions—the distilling portion A and the rectifying portion B. The operation is alike, however, in principle in both portions.



Cross-Section of Figure 6

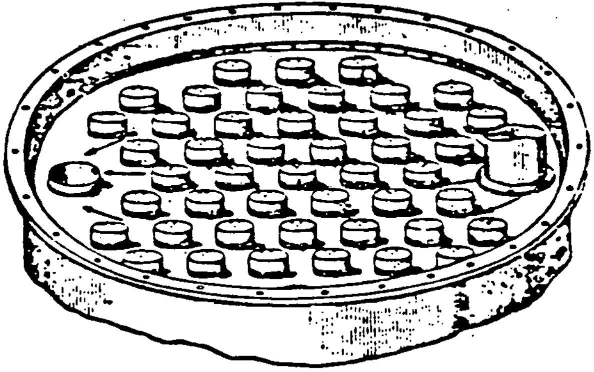


Figure 6. DISTILLING PLATE

The wash by means of a suitable pump is forced into an overhead tank or concentrator G where it is warmed by the hot vapors as will be later described. It passes around the interior of the concentrator in a coil c and then passes off by a pipe g to the uppermost plate of the distilling portion A of the column.

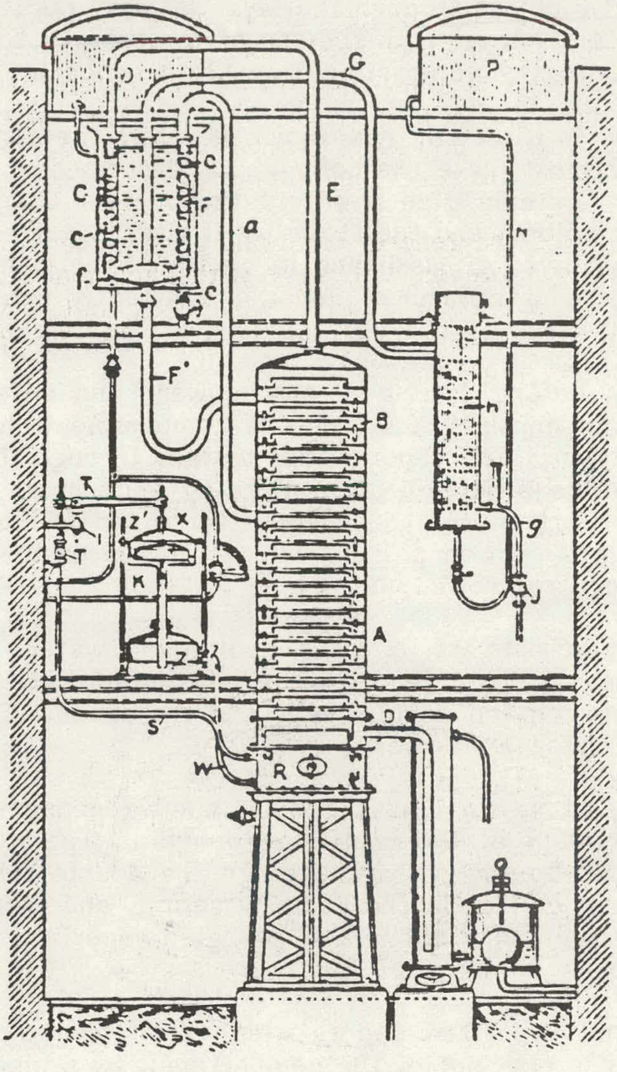


Figure 7. DIAGRAMATIC VIEW OF COLUMN STILL AND ACCESSORY APPARATUS

The plates are each formed with a dropping tube O (see Figure 6), which extends above the plate to an extent slightly less than the desired thickness of the layer of liquid on each plate, and with perforations each having an upwardly projecting rim, and each covered with a cap A. This rim and cap form a trap. The ascending vapors pass up through the perforations, down between the rim and the edge of the cap and thus out through the layer of wash contained on the cap. The wash remains constantly level with the top of the tube O, the excess running off through the tube O to the compartment or plate beneath.

To return to Figure 7, the wash by the pipe a enters the distilling portion of the column at the uppermost plate thereof and, as described above, drops down from plate to plate. A steam pipe S enters the bottom compartment of the distilling portion of the column and the steam as it rises through the little traps, bubbles out through the layer of wash and in each compartment enriches itself with alcohol. Thus the rising column of vapor is constantly weaker until at last it passes away as spent wash at the very bottom of the column by the pipe D.

The hot vapors, as before described, pass upward and enter the rectifying portion of column B. This consists of a series of compartments having perforated bottoms and dropping tubes. The vapor passes upward through these perforations of the plates—the condensed portion of it dropping back again on to the lower plates or on to the distilling plates to be again vaporized and concentrated and the more highly vaporized portion passing out at the top of the column through the pipe E to the concentrator G.

The concentrator consists of a tank containing water within which is supported a vessel F having double walls. The interior of this vessel is likewise filled with water. Between the double walls and surrounding the coiled pipe c passes the vapors from pipe E

At the bottom of the vessel F is a compartment f connected by a pipe F^1 with the upper compartment of the rectifying column. The less highly heated vapors will be condensed by the passage through the double walls of the vessel and the condensation will collect in the compartment f, and from there pass off by pipe F^1 back to the rectifying column, to be again vaporized and strengthened by the descent from plate to plate of B.

The rich and highly vaporized vapors which have passed the test of this preliminary concentration, pass out of the compartment by a pipe M. Here again the water surrounding the pipe tends to condense all but the most highly charged vapor and send it back to compartment f but the vapor which succeeds in passing over through pipe G is carried downward to a condenser H where it is finally condensed and drawn off as at g. It is necessary that the rate of mash feed be regulated so that neither too much mash shall be pumped into the mash heater G, or too little, and the pipe leading from the pump to the heater is therefore provided with a tap and an indicating dial.

In these modern stills the following are particularly important points to be especially brought to the consideration of the distiller.

It cannot be too strongly impressed that effectiveness of the distilling column depends on the plates dividing it—that is, upon the horizontality of the plates and the form of the traps or perforations. If the plates are not horizontal the wash is not maintained at a uniform level across the entire extent of the plate and hence some of the ascending vapor will pass out without contacting with the wash through uncovered traps, while others of the traps will be so deeply submerged in wash that the vapor cannot bubble through.

Again the caps should be so made as to divide the vapor into fine streams and bring it into contact with each part of the wash. Plates simply perforated and uncapped give excellent results for they molecularize the vapor ascending through the liquid contained on the plates, but they require a constant pressure of vapor, and any variations of pressure tends to discharge them. In addition these perforations gradually enlarge by the action of acids in the wash or clog up, and the apparatus soon works badly.

Good forms of capped traps are shown in Figures 8 and 9 devised by Barbet. These are provided with an interior upwardly projecting rim. Extending over the rim and down around it is a copper cap having its margin slitted.

The wash carried on the plate circulates about the caps and the alcoholic vapors bubble out through the slits and up through the wash, the vapor thus being finely divided and coming into intemate contact with each portion of the wash and thus more thoroughly depriving it of its alcohol.

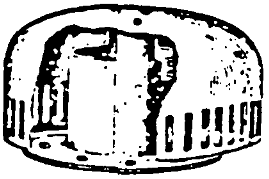


Figure 8. BARBET TRAP

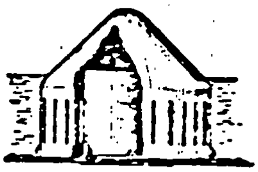


Figure 9. BARBET TRAP

Besides this there is another advantage resident in these caps, namely, that distillation may be stopped for several hours and then restarted without trouble for the reason that the wash has been retained on the plates, whereas were the plates simply perforated the wash would ooze through and the plates have to be recharged. This form of plate may be easily repaired and does not necessitate the removal or replacement of the plate itself. The caps alone need be removed.

For thick washes, which tends to obstruct the slits of the cap, Barbet has devised the cap shown in Figure 9. This cap extends down to the plate itself, and has very narrow slits in its periphery. With such a cap as shown in Figure 8, the bran, sediments, etc., would tend to settle upon the top of the cap, enter beneath it and through the slits. The cone-shape of the top of this cap prevents the deposit of dregs thereon and the very narrow slits oppose the entrance of bran or sediment.

While, for the sake of clearness, an old form of concentrator G, has been shown, the concentrator, preheater for the wash, and condensers, today, are usually composed of bundles of tubes through which the vapors pass surrounded by water or the cool wash. These should be of bronze or copper and made without solder. The tubes should be capable of being taken out for cleaning or repairing.

In many distilling apparatuses the distilling column and the rectifying column are in two parts, one beside the other. This overcomes the objection of having a very high column and also prevents the low wines, i.e., the weak alcoholic liquor after its first concentration, from passing into the wash as it would do with the continuous column.

In order that the amount of steam entering the column may be regulated, the column is usually provided with a steam regulator (Figure 10), whose principle of operation may be easily understood by referring to Figure 7. It comprises an upper and a lower chamber ZZ' connected by a central tube K which projects down nearly to the bottom of the lower chamber. A pipe W communicates with the steam chamber R of the column and enters the chamber Z above the level of the water contained therein. In the upper chamber Z', is a float X, connected to the differential level T of a steam valve T' which controls the inlet of steam passing through pipe S to the steam chest R. The principle of operation is very simple. When the pressure in the steam check R becomes too great, steam in the pipe W and chamber Z forces the water therein up in tube K, thus lifting the float X and closing the steam entrance valve T. When the pressure of steam is low, the level of the liquid in Z rises and liquid in Z' runs into Z, the float X falls opening valve T' and allowing a greater flow of steam.

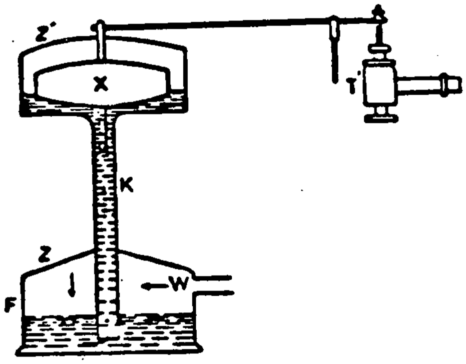


Figure 10. STEAM REGULATOR

As it is often desirable to change the pressure of steam in the column at various points in the operation, the best regulators are usually provided with means to that end.

Distilling Plants: Their General Arrangement and Equipment

When we look at the manufactories of today with their complicated machinery, their extensive equipment, their great boilers, and engines and their hundreds of employees, we are liable to forget that good work was turned out by our ancestors, with equipment of extreme simplicity and that today while there are, for instance, thousands of wood-working mills, complete in every detail and covering under a multitude of roofs every variety of complicated and perfected wood-working machinery, yet there are many more thousands of small plants, comprising a portable boiler, fed with refuse, a small engine and a few saws which are making money for the owners and doing to work of the world.

The reader therefore, must be warned against any feeling of discouragement because of the cost and complicated perfection of elaborate distilling plants. Where the business is to be entered into on a large scale, to take the products from a considerable section of country and turn them into alcohol to compete in the great markets, the best of apparatus and equipment is not too good, but the person contemplating the mere manufacture of alcohol on a small scale, to serve only a small section, must remember that distillation is really a very simple matter, for years practices with a most rudimentary apparatus and still so practiced in the country districts particularly in the South.

This is well illustrated by the fact that an illicit distille confined in one of the North Carolina penitentiaries for transgressing the revenue laws, was able while in durance, to continue his operations unknown to the prison authorities, his plant consisting of a few buckets, and a still whose body was a tin kettle, a few pieces of pipe and a worm which he had bent himself. This example is not given as encouragement to illicit or "blockade" distilling but merely to show vividly how simple the rudimentary apparatus really is.

The simplest regular plants, those of the South for instance, comprise a building of rough lumber some thirty feet by twelve wide, with a wooden floor on which the fermenting vats rest and an earthern floor immediately in front of the still and furnance. This is to permit the fires being drawn when the charge has been exhausted in the boiler. The still is of the fire-heated, intermittent variety, such as described on page 29. It consists of a brick furnace or oven, large enough to burn ordinary cord wood and supporting a copper boiler of fifteen or twenty gallons capacity. On top of this is a copper "head" with the usual goose neck, from which a copper pipe leads to a closed and locked barrel containing raw spirits, this barrel acting on the principle of the condensing chamber shown in the still in Figure 3. From the upper part of this barrel, which acts as a concentrator, the vapors pass to a copper worm immersed in a tub of cold water. Here the vapors are condensed and pass by a pipe to a receiving tank.

The fermenting vats may be six or more in number so as to allow the mash in each tank to be at a different stage of fermentation. A pump is used for pumping the contents of any of the tanks into the boiler or the still. A pump is also provided for supplying water to the vats and condensers.

In connection with the distilling and fermenting building there are small buildings for storing the grain, malt, etc.

The buildings are of the cheapest construction and arranged in the manner which compels the least labor in filling the mash vats and turning the contents into alcohol. The alcohol so produced are low grade, fiery and rough in taste, but the point is that alcohol may be and is so produced.

Between these simple beginnings and the elaborate plants of big distilleries there is a wide range, so wide that it is impossible within the limits of this manual to go into detail. The makers of distilling apparatus furnish all grades of stills and to those contemplating erecting a plant it is suggested that their best course is to communicate with such manufacturers, giving the circumstances of the case, the particular product to be worked and the capacity desired. The object of this manual is to give an understanding of the processes of distillation and of this chapter to give a general idea of the arrangement of a number of typical distilling plants, suitable for various kinds of work.

That the simple, direct-heated pot still such as referred to above, used for fifteen hundred years and over, is still used largely due to the simplicity of its construction and operation, but its capacity is small, and its operating expense relatively heavy. It is still used for making liquors, but for industrial purposes it has been entirely superceded by concentrating and rectifying stills. A simple form of the latter is found in the still shown in Figure 5 and in the distilling apparatus of Adam (Figure 4).

Originally all stills were heated by direct contact with fire. This was open to a serious objection, namely, that the mash if thick was liable to be scorched. Stirring devices were used by Pistorious but these required constant attention. As a consequence, direct firing gave place to heating bysteam, by which not only was scorching of the wash avoided but much greater certainty of operation was attained.

The steam may be used to simply heat the boiler, thus taking the place of the direct heat of the fire, but it is far better in every way to admit the steam directly to the mash as in the Coffey still and all modern stills. It is possible to apply this principle to all compound stills, but the best results with greatest economy of fuel are, of course, gotten from the plate or column stills especially constructed for steam. In order to get the best results it is necessary that the entry of steam be regulated so that there may be absolute uniformity of flow.

CHAPTER VI

BIOMASS BASED FORMULATED FUELS FOR INTERNAL COMBUSTION ENGINES

Introduction

Today, alcohols are the most readily available candidates for formulated biomass liquid fuels, separately or in conjunction with fossil fuels. In addition, at this time, ethanol and methanol are the most developed biofuels. We must recognize, however, that all biosubstances, densified by bioaction into bonded combinations of hydrogen and carbon represent stored chemical energy and are readily available for conversion into formulated fuels--again--separately, or in combination with other biomass or fossil based fuels. The transformation of biosubstances into biofuels, based on economic and energy considerations, can be accomplished through a variety of interactions to include, mechanical, chemical, heat, enzymatic, biological, sonic and electronic interactions.

Today, alcohols are the most readily available candidates for formulated biomass liquid fuels, separately or in conjunction with fossil fuels. In addition, at this time ethanol and methanol are the most developed biofuels. They are the forebearers of several energy oriented economic, political, and sociological changes in America. It is critical that we deal with these forebearers wisely, for they will help set the pace and tone for other emerging renewable energy systems that can be developed in the best interest of the public. This works focus is on alcohols but it also refers to other biomass fuels, solids, liquids, and gases, that can be made through the refining of biomass. Gasohol, alcohol and biomass fuels are the A, the B, and the C through Z of a potentially major energy system that is about to dawn.

We should point out that the major institutions were busy with fossil and nuclear fuels, while pioneers--driven more by idealism --have established the capabilities of alcohol fuel despite the unfairness of factual taboos.

- At the beginning of the century, gasoline, a by-product in the production of kerosene, displaced alcohols fuel

  For internal combustion engines only because it was cheaper. Furthermore, Edison's discovery of the electric bulb made gasoline the "horse" of the oil industry.

- From then to today, the internal combustion engine has been optimized for using fossil liquid fuel. The primitive forms of gasoline have been formulated through refining. Its burning behavior has been improved and little or no consideration has been given to other resources of liquid and gaseous fuels such as those derived from biomass.

- Today the fear of non-solvable, pollution, efficiency, and scarcity problems have returned our attention to other sources of fuel.

- The established ground for evaluation of alcohol fuels are biased and unfair when one considers that the comparisons are made between highly refined and forumlated gasoline technologies and the relatively primitive, non-optimized alcohol fuel technologies which have been dormant for nearly a hundreds years. Once formulation techniques, engines and auxiliary hardware have been optimized for biomass fuels, they will except the test.

Conclusively, alcohols are scientifically, economically and operationally a base for formulating liquid fuels for internal combustion engines and their contribution to the supply of energy must be counted.

Because of their potenial utility as a transistional fuel, alcohol fuels may be called upon to power a substantial number of vehicles configured to reflect today's internal combustion engine technology. In such a context, the first requirement is for an acceptable fuel and only after that has been accomplished do we concern ourselves as to whether it is a better fuel.

Ethanol As A Fuel

Ethyl alcohol is not only the oldest synthetic organic chemical used by man, but also one of the most important.

95% Alcohol: An Azeotrope (190 Proof)

Except for alcoholic beverages, nearly all the ethyl alcohol used is a mixture of 95% alcohol, 5% water, known simply as 95% alcohol. Although pure alcohol (known as absolute alcohol) is available, it is much more expensive and is used only when definitely required.

What is so special about the concentration of 95%? Whatever the method of preparation, ethyl alcohol is obtained first mixed with water; this mixture is then concentrated by fractional distillation. As in any distillation, the first material to distill is the one of highest volatility, that is of lowest boiling point. In a mixture of ethyl alcohol and water the lowest boiling component is not water (b.p. 100°) or ethyl alcohol (b.p. 78.3°) but a mixture of 95% alcohol and 5% water (b.p. 78.15°). If an efficient fractionating column is used, there is obtained first 95% alcohol, then a small intermediate fraction of lower concentration, and then water. But no matter how efficient the fractionating column used, 95% alcohol cannot be further concentrated.

As we know, separation of a mixture by distillation occurs because the vapor has a different composition from the liquid from which it distills; the vapor being richer in the more volatile component. We cannot separate 95% alcohol into its components by distillation because here the vapor has exactly the same composition as the liquid; toward distillation, then, 95% alcohol behaves exactly like a pure compound.

A liquid mixture that has the peculiar property of giving a vapor of the same composition is called an azeotrope or a constant-boiling mixture. Since it contains two components 95% alcohol is a binary azeotrope. Most azeotropes, like 95% alcohol, have boiling points lower than those of their compoennts and are known as minimum-boiling mixtures; azeotropes having boiling points higher than those of their components are known as maximum-boiling mixtures.

Absolute Alcohol (200 Proof)

If 95% alcohol cannot be further concentrated by distillation, the commercially available 100% ethyl alcohol known as absolute alcohol is obtained by taking advantage of the existence of an azeotrope, this time a three-component one (termary azeotrope). A mixture of 7.5% water, 18.5% ethyl alcohol, and 74% benzene forms an azeotrope of b.p. 64.9° (a minimum-boiling mixture).

Expectations of Ethanol

Quoting F. B. Wright - 1907

On June 7, 1906, however, Congress passed the "De-Naturing Act," as it is called, which provided in brief that alcohol, which had been mixed with a certain proportion of de-naturing materials sufficient to prevent its use as a beverage should not be taxed.

The passage of this Act was alcohol's new day, and is destined to have a wide influence upon the agricultural pursuits of the country.

In the matter of small engines and motors alone, one estimate places the farm use of these at three hundred thousand with an annual increase of one hundred thousand. This means an economical displacing of horse and muscle power in farm work almost beyond comprehension. If now the farmer can make from surplus or cheaply grown crops the fuels for his motors, he is placed in a still more independent and commanding position in the industrial race.

As an illuminant the untaxed alcohol is bound to introduce some interesting as well as novel conditions. The general estimate of the value of alcohol for lighting gives it about double the power of kerosene, a gallon of alcohol lasting as long as two gallons of oil. In Germany, where the use of alcohol in lamps is most fully developed, a mantle is used. Thus in a short time it may be expected that an entirely new industry will spring up to meet the demand for the illuminating lamps embodying the latest approved form of mantle. The adapting of the gasoline motors of automobiles to alcohol fuel will in itself create a vast new manufacturing undertaking. When this is accomplished it is believed that we shall no more be troubled with the malodorous "auto" and "cycle" gasoline burners on our public streets and parkways.

De-natured alcohol is simply alcohol which has been so treated as to spoil it for use as a beverage or medicine and prevent its use in any manner except for industrial purposes.

The use of de-natured alcohol as a fuel has yet to be fully developed. Although alcohol has only about half the heating power or kerosene or gasoline, gallon for gallon, yet it has many valuable properties which may enable it to compete successfully in spite of its lower fuel value. In the first place it is very much safer. Alcohol has a tendency to simply heat the surrounding vapors and produce currents of hot gases which are not usually brought to high enough temperature to inflame articles at a distance. It can be easily diluted with water, and when it is diluted to more than one-half it ceases to be inflammable. Hence it may be readily extinguished; while burning gasoline, by floating on the water, simply spreads its flame when water is applied to it. Although alcohol has far less heating capacity than gasoline, the best experts believe that it will develop a much higher percentage of efficiency in motors than does gasoline.

A recent exhibition in Germany gave a good illustration of the broad field in which de-natured alcohol may be used.

Here were shown alcohol engines of a large number of different makes; alcohol boat motors as devised for the Russian navy; and motors for threshing, grinding, woodcutting, and other agricultural purposes.

The department of lighting apparatus included a large and varied display of lamps, chandeliers, and street and corridor lights, in which alcohol vapor is burned like gas in a hooded flame covered by a Welsbach mantle.

Under such conditions alcohol vapor burns with an incandescent flame which rivals the arc light in brilliancy and must be shaded to adapt it to the endurance of the human eye.

Similarly attractive and interesting was the large display of alcohol heating stoves, which, for warming corridors, sleeping rooms, and certain other locations, are highly esteemed. They are made of japanned-iron plate in decorative forms, with concave copper reflectors; are readily portable; and, when provided with chimney connections for the escape of gases of combustion, furnish a clean, odorless, and convenient heating apparatus.

Cooking stoves of all sizes, forms, and capacities (from the complete range, which has baking and roasting ovens, broilers, etc., to the simple tea and coffee lamp) were also displayed in endless variety.

Enough has been said to give an idea of the capabilities and values of this new form of fuel, at least, and as far as the United States is concerned.

With its advent not only will American genius perfect the machinery for its use, but the American farmer is given a new market for his crops.

Distilleries, big and little, are likely to be set up all over the country, and the time is not far distant when the farmer will be able to carry his corn to the distillery, and either return with the money in his pocket or with fuel for farm engines, machinery, and perchance his automobile.

ALCOHOL FUELS - 1980 EXPECTATIONS

EXCERPT FROM "THE REPORT OF THE ALCOHOL FUELS POLICY REVIEW"

U.S. Department of Energy
Assistant Secretary for Policy Evaluation
Washington, D.C. 20585

INTRODUCTION

The steadily increasing demand for premium fuels—especially oil and gas—cannot continue to be met by traditional sources at traditional prices. As the more attractive and economic domestic resources are being depleted, the Nation has turned increasingly to imports, which now account for half the liquid fuels consumed in the United States. Events of the past decade have illustrated both the substantial economic cost and the instability and economic vulnerability that such imports entail.

Over the longer term, worldwide production cannot long continue to keep pace with increasing demand, leading to a period of tighter supplies and higher prices. Thus, there will be a transition to the use of large but finite resources that are not now in widespread use. There must later be a second transition to resources that are renewable or essentially inexhaustible.

In that process, the uses of energy—and the forms in which energy will be used—will become increasingly important. Over half the liquid fuels consumed in the United States today are used in transportation, and about three-quarters of that amount is in the form of gasoline used in automobiles.

This Administration has developed a long-term national energy policy that will reduce dependence on foreign oil in the short term and develop renewable and essentially inexhaustible sources of energy in the long term. To meet these objectives, development of alternative sources of liquid fuels will be necessary. Alcohol fuels represent sources that can substitute for petroleum products now and increasingly through the 1980's, drawing on abundant supplies of renewable materials and coal.

PRIVATE SECTOR INITIATIVE

The past year has witnessed growing support and enthusiasm for alcohol fuels. A genuine grass roots movement has developed, giving alcohol fuels an unprecedented broad base of support. This growth in alcohol fuels production and use is now making a contribution to the Nation's supply of liquid fuel. Equally important, it has visibly demonstrated the importance of State and private sector efforts in developing energy supplies.

The Department of Energy welcomes and encourages the initiative the public and private sector have demonstrated to augment our energy supplies. States, localities, companies, and individual citizens have played key roles in increasing awareness of alcohol fuels' potential by taking steps to produce and market fuel. This entrepreneurial spirit and public involvement in developing new energy resources are essential. In all areas of energy conservation and supply, such spirit and involvement are important to securing a sound energy future for the Nation.

SUMMARY OF MAIN FINDINGS

Alcohol fuels (both ethanol and methanol) can contribute to U.S. energy resources by using domestic, renewable resources and coal to extend supplies of high-quality liquid fuels. Indeed, ethanol is the only alternative fuel commercially available now, and the only one likely to be available in quantity before 1985. Methanol can be made from coal using commercially available technology, and could be produced in large quantities in the mid-to-late 1980's, when plants—if begun soon—could be completed and begin operating. Maximizing ethanol's contribution will require minimizing the use of oil and gas in producing feedstocks and in converting them to alcohol.

Through 1985, the contribution of alcohol fuels is exected to be modest nationally—perhaps displacing as many as 40,000 barrels per day of oil once recent presidential initiatives are put into practice. Production will be limited by the capacity to convert agricultural and waste material into alcohol. The impact is likely to be much greater regionally, however. In agricultural states, alcohol fuels may become significant sources of local supply. The potential beyond 1985 may be quite large—especially if major new ethanol and methanol facilities are developed during the early 1980's and if fuel users adapt to take advantage of alcohol fuels' properties.

It is important to note that no one energy source can solve our national energy problems. Though alcohol fuels cannot be a total or, in the near term, even a major solution to our national energy needs, they do represent an important energy component and building block for the longer term. Our national energy needs must be met by actively conserving and by aggressively developing contributions from a large number of energy supplies, building on the Nation's abundant resources. Alcohol fuels represent important supplies based on the American agricultural system and on the potential of U.S. coal.

ALCOHOL'S POTENTIAL FOR PETROLEUM SAVINGS

Blended with gasoline, alcohols can supplement U.S. oil supplies as motor fuel extenders and octane improvers. Indeed, in the near term (1979 to 1985), the contribution will come primarily from alcohol blends with gasoline, especially gasohol—a mixture of 10 percent ethanol and 90 percent gasoline. Gasohol can be burned in present motor vehicles with, at most, very minor materials or engine modifications. Adding the ethanol to unleaded gasoline not only extends gasoline supplies but also raises the octane. Three percent ethanol raises typical gasoline octane (measured as the average of "research" and "motor" octane) by roughly one point; 10 percent increases the octane by 2 to 3 points, depending on the composition of the gasoline.

Methanol enhances gasoline octane similarly. Low concentrations of methanol in gasoline can be burned in present cars; concentrations up to several percent can be used with only a few modifications (replacement of particularly sensitive plastic or rubber seals, for example). Higher concentrations require further changes in materials to minimize contact of methanol with those metals that it corrodes, e.g., lead, zinc, and magnesium. In higher concentrations, both ethanol and methanol (as high-octane motor fuels) permit the use of efficient engines with compression ratios higher than can be used with gasoline alone.

The octane-boosting properties of alcohol fuels are particularly attractive at a time when higher octane lead-free gasolines are in short supply and other octane enhancers such as MMT (methylcyclopentadienyl manganese tricarbonyl) and lead are under restrictions. Ethanol has been permitted by the Environmental Protection Agency for use as a gasoline additive under Section 211(f) of the Clean Air Act. Two other chemicals—TBA (tertiary-butyl alcohol) and MTBE (methyl tertiary butyl ether) also have been permitted as octane enhancers. However, both are currently made largely from petroleum. Through the early 1980's, U.S. octane production capacity will continue to be limited. Alcohol fuels may thus help to increase U.S. capability to produce unleaded gasoline and reduce energy losses that occur in the severe reforming needed to make high-octane gasoline blending components.

For most of the 1980's, production capacity for converting raw materials to ethanol will limit the production and use of gasohol. Abundant supplies of raw materials are available, and far exceed the production capacity of alcohol plants expected to be operating by the mid-1980's.

Present incentives appear likely to increase ethanol fuel production from a current level of approximately 60 million gallons per year (4,000 barrels per day) to a level of approximately 300 million gallons per year (20,000 barrels per day) by 1982, with gasohol use thus reaching 3 billion gallons per year or 3 percent of present gasoline consumption. This increase in production capacity is likely to come predominantly from use of unused distillery capacity and the expansion of currently operating facilities.

Permanent extension of the Federal motor fuel excise tax exemption for fuel containing biomass alcohol, as the President recently proposed, would encourage investors to build new alcohol fuel facilities. By 1985, stimulated by these incentives, biomass alcohol fuel production could reach 500 to 600 million gallons per year. This quantity would be roughly twice total non-beverage U.S. ethanol production in 1977 (two-thirds of which came from petroleum) and five to eight times the biomass alcohol fuel production estimated for late 1979. It would substitute for 30,000 to 40,000 barrels per day of petroleum, and could reduce petroleum imports by up to 0.4 percent if minimal petroleum is used in the manufacture of ethanol.

Beyond 1985, ethanol use will depend on the amount of new conversion capacity built, on the availability of inexpensive feedstocks, on new developments in technology and their impact on costs, and on the relative costs of competing fuels. As crude oil and gasoline prices continue to climb, the cost of alcohol fuels may become more competitive with petroleum. Costs for ethanol fuels should be reduced by new technologies, especially those that reduce the capital and energy needed for conversion and those that improve the value of the co-products produced with the alcohol.

Methanol derived from biomass and from coal is expected to play a larger role in the long term, as its use in turbines and other stationary equipment increases and as materials and engines are adapted to facilitate its extensive use in motor vehicles. Technology to produce methanol from coal exists today and could be built on a commercial scale as soon as investors perceive the economic opportunity to be favorable.

To be economically attractive, methanol production plants must be large—each producing 20,000 to 50,000 barrels per day. Such plants cost from $500 million to over a billion dollars each, and require three to four years to build, after several years of negotiating for sites and permits. Once such plants are built, methanol could be produced in much larger quantities than ethanol and should be less expensive. Until the late 1980's, when methanol could become widely available, ethanol will be the main fuel supplement available. Even if a general transition to methanol should take place, ethanol appears likely to continue to be marketed as a high-octane motor fuel blending component.

If adapting motor vehicles and/or distribution systems to accommodate methanol should prove difficult, methanol may also be converted directly to high-quality gasoline or to MTBE, which is chemically closer to petroleum. Both ethanol and methanol fuels may also find use in diesel engines, advanced heat engines, adapted boilers, and fuel cells.

The Department of Energy has already taken steps to remove regulatory and institutional barriers to alcohol development. In 1978, the Department of Energy's Economic Regulatory Administration (ERA) adopted pricing regulations that encourage gasohol production by permitting the full cost of ethanol in gasohol to be passed through by retailers. To facilitate gasohol production, the Department's Office of Hearings and Appeals recently proposed to grant an exception to gasoline allocation rules to assure gasoline supply for gasohol blending to a gasohol marketing firm. ERA has proposed to permit the costs of alcohols added to gasoline to be allocated across all gasoline production, rather than only to gasohol, per se.

DEMAND FOR GASOHOL

A year ago, a primary concern was how to launch an alcohol fuels industry. Today, stimulated by a grass roots movement, local and State actions, and significant Federal and State subsidies, an industry has been launched and is growing rapidly. Demand for alcohol fuels has at times exceeded the supply of alcohol immediately available for fuel use. Producers that dealt solely with beverage and industrial markets are now expanding production to enter the alcohol fuel market, and many potential small-scale producers are planning to build facilities.

In one year, the number of retail outlets marketing gasohol has increased from a few to well over 800. Gasohol is currently being sold in California, Colorado, Delaware, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nebraska, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, South Dakota, Virginia, Wisconsin, and Wyoming. Sales are expected to continue to expand as additional supplies of alcohol become available.

Several States have provided incentives for gasohol. For example, Iowa has exempted gasohol from State gasoline taxes of 6½ cents per gallon; as Table 1 shows, together with the Federal exemption, the State exemption gives a total subsidy exceeding $1.00 per gallon of alcohol, or over $42.00 per barrel (e.g., the difference between $63.00 and $17.50 is $45.50 per barrel of ethanol). Sales of gasohol in Iowa have increased rapidly from 600 thousand gallons in November 1978 to 4 million gallons in January 1979 to 5.6 million gallons in March 1979. March gasohol sales represented approximately 2.5 percent of all gasoline sold in Iowa that month, demonstrating that alcohol fuels can contribute on a regional level.

The large increase in demand for gasohol is based on consumer preference for vehicle fuel derived from renewable sources, a selling price competitive with premium unleaded gasolines (as Table 3 illustrates), and consumer perception of the fuel as a high quality motor fuel. Gasohol is an attractive fuel to many motorists who feel they need higher octane unleaded fuel. Whatever the motivation, it is clear that a broad-based grass roots movement to develop and support alternative domestic supplies of liquid fuel has been at the heart of gasohol's initial success.

TABLE 3.—Examples of Comparative Prices [1] for Gasoline and Gasohol

Fuel	Price (cents per gallon)	
	Iowa	Virginia
Unleaded regular	84.9	77.9–84.9
Gasohol (including 4 cents exemption)	86.9	82.9 [2]
Unleaded premium	88.9–89.9	85.9–90.9

[1] As of May 3, 1979, at stations sampled.

[2] Includes 1.7 cents per gallon for shipping alcohol from Illinois.

Recognizing the growth in alcohol fuels use, two major U.S. auto manufacturers have broadened their warranty policies to permit the use of gasohol in cars and trucks, to encourage development and use of alternative fuels. Three major automotive firms have active alternative fuels research programs; at least one is working on engines to use straight alcohol fuels as well as blends such as gasohol.

NET ENERGY BALANCE

One question often raised about ethanol production is whether it yields a net energy gain. This is an important question, for it would be unwise national policy to encourage development of a fuel whose manufacture consumed more useful energy than it delivered.

The question arises because some older distilleries (designed for beverage rather than fuel alcohol) use more Btu's of oil and gas to make alcohol than there are Btu's in the alcohol product. Including the oil and gas used to grow and transport the raw material worsens this balance. If all ethanol producers were to use so much oil, the Nation might end up importing more oil than it would save.

Ethanol, however, can be produced to yield a net gain in liquid fuel (as Tables 6 and 7 illustrate). New ethanol conversion facilities can have much greater energy efficiency than existing facilities, which were built when energy costs were much lower than they are now. Indeed, a modern facility could have a clearly positive (though small) net energy balance even if all the fuel used were oil and gas, taking credit for the "free" solar energy stored in the raw materials.

Second, ethanol conversion facilities can readily be designed to use fuel sources other than oil or gas. Then they can be viewed as means of converting less scarce energy forms (such as coal, wood, agricultural residues, solar energy, or waste heat) into high-quality transportation fuel. In this view, ethanol production could be seen as similar to electric generation, in which 9,000 to 10,500 Btu's of coal are converted into 3,413 Btu's equivalent of electricity.

Clearly both approaches must be followed so that ethanol fuels can be produced to yield a significant net gain in fuel. Increasing the net oil displacement value of alcohol depends on reducing the petroleum and natural gas used in growing and converting materials. As described below, national benefit also depends on technical details of ultimate use, including automobile mileage using gasohol and the value of incremental octane additions.

To minimize petroleum use, alcohol production facilities (which require only relatively low temperature heat) should be designed or redesigned to run on coal, on agricultural or wood wastes, on solar heat where economic, or on waste heat from industry or utilities where it is available.

The energy required to grow and transport crops may amount to a significant fraction of the resulting alcohol energy value. Therefore, the materials used to produce alcohol should in general be wastes, by-products, or spoiled products, since additional energy is not required to produce them. Where virgin materials are used, alcohol should be one of many co-products, to minimize the energy cost of the alcohol.

When alcohol fuel production uses minimal oil or natural gas, net energy balance need not be a concern.

Net Energy Analysis of Alcohol Fuels

American Petroleum Institute
2101 L Street, Northwest
Washington, D.C. 20037

PUBLICATION NO. 4312

API's Alcohol Fuels Task Force selected Battelle Columbus Laboratories to produce the study in part on the basis of reputation for expertise in agronomy, fermentation, and wood gasification technology and in part on the basis of proposals submitted by Battelle and other candidate contractors. Although the task force met with the authors of this study on two occasions to discuss scope and clarity of presentation, the work remains entirely their own and does not necessarily reflect the views of individual task force members or the API.

SUMMARY

Battelle Columbus was commissioned by the American Petroleum Institute to make an independent and objective analysis of the net energy required to make alcohol fuels. This report presents the findings of the analysis.

Five alcohol technologies are considered in this analysis. These are the manufacture of:

- Ethanol from sugar cane,
- Ethanol from corn,
- Ethanol from corn stover,
- Methanol from wood (Purox technology), and
- Methanol from wood (Battelle technology).

The energy balances for the first two processes are based on commercially proven technologies, whereas the latter three are based in part on conceptual designs of developing technologies. Two energy balances were made for the ethanol from corn case, one using the traditional plant design and the other using modern energy conserving technology.

Each of the feedstocks is grown in the United States. Although the potential for growing additional sugar cane is limited, sweet sorghum, which is very similar to sugar cane, can be grown throughout the U.S. grain belt. Corn is widely grown, is the most economic grain in the United States, and is similar to other widely grown grains in the energy required to grow[*] and convert it to alcohol. Corn stover (the residue usually left in the field) is representative of agricultural residues.

The energy analysis considered the total system energy inputs. These included fuel to grow feedstock, fuel to make fertilizer to grow feedstock, and fuel to run the alcohol process. Byproduct fuel was credited at its energy content. Non-fuel byproducts like distillers grains were credited as fuel required to produce alternative products. (The fuel to grow an amount of soybeans with the same protein value was used as credit for distillers grains).

The analysis indicated that ethanol from sugar cane and methanol from wood are net energy producers while ethanol from corn or corn stover are net consumers of energy. The results of our analysis are summarized below and are displayed graphically in Figures 1 and 2.

	Net energy consumed Btu/Btu liquid and gaseous fuel produced
Ethanol from sugar cane	0.33
Ethanol from corn:	
Traditional technology	2.20
Energy conserving technology	1.20
Ethanol from corn stover	1.53
Methanol from wood (Purox)	0.46
Methanol from wood (Battelle)	0.45

A value less than one represents net energy production while a value greater than one indicates net consumption. The net energy for ethanol from corn made in a plant with the energy conserving technology is much lower than that obtained with traditional technology. Traditional corn-based alcohol plants consume about 2.2 Btu/Btu ethanol produced.

Figures 1 and 2 show only net fuel consumed to make liquid fuels. The fuel provided by process residues (bagasse, corn stover, and wood char), is not included. These fuels are both produced and consumed within the process. The manufacture of ethanol from sugar cane actually requires more fuel than does ethanol from corn, but the fuel is supplied by burning the bagasse residue. Similarly, wood residues provide the process heat in the methanol processes.

There are significant quantities of fuel gas coproduced in both methanol processes, and this gas has been counted with the liquid product. There is so much gas coproduced in these processes that considering it as a byproduct seriously distorts the results. Such gas may be considered a substitute for petroleum and liquefied natural gas imports. It would be possible to convert this gas to methanol with the expenditure of additional energy.

The net energy consumption estimates are affected somewhat by the underlying assumptions, but these do not affect the conclusion: Sugar cane and wood based alcohol processes are net energy producers, while corn and corn stover processes are net consumers of energy. The sensitivity to these assumptions is discussed in the report.

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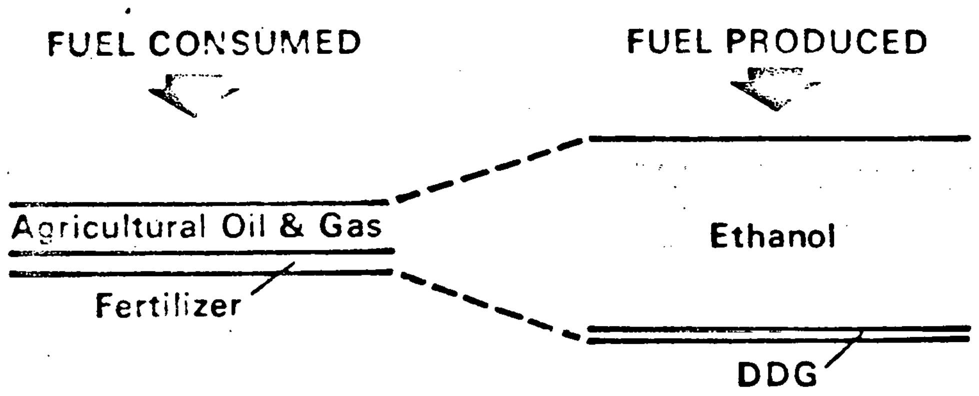
[*] Except grain sorghum, which requires about 1.5 times as much energy to grow as corn.



ETHANOL FROM SUGAR CANE

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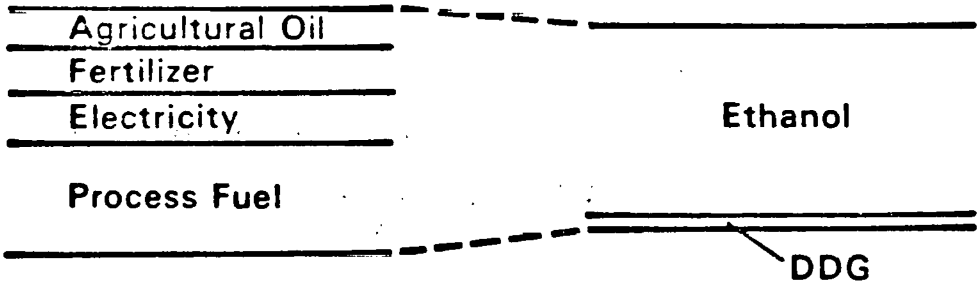

ETHANOL FROM CORN

(ENERGY CONSERVING TECHNOLOGY)

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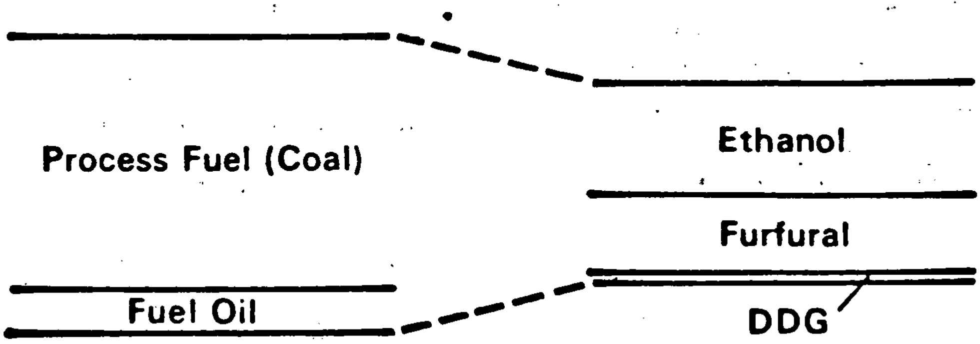
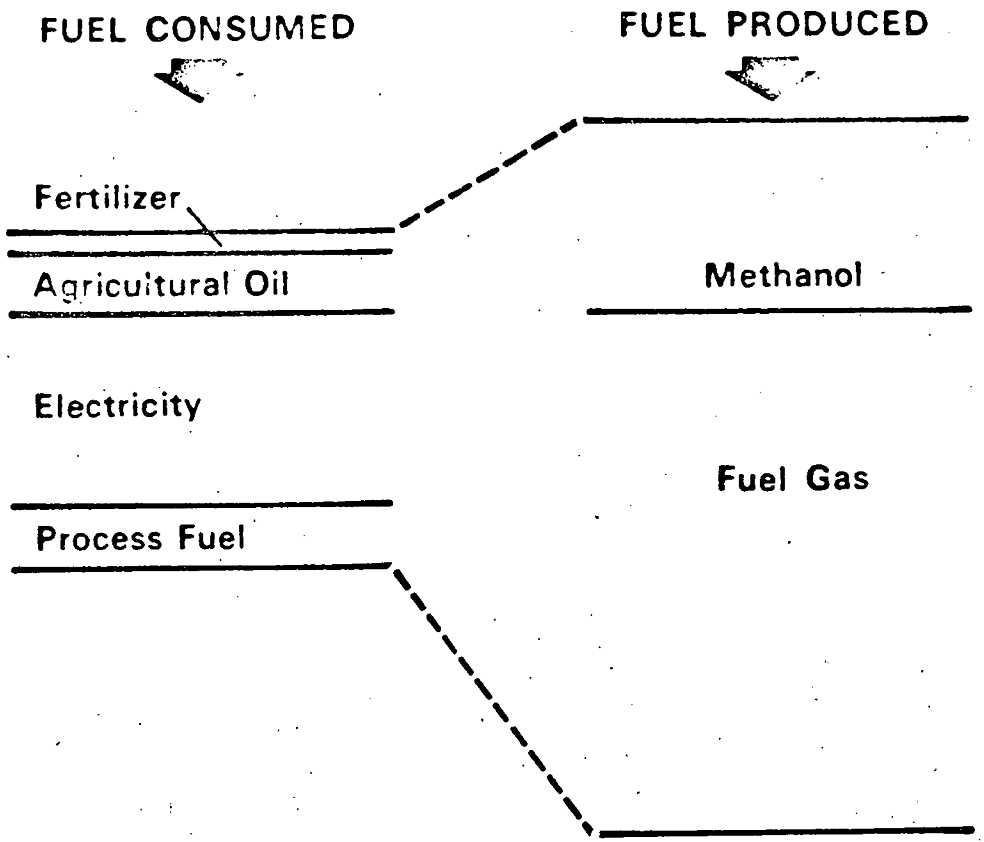


ETHANOL FROM CORN STOVER

FIGURE 1. NET ENERGY BALANCE FOR ETHANOL MANUFACTURE



PUROX PROCESS

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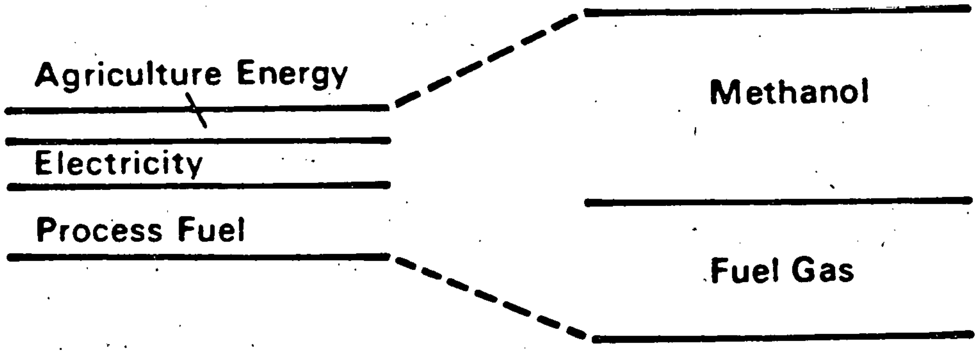

BATTELLE PROCESS

FIGURE 2. NET ENERGY BALANCE FOR METHANOL MANUFACTURE

The use of agricultural residues instead of coal as plant fuel would reduce the net fossil fuel energy consumption to 0.58 Btu/Btu liquid fuel in the ethanol-to-corn case and to 0.22 Btu/Btu in the case of corn stover. Unfortunately, there are several problems with using agricultural residues like corn stover as either a fuel or as feedstock. The major problems relate to the difficulty in collecting and storing sufficient residue at the alcohol plant. Agricultural residues occupy about ten times the volume of oil with equivalent heating value. Furthermore, they are available only during a few months each year. Therefore, nearly a full year's inventory must be stored. For purposes of analysis of the corn stover-to-ethanol plant, we have assumed that these problems could be overcome, but we remain convinced that agricultural residues are not practical fuels for most industrial plants. If they were, they would be used at many industrial sites, not just at alcohol plants.

INTRODUCTION

Obtaining an adequate supply of energy is one of the most important issues facing the nation today. Of particular concern is the rising cost of petroleum imports and the high dependence of the United States upon imported oil to balance its energy budget. One of the methods proposed to alleviate this problem is the manufacture of liquid fuels from domestically grown biomass, i.e. plant material.

There has been considerable debate in both the popular and technical press regarding the merits of manufacturing liquid fuels from biomass. Much of this controversy has centered on the manufacture of ethanol (or ethyl alcohol) from grain. It is hoped that the results of this study will help resolve some of the controversy surrounding the question of the feasibility of manufacturing liquid fuels from biomass.

The objective of this study is to determine the net fuel consumption for the production of liquid fuels from biomass. Consideration of the relative combustion efficiencies of gasoline vs. alcohols, beyond the scope of this report, has been addressed elsewhere.*

Five different technologies were considered in this study. Three of these technologies manufacture ethanol, while two have methanol (and fuel gas) as their primary product. The three ethanol processes considered consume sugar cane, corn, and corn stover as raw materials.

The manufacture of ethanol from corn was selected for study because this process is frequently proposed and because its merits are most frequently debated in the press. The technology is well established and is commercially practiced. The manufacture of ethanol from corn is similar to its manufacture from other grains (i.e., wheat, barley, and milo). Corn is the least expensive of the grains suitable for ethanol manufacture in the United States.

Sugar cane was selected as an ethanol feedstock because (1) a commercially established technology for its conversion to ethanol exists and (2) it can be grown in the United States. The process energy balance differs significantly from the grain-based process. Although sugar cane can be grown in only a limited part of the United States, the technology and energy balance for making ethanol from sweet sorghum would be similar. Sweet sorghum could be grown in much of the U.S. agricultural area.

Corn stover is the residue consisting of leaves, husks, stalks, and cobs which are left behind in conventional corn harvesting. At present, there is no commercially practiced manufacture of ethanol from corn stover. Rather, this technology is still being developed under sponsorship of the U.S. Department of Energy. The research is still in the early stages, and the energy analysis was made on a conceptual design based on research findings to date. On the other hand, energy analyses from corn and sugar cane are based on proven technology.

Manioc or cassava, which is used in Brazil for manufacture of ethanol, is not grown in the United States and was not considered in this study.

Two process schemes were investigated for the manufacture of methanol from wood. One scheme uses the Purox gasification system developed by Union Carbide to convert the wood to a synthesis gas. This is followed by a conventional gas clean-up (Benfield hot carbonate system), water gas shift reaction, and finally by the ICI low-pressure methanol process. The second process scheme substitutes a Battelle fluidized-bed gasification process for Purox. The Purox process has been demonstrated on a pilot scale in the gasification of municipal solid waste. A plant to manufacture methanol was designed by Seattle, Washington, but was never built. Municipal waste is chemically similar to wood. The Battelle process has been demonstrated on a bench scale for the gasification of wood. Benfield, shift, and the ICI methanol process are commercially practiced in numerous locations.

Purox was selected as the most advanced wood gasification technology, while the Battelle process was selected as representative of the several improved technologies under development.

DEFINITIONS

In this report, net energy consumption ratio is defined as:

$$\frac{\text{total energy consumed} - \text{byproduct energy}}{\text{energy in saleable liquid fuel.}}$$

A ratio of greater than one means the overall system consumes more energy than it produces, while a ratio of less than one indicates the system is a net energy producer.

The total energy consumed includes fuel used directly to grow feedstock, fuel consumed in the manufacture of fertilizer for growing feedstock, and fuel consumed in the manufacturing process.

The reader may note that our approach includes the energy inputs to the total system. This differs from the approach used in many other studies. Other authors have used the heat of combustion of the feedstock (e.g., corn), whereas we use the fuel consumed to grow the feedstock. Similarly,

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* American Petroleum Institute, *Alcohols—A Technical Assessment of Their Application As Fuels*, API Publication 4261 (July, 1976).

others have used the heat of combustion of all byproducts, while we have considered the use of the byproduct.

In the case of byproducts used as fuels—for example, bagasse in the sugar cane process or fuel gas from methanol processes—the heat of combustion was used as the appropriate measure. For byproducts not used as fuel, however, the heat of combustion is not an appropriate measure of the energy credit. The credit taken for dried distillers grains (DDG), which are used for their protein value in animal feed, was taken as the energy required to grow soybeans of equivalent protein value.

The lower heating value (LHV) was used for the heat of combustion throughout this study, unless otherwise stated. The lower heating value is defined as the heat of combustion where the water produced in combustion is a vapor, which is the case in most combustion situations. The higher heating value (HHV), which is used in some analyses, is calculated with water from combustion of fuel in the liquid state. The use of lower heating values facilitates comparison of alternative fuels, particularly when the hydrogen-to-carbon ratios of the fuels vary.

BASIC ENERGY BALANCE

Ethanol

The basic energy balance for the manufacture of ethanol by four processes is shown in Table 1. The manufacture of ethanol from sugar cane consumes only 0.33 Btu/Btu liquid fuel made. That is, ethanol from sugar cane is a net producer of fuel. On the other hand, the manufacture of ethanol from corn or from corn stover requires more energy than can be produced. Ethanol from corn made by traditional technology consumes 2.2 Btu/Btu liquid fuel and from corn stover 1.5 Btu/Btu liquid fuel. Using modern energy-conserving technology, fuel grade ethanol could be made from corn with the consumption of about 1.2 Btu/Btu. To our knowledge, no ethanol plant has yet been built incorporating all of these energy conserving features. Nevertheless, the technology is proven in other applications.

The major reason that the ethanol from sugar cane is a net producer, whereas ethanol from corn is a net consumer of energy, is that sugar cane contains both sugar, which can be converted into alcohol, and a cellulosic residue called "bagasse." This bagasse is harvested, collected, and transported to the plant with the cane juice as part of the sugar cane and can be used to provide all of the processing energy. With corn, on the other hand, only the grain is typically harvested and shipped to the alcohol plant. The conversion of grain to alcohol requires the consumption of about 0.86 Btu coal/Btu ethanol manufactured, using energy-conserving technology.

It should also be noted that more energy is required to grow and harvest corn than is required for sugar cane. Most of the energy required to grow corn is consumed in fertilizer manufacture. Most of the energy required to grow and harvest sugar cane is for the planting and harvesting. For both crops, the fuel required to grow and harvest is predominantly petroleum, plus some liquefied petroleum gas or natural gas.

The amount of processing fuel required to manufacture ethanol from corn is lower than that required for sugar cane. This is due primarily to the lower efficiency of the bagasse-burning boilers used in the sugar cane plant. The major cause of this lower efficiency is the high moisture content of bagasse.

There is little incentive to improve the energy efficiency of ethanol from sugar cane plants because the fuel (bagasse) must be burned. In theory, less energy could be used in the sugar cane process and the excess converted to electricity for sale. There are several institutional and economic barriers to such energy export.

Unlike the manufacture of ethanol from either corn or sugar cane, the manufacture of ethanol from corn stover is a speculative process. Whereas the others are practiced commercially, the manufacture of ethanol from agriculture residues like corn stover is currently in the research and development stages. The U.S. Department of Energy has a sizable program underway to develop this technology. In the version of the process chosen for this analysis, two liquid fuel products, ethanol and furfural, are made. Furfural might be used either as a liquid fuel or as a chemical.

The net energy consumed in the manufacture of ethanol from corn stover is about 1.9 Btu/Btu ethanol or about 1.5 Btu/Btu liquid fuels, assuming both ethanol and furfural are used for fuels. Of the 1.5 Btu/Btu, 0.4 Btu must be supplied as petroleum or natural gas for drying. A rotary dryer which requires a clean-burning fuel is used.

If furfural were sold as a chemical, the credit would approximate the energy used in the furfural plant. The net energy consumed would then be about 1.1 Btu/Btu ethanol instead of the 1.5 Btu/Btu liquid fuel reported in Table 1. The market for furfural is extremely small, however, compared to the volumes that would be coproduced with enough ethanol to provide even one percent of the U.S. gasoline needs. The use of furfural as a chemical therefore, should not be considered as a byproduct of ethanol fuel manufacture.

Furfural itself is a rather unstable chemical; it tends to polymerize. It would have to be converted to a more stable material before it could be incorporated in liquid fuels. This

TABLE 1.—NET ENERGY ANALYSIS OF ETHANOL MANUFACTURE, Btu/Btu Ethanol(a)

	Sugar Cane	Corn Energy Conserving	Corn Traditional	Corn Stover
Grow and Harvest				
Petroleum & LPG	0.258	0.189	0.189	0.001(d)
Petroleum & Gas for Fertilizer & Pesticides	0.094	0.255	0.255	
Coal	0.020	0.008	0.008	
Process Energy				
Coal for Electricity		0.24	0.26	0.057
Coal for Process(c)		0.62	1.61	2.244
Bagasse	2.27			
Stover Residue				1.22
Fuel Oil				0.40
Total Energy Consumed	2.642	1.312	2.322	3.922
Byproduct Credit				
Furfural				(0.71)
Fusel Oil		(0.01)	(0.01)	(0.01)
Bagasse or Stover	(2.27)			(1.22)
Process Fuel		(0.03)	(0.03)	(0.03)
Dried Distillers Grains	(0.042)	(0.075)	(0.075)	(0.042)
Total Credits	(2.312)	(0.115)	(0.115)	(2.012)
Net Energy Consumed Btu/Btu EtOH	0.33	1.20	2.21	1.91
Net Energy Consumed Btu/Btu Liquid Fuel(b)	0.33	1.20	2.20	1.53

(a) Energies in this table are lower heating values.

(b) Liquid fuel includes ethanol, fusel oil, and furfural. For corn stover the calculation is

$$\frac{3.92 - 1.22 - 0.03 - 0.04}{1.0 + 0.71 + 0.01} = 1.53$$

(c) It is assumed that process energy would be supplied by coal in an ethanol plant intended for liquid fuel, even though most existing distilleries use natural gas or petroleum fuels.

(d) Collection and transportation energy. This energy, including fertilizer used to grow the corn, is charged entirely to the grain.

could be accomplished by mild hydrogenation reaction. The energy for this reaction was not included in the energy analysis.

The energy to grow and harvest corn stover is very low because it was assumed that stover is a byproduct of growing corn. All energy to plant, plow, fertilize, and harvest corn is attributed to the corn grain. Only the energy for harvesting and transportation of stover is attributed to stover.

The credit taken for the dried distillers grains (DDG) from all three processes was based upon the energy required to grow soybeans of equivalent protein content. Typically, the dried distillers grains would be used to supplement animal feed and would displace other forms of protein like soybean meal or alfalfa meal. The corn distillers grains contain more protein than those from either sugar or stover and would be a better quality feed ingredient. The use of distillers residues from the fermentation of sugar cane juice might be limited because of the high content of various salts. The distillers residues from the stover process were assumed to be similar to those from the sugar cane process.

It is sometimes argued that only liquid fuels should be considered in the net energy balance because the objective of biomass energy programs is to reduce U.S. dependence on imported petroleum. To minimize use of petroleum and natural gas, we have assumed that all process fuel purchased by the ethanol plant would be coal. Current ethanol plants use either natural gas or petroleum, but it is likely that future plants would use coal. If one also assumes that all electricity used in ethanol production is generated in coal-fired plants, and further assumes that the natural gas used for fertilizer manufacture is a petroleum substitute (and therefore treated like a liquid fuel), one finds that the net liquid fuel consumption[*] can be much smaller than net energy consumption.

	Petroleum Fuel Consumed, Btu/Btu of Liquid Fuel Produced	Net Energy Consumed, Btu/Btu of Liquid Fuel Produced
Sugar Cane	0.31	0.33
Corn—		
traditional technology	0.37	2.20
energy-conserving technology	0.37	1.20
Stover	0.21	1.53

The reader should remember, however, that the last two processes convert large quantities of solid fuel (coal) to liquids. In this regard, they should be compared to coal liquefaction. Typical coal liquefaction processes are reported to have overall energy efficiencies of about 63 to 70 percent.[**] This does not include the energy to mine and transport coal. At 65 percent efficiency, coal liquefaction would have a net energy consumption of about 1.5 Btu/Btu, which is the same range as ethanol from corn stover.

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[*] Net liquid fuel is (agricultural energy − liquid fuel credits)/saleable liquid fuels. For corn this is (0.189 + 0.255 − 0.075)/(1. + 0.01) = 0.37 Btu/Btu. This is the same for both traditional and energy-conserving technologies.

[**] Kleinpeter, J. A., "The Outlook for Clean Liquid Fuels from Coal," presented at American Chemical Society, Miami Beach (September 13, 1978).

Methanol From Wood

The basic energy balance for the manufacture of methanol from wood is summarized in Table 2. Two processes were analyzed, one incorporating the Union Carbide Purox Process and the other a process currently being developed by Battelle. Both the Purox and Battelle processes result in a net energy production.

Purox was selected because it is one of the most advanced processes for gasifying cellulosic materials. The Battelle process was selected as typical of advanced processes which obtain better yields of liquids and manufacture less fuel gas.

The Purox gasification process is in a fairly advanced state of development, although no commercial wood gasification systems using Purox have been built. The Battelle gasification process, on the other hand, is in the early stages of process development. These processes are described in Appendix A. Following gasification, both processes use a hot carbonate gas cleaning process and a low pressure methanol synthesis. Gas-cleaning and methanol synthesis are both commercially practiced technologies. Both the Purox and Battelle processes make large quantities of fuel gas in addition to methanol. The gas from Purox is pipeline-quality, high-Btu gas (1200 Btu/cu ft HHV),* while the gas from the Battelle process is a good medium-Btu gas (615 Btu/cu ft HHV).

The large quantities of coproduct gas distort the energy consumption if the gas is considered to be a byproduct.** Also, the gas can be considered a substitute for liquid petroleum fuels in many applications. Therefore, both liquid methanol and fuel gas have been considered to be energy products. On this basis, the net energy consumed is about 0.45 Btu/Btu product energy for both processes.

If one considers only liquid and gaseous fuel consumption rather than total energy, the wood-to-methanol processes consume about 0.1 Btu liquid fuel per Btu liquid and gaseous fuel produced.

TABLE 2.—NET ENERGY ANALYSIS OF METHANOL FROM WOOD, Btu/Btu Methanol[a]

	Purox	*Battelle*
Grow and Harvest		
Petroleum	0.319	0.133
Fertilizer	0.106	0.044
Process Energy		
Coal for electricity	1.012	0.377
Coal, direct for process	0.315	0.220
Total energy consumed	1.752	0.774
Product Credits		
Methanol	(1.0)	(1.0)
Fuel gas	(2.772)	(0.707)
Total Credits	(3.772)	(1.707)
Total	(2.020)	(0.933)
Net Energy Consumed, Btu/Btu MeOH	(1.020)	0.067
Net Energy Consumed, Btu/Btu MeOH + gas[b]	0.46	0.45

(a) Energies in this table are lower heating values.

(b) Net energy consumed per saleable energy

Purox process	1.752/3.772 = 0.46
Battelle process	0.774/1.707 = 0.45

It would be possible to place a reformer in the process to convert some of these hydrocarbon byproduct gases to synthesis gases suitable for the manufacture of methanol. Local market conditions, especially the relative value of gas and methanol fuels, would determine whether the gas would be converted to methanol in an actual plant. Such reforming would increase the methanol yield, but would also increase energy consumption.

Wood is not only a feedstock for these processes, but also a fuel. Much of the energy consumed in these processes is supplied by wood. The energy needed to grow and harvest wood is less than one-tenth the heating value of the wood. Consequently, the processes are net energy producers.

IMPACT OF MAJOR ASSUMPTIONS

Agriculture and Silviculture

The energy required to grow various crops is affected significantly by geography. Some of these geographic variations and their impact on the net energy analysis are discussed below. The agriculture energy consumption is based on actual U.S. Department of Agriculture data, while the silviculture numbers are estimates.

Sugar Crops. The energy required to grow and harvest sugar cane of 0.372 Btu/Btu ethanol is representative of the average energy required in Florida. Both the energy consumed per ton of cane and the yield of sugar cane in Florida lie between figures for Texas and Louisiana. In Texas, the energy required to produce sugar cane would be about 80 percent of that required in Florida, while energy requirements in Louisiana are about 140 percent. Hawaii, which is the fourth major cane-growing state, has greatly different agricultural practices but still has a total energy requirement per ton of cane similar to that of Florida. Thus, one might expect the energy inputs from agriculture to grow sugar

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* In the case of Purox, the energy value of the gas exceeds the energy to grow the wood and to operate the process.

** We are somewhat skeptical about the high content of C_2 + hydrocarbons claimed by Union Carbide for the Purox synthetic gas. These hydrocarbons result in the large quantities of high-Btu gas byproduct.

cane to range from about 0.3 Btu/Btu ethanol to 0.5 Btu/Btu.

Sugar beets can be grown in Northern climates which are not suitable for sugar cane. In general, sugar beets require more energy than sugar cane. In Minnesota, sugar beets would typically require about 1.85 times as much energy per ton as sugar cane grown in Florida.

Another possible sugar crop that could be grown in the Midwest corn belt as well as on the Gulf Coast is sweet sorghum. Except for their seed heads, the tall, slender stalks of sweet sorghum resemble sugar cane in physical appearance and sugar content. Sweet sorghum's adaptability to various soils and climatic conditions suggests that it could be cultivated extensively as an energy crop or a sugar crop.[*] Currently, probably less than 5,000 acres of sweet sorghum is grown commercially in the United States. Therefore, there are no published data on the energy required to grow the crop. However, we estimate that the energy to grow and harvest sweet sorghum (per dry ton) is about 65–75 percent of that required for sugar cane. The ethanol yield would be similar to that from sugar cane.

The energy required to grow sugar cane, sugar beets, and most agricultural products is primarily petroleum fuels for tractors and trucks, and petroleum or natural gas for the manufacture of fertilizer.

Corn. The energy required to grow and harvest corn used in the net energy analysis was 0.452 Btu/Btu ethanol. This estimate, which includes 0.19 Btu/Btu for direct farming operations and 0.26 Btu/Btu for the petroleum and natural gas required to manufacture fertilizer, is typical of energy consumption in Illinois. Illinois was selected because it is one of the largest corn-producing states and because the energy required per bushel of corn was near the national average. The energy required to grow corn in 1974 in Illinois was 95,000 Btu/bu (higher heating value) compared to the national average of 107,000 Btu/bu.[†] In Iowa, another major corn-producing state, slightly less fertilizer is used and the typical energy requirement is about 90 percent of that in Illinois. Nebraska has one of the higher energy requirements to grow corn, primarily because much of the Nebraska corn land requires irrigation. It requires about 1.78 times as much energy to grow corn in Nebraska as in Illinois. Thus, on the average, the energy required to grow and harvest the feedstock for corn-derived ethanol in Nebraska would be about 0.8 Btu/Btu ethanol compared to 0.45 Btu/Btu in Illinois. Dr. Scheller of the University of Nebraska has estimated agricultural energy at 46,000 HHV Btu/gal ethanol or 0.57 Btu/Btu ethanol.[**] Perhaps his estimate is based on non-irrigated farms in eastern Nebraska rather than the Nebraska average.

Other Grains. The energy (U.S. average) required to grow winter wheat is about the same as that for corn. Grain sorghum requires about 50 percent more energy per bushel than corn. The yield of alcohol from all three grains is the same.

Corn Stover. In estimating the energy required to grow and harvest corn stover, only the collection and transportation operations were considered. The energy associated with tilling, fertilizing, and harvesting the corn grain was all attributed to the grain. Therefore, very little energy is attributed to the harvesting and growing of corn stover. The actual energy required can vary by a factor of 2 or 3, depending on the extent of drying which occurs in the field. The estimated energy to harvest corn stover of 0.001 Btu/Btu ethanol is intermediate between collecting wet stover (57 percent moisture) and drying at the processing plant and field-drying to 20 percent moisture.

Dried Distillers Grains. The energy associated with dried distillers grains, which are a byproduct from the manufacture of ethanol, was estimated as the energy to grow soybeans of equivalent protein content. Illinois was selected in part because it is a significant soybean producer and in part because it was the state selected for corn production. The lower heating value energy requirement for soybeans grown in Illinois is 85,700 Btu/bu.

Actually, soybean meal, not soybeans, is used in animal feed in direct competition with distillers dried grains. Therefore, implicit in our analysis are the following assumptions: (1) the energy to grow soybeans is distributed between soybean meal and oil in proportion to the weight yield, (2) all energy for oil expression from the bean is charged to the oil, (3) soybean meal is directly substitutable for dried distillers grains on a protein equivalent basis. The above assumptions are generally true, except that the high salt content of distillers residues from sugar fermentation limit their application in animal feed to rather low concentrations. There is technology available to recover these salts with negligible energy expenditure.

Wood. For the net energy analysis, it was assumed that wood would be grown on silviculture farms in Wisconsin. The energy required to grow the wood would be about 1.5 million Btu per dry ton. If the silviculture farm were in Louisiana, the energy requirement would be about 1 million Btu per dry ton. Wisconsin is typical of a fairly low-yield area (5 tons/acre-year) compared to Louisiana, which is a high-yield area with about 12 tons/acre yield per year.

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[*] Smith, B. A., "Sweet Sorghum as a Source of Sugar," Agricultural Research Service; U.S. Department of Agriculture, Publication CA-H-6; June, 1974.

[†] 1974 was a dry year with low crop yields. In a good year, Illinois corn yields would average 105 to 115 bu/acre, which would require about 70,000 to 75,000 Btu/bu. Nevertheless, widespread use of alcohol fuels will necessitate use of marginal land, requiring more fertilizer and higher energy consumption per bushel. The 1974 data are considered realistic for net energy analysis.

[**] Scheller, W. A., Testimony presented at the U.S. DOE Hearing on Gasohol, Chicago, Illinois (April 6, 1978).

These differences are due to climate, soil fertility, selection of tree species, and other factors.

In determining the energy required for silviculture, very intensive farming was assumed. This includes fertilization and irrigation during the first three years of the crop. One could use less intensive silviculture techniques, but this would reduce the use of marginal land. In any case, the energy required to grow wood is small compared to the fuels that can be produced from the wood.

Additional data on energy for agriculture and silviculture are presented in Appendix B.

Process Energy Considerations

The process energy consumption for any process is dependent upon the specific design. This is illustrated by the large difference between the energy requirements of the traditional and energy-conserving designs for manufacturing ethanol from corn. In general, there are trade-offs between saving energy and capital. The energy efficiency of any plant design is also affected by considerations of safety, pollution abatement, and general plant operability.

Comparison With Other Studies. Most of the controversy surrounding the net energy analysis of manufacturing ethanol from biomass has centered on the manufacture of ethanol from corn. The results of some of the more often quoted studies are summarized in Table 3. It is interesting to note that the net energy consumption estimated by most authors is generally in the same range as our traditional technology case. This traditional energy requirement can be halved by design changes discussed below.

Most authors quote energy consumption on the basis of higher heating values. To adjust their results from a higher heating to a lower heating value basis, it was assumed that coal was used as a fuel and that the lower heating value was 0.968 times the higher heating value. The lower heating value of ethanol was taken as 75,670 Btu/gal.

Cray is the only author who has published actual plant operating data. His value of energy consumption is based on the operating experience of Midwest Solvents Corporation, which is considered one of the most efficient plants in the United States. This plant manufactures a 190-proof (95 percent) ethanol. We estimate that further concentration to anhydrous ethanol by traditional azeotropic distillation consumes about 0.19 Btu/Btu ethanol. On this basis, the Midwest Solvents energy consumption for anhydrous ethanol would be about 1.86 Btu/Btu ethanol, which is in excellent agreement with our estimate. Cray has estimated that it would take 139,600 HHV Btu/gal to make anhydrous ethanol. This would be equivalent to 1.78 Btu/Btu ethanol.

Energy Conservation. Modern technology can reduce energy consumption significantly. Many alcohol plants, which are typical of the traditional design, were built in an era of cheap energy. Our energy-conserving design uses technologies which have been demonstrated on a commercial scale. These technologies include cogeneration (using steam for both motive power and process heat), vapor recompression evaporators, and extensive heat recovery. However, we are not aware of any ethanol plant that currently utilizes all of the energy-minimizing technology incorporated in our design.

We estimate that process energy requirements can be reduced to 0.86 Btu/Btu ethanol. Moon *et al.* have recently published a design that is expected to achieve 0.7 Btu/Btu. If this energy consumption could be achieved in commercial operation, the net energy for the entire system (agriculture plus process) would be near break-even. About one Btu would be required to make one Btu liquid fuel.

The major difference between our design and Moon's is in the energy required for corn handling and milling, for general services, and for drying distillers grains. The last of these is most significant and is discussed below under the section titled "Distillers Dry Grains."

Although there are some energy savings achievable in each part of the ethanol process, the greatest savings can be achieved in the distillation of ethanol and recovery of byproduct distillers grains. These operations are discussed below.

Distillation. Of the various parts of the alcohol processes, the separation and recovery of the alcohol offers the greatest opportunity to attempt energy savings. R. Katzen Associates, Vulcan Cincinnati, Stone and Webster, and Dr. Scheller of the University of Nebraska claim to have designs which will significantly reduce the energy required to recover ethanol in grain fermentation processes. Stone and Webster and Dr. Scheller declined to discuss their improved distillation schemes. Presumably, Dr. Scheller's improvement is reflected in the reduction in energy consumption between the earlier estimates of Scheller and Mohr and his most recent estimate shown in Table 3. The Katzen and Vulcan Cincinnati improvements include the cascading of distillation towers so that the condenser from one tower becomes the reboiler for another. This requires balancing distillation temperatures by adjusting pressure. The energy savings that can be realized by this technique are similar to those obtained with multiple-effect evaporation.

The total steam requirement for recovery of the anhydrous ethanol from fermentation beer is estimated at 21.5 pounds steam per gallon ethanol. Assuming an 83 percent boiler efficiency, the separation of ethanol would then require only 0.32 Btu/Btu ethanol, rather than the 0.68 Btu/Btu estimate from the corn to ethanol case. Somewhat lower steam consumption may be achieved if the alcohol concentration in the beer is fairly high. One synthetic ethanol plant is making anhydrous ethanol with the consumption of about 17 pounds per gallon. The steam consumption for distillation may be reduced by the availability of process heat from other plant sections. By way of comparison, Chenu reports that current Brazilian practice for distillation of alcohol

TABLE 3.—COMPARISON OF PROCESS ENERGY TO MAKE ETHANOL FROM CORN[a]

Author	HHV Energy Reported Btu/gal	LHV Energy Btu/Btu Ethanol	Ethanol Type
This study, traditional technology		1.87	anhydrous
Scheller (1978)	157,000	2.01	anhydrous
Scheller & Mohr (1976)	171,000	2.19	anhydrous
Reilly (1978)	130,400–151,500	1.67–1.93	anhydrous
Cray (1977)	131,200	1.67	190-Proof
	139,000	1.78	anhydrous
This study, energy conservation technology		0.86	anhydrous
Moon (1979)	54,870	0.70	anhydrous

[a] Includes energy to make alcohol and to dry distillers grains.

made from sugar cane consumes about 37.5 pounds steam per gallon.

The distillation design used in estimating energy for the sugar cane-to-ethanol case was more energy efficient than that for the traditional corn case, but less efficient than the energy-conserving corn and corn stover designs. Due to the lower efficiency of bagasse-fired boilers, the amount of fuel required was about the same as the traditional corn design.* The design used for the sugar cane process was essentially that of the Katzen patents. It is difficult to make direct comparisons because the energy required for distillation is affected somewhat by the evaporation and other energy requirements in other parts of the process. Using this more efficient technology, and assuming an 83 percent boiler efficiency burning coal, the energy required for the manufacture of ethanol from corn or corn stover could be reduced by up to 0.18 Btu/Btu. There is no incentive to achieve this saving, however, because the fuel for the sugar cane plant is bagasse which must be burned. In theory, less energy could be used to make ethanol from sugar cane, but there are several economic and institutional barriers to power export at most locations.

Distillers Dry Grains. The recovery of distillers dry grains (DDG) from the stillage is an integral part of the manufacture of the ethanol by fermentation. Furthermore, it is a very energy intensive step. We estimate that in the traditional manufacture of ethanol from corn, recovery of this byproduct consumes 0.48 Btu/Btu ethanol, which can be reduced to 0.24 Btu/Btu with energy conserving technology.

The recovery of DDG includes centrifuging the stillage, evaporation of the centrifugate, and drying. In the traditional technology the evaporation is conducted in multiple-effect evaporators. Energy requirements can be reduced by using vapor recompression evaporation. This requires mechanical energy rather than heat. The evaporated stillage is mixed with solids from the centrifuge, dried, and sold as animal feed.

The minimum energy design of Moon *et al.*, which we believe achieves the lowest published energy to make ethanol, uses flue gas from the coal-fired boiler to dry DDG. The impact on product quality and saleability of this design are unknown. The energy requirement is lower than that of our energy-conserving design, which uses a steam-heated dryer.

Some observers argue that the energy required to recover distillers dry grains should not be included in the net energy to manufacture ethanol. Our method of calculating the energy content of this distillers dry grain byproduct as the fuel required to grow soybeans of equivalent protein does indeed penalize the net energy of the process. Nevertheless, the recovery of this byproduct is essential for the economics of the ethanol manufacturing process. When the price of DDG is $100/ton, the byproduct credit amounts to about $1.00/bu corn or $0.38/gal ethanol. The recent price range was $113–$120/ton.*

Although one could not economically operate a fermentation ethanol plant without a credit for the protein in distillers grains, the stillage could be fed wet. This would require integration of a feed lot with the alcohol plant and might cause significant storage and scheduling problems (particularly if the markets for ethanol and beef were not in phase).

Without recovery of DDG, the disposal of the stillage would be a significant and potentially expensive pollution problem. If DDG were not recovered, plant effluent would be high in BOD (biological oxygen demand) and COD (chemical oxygen demand).

One technology which has been suggested is anaerobic digestion of the stillage. It is anticipated that such anaerobic digestion would make a medium Btu gaseous fuel at very low energy consumption. This technology has not been reduced to commercial practice and was not investigated in this study.

Cogeneration. The use of high-pressure steam in back-pressure turbines to provide shaft power for rotating equipment or electricity generators has been common practice in sugar cane plants. The low-pressure exhaust steam is used for process heat. This same principle can be applied in

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* The energy (fuel) calculated for distillation was 0.68 Btu coal/Btu ethanol in the traditional corn process compared to 0.65 Btu bagasse/Btu in the sugar cane process.

* Feed Market News, 61, p. 3, Agricultural Marketing Service, U.S. Department of Agriculture (August 30, 1978).

ethanol-from-grain plants, with a net energy saving of about 0.07 Btu/Btu ethanol.

Agricultural Residue as Process Fuel. One of the advantages of manufacturing ethanol from sugar cane is that bagasse can supply all of the fuel requirements to operate the plant. Proponents of the manufacture of alcohol from grain frequently suggest that agricultural residues like corn stover or straw be used to fuel alcohol from grain plants.

Since the fuel required to collect and transport agricultural residues to a nearby processing plant is small compared to the process energy, such use of agricultural residues would significantly reduce the net energy consumption for grain to ethanol. Substitution of agricultural residues for the process coal shown in Table 1 would reduce the net energy to 0.58 Btu/Btu liquid fuel in the corn-to-ethanol case and to 0.22 Btu/Btu in the corn stover case.

There are, however, several practical problems to the use of agricultural residues as plant fuel.* The first of these problems is the collection of enough residue to use as fuel. Estimates of the ratio of residues to grain can vary greatly. Some of the estimates of the percentage of corn grain and corn stover on a dry weight basis are summarized below:

	Corn	Stover
(1) Aldrich (1975)	45%	55%
(2) Vetter (1973)	53%	47%
(3) Inman & Alich (1976)	59%	41%

The ratio will depend upon the variety of corn, climatic conditions, etc. The first two authors reported data for their Iowa location, the last for Texas. If one assumes on average that the quantity of dry corn stover would equal the quantity of dry corn from a typical midwestern field, and if one further assumes that the stover is dried to 20-percent moisture before burning, one could obtain about 1.36 Btu/Btu ethanol by burning all the stover produced with the corn grain.

In actual practice, it is desirable to leave some residue on the field as a soil conditioner. It is generally assumed that between 25 and 50 percent of the residue must be left on the field. Since farmers tend to be conservative, they would probably tend to leave closer to 50 percent on the field, thereby reducing the fuel available from stover. On the other hand, much more corn would be grown for feed than for alcohol. Therefore, it should be possible to obtain additional stover from farmers selling their grain for use as feed.

A second problem with using agricultural residue as fuel is consistency. In estimating the energy which could be obtained by burning corn stover, we have assumed that stover was dried to 20 percent moisture in the field. Field drying depends upon the weather conditions near the harvesting season and is greatly dependent upon the time of year that the stover is recovered. If the stover had to be dried in the plant, or if it were burned wet, the available energy would be significantly reduced. These problems can, of course, be overcome. In a typical sugar plant, moist bagasse is burned successfully at about 50 percent moisture.

A third problem is the low bulk density of agricultural residues. We have estimated that the bulk density of corn stover is about 15.8 dry pounds/cu ft. Because of this low density, a Btu of corn stover occupies 10 times the space of a Btu of oil. In an ethanol-from-sugar cane plant, the cane is continuously processed as received, and there is very little storage of bagasse for fuel. The practice in an ethanol-from-grain plant, however, is to store the corn grain and process it throughout the year. Very large inventories of stover would be required to fuel a year round operation. The cost of this storage would probably be prohibitive. In addition, special measures would have to be taken to prevent degradation or spontaneous combustion during the storage. If a grain-to-alcohol plant were operated seasonally like typical sugar cane plants, the price of grain would have to be reduced to permit economic operation.

A final disadvantage of residues as fuel is the low efficiency with which they are burned. Whereas a typical coal-fired boiler can convert the energy in the fuel to steam with an efficiency of about 83 percent (based on higher heating value), a typical bagasse boiler operates at an efficiency of 63.5 percent. This reduced combustion efficiency aggravates the problems of storage and handling associated with low fuel density.

Other Considerations. As mentioned previously, the processes for the manufacture of fuels from corn stover and from wood are not commercially proven technologies. The manufacture of methanol from wood and ethanol from corn stover or other cellulosic biomass are in the developmental stages. One would expect that a detailed plant design prior to plant construction would uncover some opportunities to conserve energy by further utilizing process heat.

There is a new technology being developed (Tilby Process) to separate sugar from bagasse without the conventional crushing and maceration. This technology would be applicable to both sugar cane and sweet sorghum. The energy required to extract sugar from the cane would be reduced if the process were commercially adopted. But it would leave an excess of bagasse at the plant. At the present time, it is not certain whether such bagasse would be an exportable form of energy, a valuable byproduct, or a disposal problem.

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* These same problems apply to use of corn stover as a feedstock. For the purpose of analysis of the corn stover energy it was assumed that these problems could be solved.

BIBLIOGRAPHY

(1) American Petroleum Institute, "Alcohols—A Technical Assessment of Their Application As Fuels," API Publication 4261 (July, 1976).

(2) Scheller, W. A. and Mohr, B. J., "Net Energy Analysis of Ethanol Production," proceedings of the 171st National American Chemical Society meeting, Division of Fuels, *21* (2), held in New York (April, 1976), 29–35.

(3) Scheller, W. A., Testimony presented at the U.S. DOE hearing on Gasohol, Chicago, Illinois (April, 1978).

(4) Reilly, P. J., "Report on Corn as a Fuel Additive," presented at Iowa Farm Bureau Energy Conference, Des Moines, Iowa (October 20, 1977).

(5) Cray, C. L., Paper at Gasohol Seminar, Rio de Janeiro, Brazil (Sept. 26, 1977).

(6) Katzen, R. and Diebold, V. B., U.S. Patent 3,990,952, Alcohol Distillation Process (November 9, 1976).

(7) Katzen, R., Diebold, V. B. and Moon, Jr., G. D., U.S. Patent 3,445,345, Extractive Distillation of C_1 to C_3 Alcohols, assigned to Raphael Katzen Associates (May 20, 1969).

(8) Lipinsky, E. S., *et al.*, "Systems Study of Fuels From Sugarcane, Sweet Sorghum, Sugar Beets, and Corn," Vol. IV, Report to ERDA (March, 1977).

(9) Inman, R. E., *Silviculture Biomass Farms*, MITRE technical report 7347, Volumes I and IV, report to ERDA (May, 1977).

(10) Carpenter, L. F., "Nutrient Composition of Distillers Feeds," Proceedings Distillers Feed Research Council *25* (March 31, 1971).

(11) Energy and U.S. Agriculture: 1974 Data Base: Volume 2: Commodity Series of Energy Tables, U.S. Department of Agriculture and Federal Energy Administration; Washington, D.C. (April, 1977).

(12) Inman, R. E. and Alich, J. A., *An Evaluation of the Use of Agricultural Residues as an Energy Feedstock*, Volume I, Stanford Research Institute (July, 1976).

(13) Smith, B. A., "Sweet Sorghum as a Source of Sugar," Agricultural Research Service: U.S. Department of Agriculture, Publication CA–H–6, (June, 1974).

(14) Aldrich, S. R., *et al.*, *Modern Corn Production*, A & L Publications, Champaign, Illinois (1975).

(15) Vetter, R. L., "Evaluation of Chemical and Nutritional Quality of Crop Residues," Crop Residue Symposium sponsored by American Society of Agronomy, Lincoln, Nebraska (September, 1973).

(16) *Feed Industry Redbook*, Communications Marketing, Inc., Edina, Minnesota (1974).

(17) Feldman, H. F., "Conversion of Forest Residues to a Methane-Rich Gas," paper presented at Symposium on Energy From Biomass and Wastes, Washington, D.C. (August 14–18, 1978).

(18) Tsao, G., Purdue University, personal communication (June, 1978).

(19) Cysewski, G. R. and Wilke, C. R., "Fermentation Kinetics and Process Economics for the Production of Ethanol," Lawrence Berkeley report to ERDA (March, 1976).

(20) Chenu, P.M.A.M., "Alcohol Manufacture in a Sugar Factory," paper presented at International Society of Sugar Cane Technologists Congress, Sao Paulo, Brazil (1977).

(21) Schaeffer, F. C. and Associates, "Economic Study of Alcohol From Cane Juice," report to Battelle (April, 1978).

(22) Kleinpeter, J. F., "The Outlook for Clean Liquid Fuels From Coal in the United States," paper presented at American Chemical Society Meeting, Miami Beach (September 13, 1978).

(23) Lindsey, F., Corcoran, W. P., and Brackett, A. T., "Indiana Grain Fermentation Alcohol Plant," Indiana Department of Commerce (1976).

(24) Katzen, R., Raphael Katzen Associates, private communication (September, 1978).

(25) Tong, G., Stone & Webster Engineering Corporation, private communication (July, 1978).

(26) Jenkins, D. M., "Technical Economic Analysis of the Manufacture of Ethanol from Corn Stover," Battelle Columbus report to Department of Energy (November, 1977).

(27) Jenkins, D. M., Reddy, T. S. and Harrington, J. R., "Economics of Manufacturing Liquid Fuels from Corn Stover," Battelle Columbus report to Department of Energy (October, 1978).

(28) Paul, R. S., Union Carbide Corporation, private communication (July, 1978).

(29) Moon, G. G., Jr., *et al.*, "Grain Motor Fuel Alcohol Technical and Economic Assessment Study," Raphael Katzen Associates report to Department of Energy (December, 1978).

GLOSSARY

Bagasse	The cellulosic residue left after sugar is extracted from sugar cane.
BOD	Biological oxygen demand. A measure of water pollution.
COD	Chemical oxygen demand. A measure of water pollution.
DDG	Distillers dried grains. The dried residue from ethanol fermentation which is used as animal feed because of its protein value.
EtOH	Ethanol or ethyl alcohol.
HHV	Higher heating value. The heat released during combustion of fuel if all products are cooled to room temperature and water is condensed to a liquid. The term is most frequently used in the U.S.
LHV	Lower heating value. The heat released during combustion of fuel if all products are cooled to room temperature while water remains as steam. The lower heating value is more representative of typical fuel burning. The term is frequently used in European literature.
MeOH	Methanol or methyl alcohol.
Stover	The residue (stalks, leaves, and cobs) of corn after the grain has been removed.

APPENDIX A

PROCESS DESCRIPTIONS AND ENERGY CONSIDERATIONS

Ethanol From Corn: Traditional Process

A block flow diagram showing the steps in the manufacture of ethanol from corn is presented in Figure A–1. Although corn is generally selected because it is the most economic grain in the United States, the process is representative of the manufacture of alcohol from other grains. The energy and materials requirements for the traditional process are summarized in Tables A–1 and A–2. The material and energy balance were based on a plant manufacturing 20 million gallons anhydrous ethanol per year and operating around the clock 330 days per year. The selection of plant scale does not affect the net energy balance, which is based on energy consumed per unit of energy produced as liquid fuel.

The corn or other grain used in the manufacture of alcohol can be conveniently stored for long periods of time. This is in contrast to sugar cane, which must be processed soon after it is brought from the field. Therefore, the alcohol from grain plants are generally designed to operate on a year-round basis while alcohol from sugar cane plants operate only during harvesting season. This variation has a greater effect on the economics than net energy consumption. Nevertheless, it is sometimes proposed to harvest the corn stover and use it as a fuel in the alcohol from corn plants. Because the stover has a relatively low density and because the storage stability of the stover has not been adequately demonstrated, many agricultural experts believe that the use of corn stover as a fuel for year-round operation would not be feasible.

The first step in the corn-to-ethanol process shown in Figure A–1 is size reduction. When alcohol is the primary product, this can be accomplished by hammer milling. The ground corn is then conveyed to a pre-cooker where it is mixed with water and recycled stillage at about 150 F. The corn slurry is then cooked for about 10 minutes at 250 F in a continuous cooker.

The cooked mash is then cooled to about 80 F in a series of flash coolers which operate at progressively lower temperatures. After cooling, an enzyme (amylase) is added to convert starch to sugar. This enzymatic hydrolysis is known as saccharification.

Following the hydrolysis, the mash is cooled to about 70 F and combined with recycled stillage to reduce the pH and to provide buffering capacity during the fermentation. Chemical nutrients and yeast are added and the mixture is allowed to ferment in batch fermenters. Continuous fermentation has been proposed and has been demonstrated on a pilot scale and in some commercial operations. Changing from batch to continuous operation might improve the economics but would have little effect on the energy requirements. During the fermentation, the mixture is kept between 77 and 90 F. Carbon dioxide released by the fermentation is exhausted to the atmosphere through a condenser, which removes entrained liquid and returns it to the fermenter.

Upon completion of the fermentation, the alcohol is purified and recovered in a series of distillation columns. The bottom stream from the first column, which is known as the beer still, contains water and organic materials. This stream is concentrated by evaporation, dried, and sold as distillers dry grains. As can be seen from Table A–1, the evaporation and drying of distillers dry grains is one of the major energy consumers. Nevertheless, recovery of this byproduct is essential to the overall economics of ethanol manufacture from grain.

The overhead from the first still contains a mixture of water, ethanol, and impurities. These include both low-boiling impurities (ester-aldehyde) and high-boiling impurities (fusel oil). In the design used for this study, it was assumed that the ester-aldehyde would be recovered and recycled to boilers for use as fuel within the plant. A fairly significant credit of 0.03 Btu/Btu ethanol was taken for this boiler fuel. The quantity depends upon the way in which the fermentation is operated. We believe that many commercial fermentations have lower yields of ester-aldehyde. Therefore, the calculated net energy requirement is slightly low. In the rectifying column, ethanol is concentrated to about 95 percent by volume and sent to a benzene column where it is further concentrated to anhydrous ethanol by azeotropic distillation. Fusel oil, which is removed from an intermediate plate of the distillation columns and separated by decantation, is combined with the anhydrous alcohol. This fusel oil contributes slightly to the energy content of the liquid fuel. There are small benzene losses during the azeotropic distillation. This small benzene loss was not included in the net energy balance because it is believed that most of the loss goes with the liquid fuel product.

As can be seen from Table A–1, the total process energy requirement is estimated at 1.87 Btu/Btu ethanol. Considering the use of ester-aldehyde as boiler fuel, the net process energy consumption is estimated at 1.84 Btu/Btu. Essentially all of this process energy could be normally supplied as coal for the generation of processed steam. A small portion would be supplied as coal for generation of electricity used in the process. Of course, other fuels could be substituted for the generation of steam.

Ethanol From Corn: Modern, Energy-Conserving Technology

Significant energy savings over the traditional process for manufacture of ethanol can be achieved by application of modern technology. Most existing ethanol plants were constructed before 1970 in an era of cheap energy. Energy min-

TABLE A-1.—ETHANOL FROM CORN. TRADITIONAL PROCESS ENERGY BALANCE

Basis: 20 million gallons anhydrous ethanol/yr
330 days/yr–24 hrs/day:
Lower heating value 75,670 Btu/gal at 68 F.

	Direct Energy				
Unit Operations	Amount	Form	Conversion Assumptions	Fuel Required Btu/Btu EtOH	Fuel
Feed Preparation					
Screening, grinding and material handling	5050 kw	Electricity	10,000 Btu/kwh	0.26	Coal
Process					
Cooking and enzyme preparation	25 MM Btu/hr	Steam	83% boiler efficiency	0.16	Coal
Separation and Recovery					
Stripping column	44.7 MM Btu/hr	Steam	83% boiler efficiency	0.28	Coal
Rectifying column	32.6 MM Btu/hr	Steam	83% boiler efficiency	0.21	Coal
Dehydration column	30 MM Btu/hr	Steam	83% boiler efficiency	0.19	Coal
Byproduct Recovery					
Evaporators	46.0 MM Btu/hr	Steam	83% boiler efficiency	0.29	Coal
Dryers	30.0 MM Btu/hr	Steam	83% Boiler efficiency	0.19	Coal
Auxiliary					
Boiler feedwater heating	21.00 MM Btu/hr	Steam	83% boiler efficiency	0.13	Coal
Plant building serices	25.00 MM Btu/hr	Steam	83% boiler efficiency	0.16	Coal
Total Process Energy				1.87	

imization was not economic in these older plants. In addition, fuel grade ethanol may include many higher boiling compounds (fusel oil), which are unacceptable in industrial grade ethanol. Less energy intensive separations are required for the fuel grade ethanol.

Modern energy efficient technology generally is similar to the traditional technology described in Figure A–1, except that materials other than benzene are used for azeotropic distillation for anhydrous ethanol. Energy savings are achieved by (1) greater heat recovery and (2) by using high pressure steam in back pressure turbines to turn rotating equipment or to generate electricity, while the low pressure steam from the turbine exhaust is used for process heat.

The most significant savings occur in the separation and alcohol recovery. Katzen Associates[*] have recently published a design which minimizes the energy consumption in recovery of 99.5 percent ethanol. Vulcan Cincinnati has actually built several anhydrous ethanol systems which minimize steam requirements. Both designs require about 21.5 pounds steam per gallon anhydrous ethanol.

TABLE A-2—ETHANOL FROM CORN. MATERIALS REQUIREMENTS

Basis: 20 million gallons anhydrous ethanol per year, 330 days/yr, 24 h/day or 60,600 gal/stream day, lower heating value 75,670 Btu/gal EtOH @ 68 F

Material	Amount	Fuel Equivalent[a] Btu/Btu EtOH	Use
Corn	53,737 lb/hr	0.452	raw material
Ethanol	2525 gal/hr	(1.0)	liquid fuel
Fusel Oil	12 gal/hr	(0.01)	liquid fuel
Dried distillers grain	8.21 tons/hr	(0.075)	animal feed
Ester-aldehyde	78.7 gal/hr	(0.03)	boiler fuel

[a] Fuel equivalents taken at lower heating value, corn at fuel to grow and harvest, DDG at fuel to grow equivalent protein as soybeans.

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[*] Moon, G. G., Jr., *et al.*, "Grain Motor Fuel Alcohol Technical and Economic Assessment Study," Raphael Katzen Associates report to Department of Energy (December, 1978).

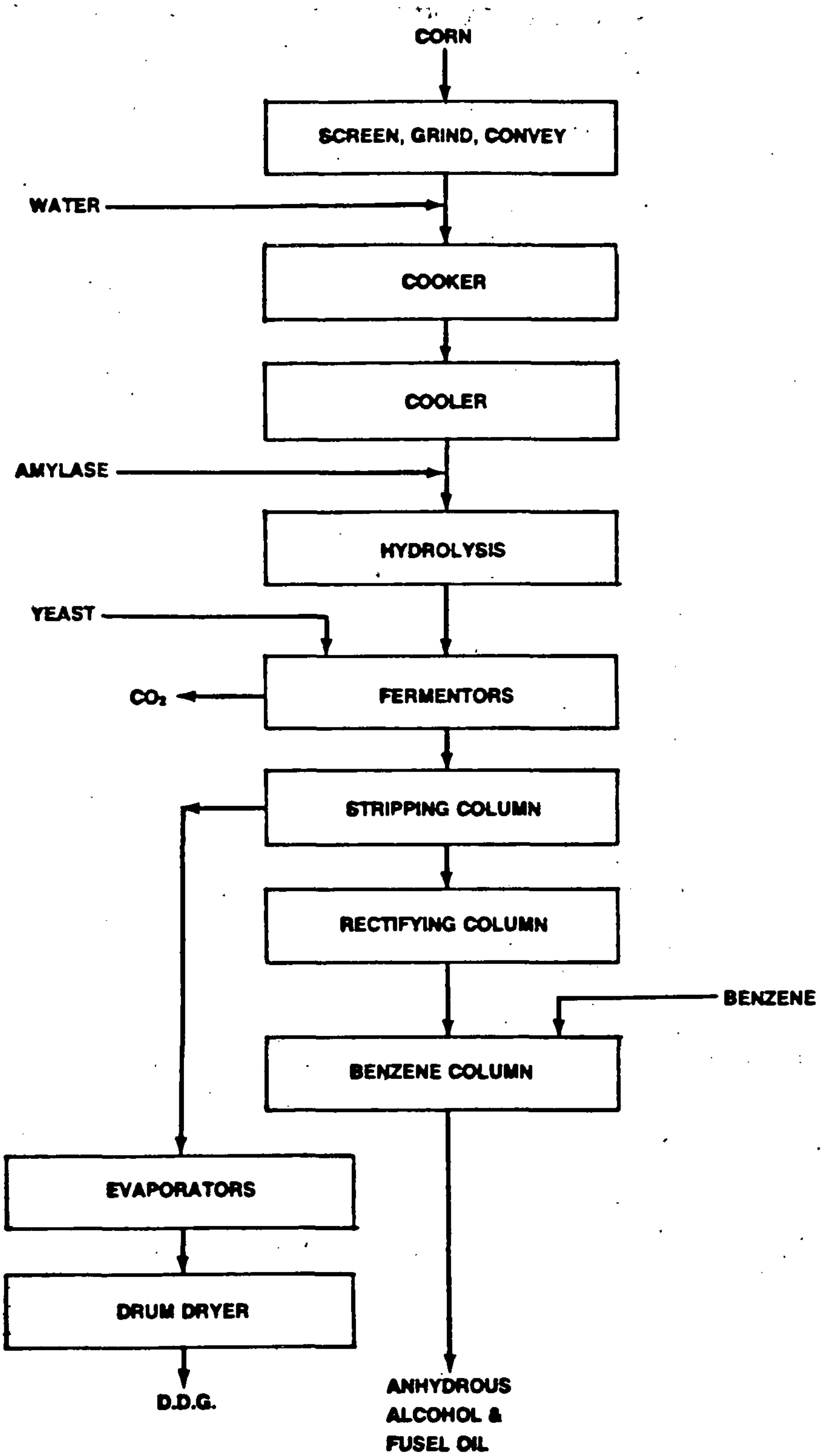

FIGURE A-1. ETHANOL FROM CORN, BLOCK FLOW DIAGRAM.

TABLE A-3.—ETHANOL FROM CORN ENERGY CONSERVATION DESIGN

Basis: 1 gallon anhydrous ethanol. Lower heating value 75,670 Btu/gal at 68 F.

Unit Operations	Direct Energy	Fuel Required Btu/Btu EtOH
Feed Preparation		
Grinding and material handling	0.308 kwhr	0.04
Process		
Cooking and enzyme preparation	7.1 lb steam 0.30 kwhr	0.11 0.04
Fermentation	0.053 kwhr	0.01
Separation and Recovery		
Distillation Towers	21.5 lb steam	0.32
Byproduct Recovery		
Evaporators	0.746 kwhr	0.10
Dryers	6.0 lb steam	0.09
Centrifuges, etc.	0.356 kwhr	0.05
Auxiliary and Miscellaneous		
Boiler Feedwater Heating	3.4 lb steam	0.05
Miscellaneous Power	0.50 kwhr	0.07
Plant Building Services	3.4 lb steam	0.05
SUBTOTAL		0.93
Cogeneration Credits		
Electricity Saved	0.946 kwh	(0.13)
Fuel Consumed for Rotary Equipment	0.946 kwh	0.06
TOTAL		0.86

Conversion Assumptions: Shaft power and electricity assume 10,000 Btu coal/kwhr
Steam assumes 83% boiler efficiency

Evaporation of stillage and drying of dark distillers grains also are significant energy consumers. Although triple effect evaporation is usually practiced in alcohol plants, the use of vapor recompression evaporators can result in large energy savings.

The energy requirements using modern, energy-conserving technology is summarized in Table A-3. The process energy requirements are about half those needed for the traditional technology. Even further savings can be achieved by cogeneration of process steam and either electricity or shaft power.

It should be noted that most of the energy savings are achieved at the expense of additional capital investment. The material balance remains essentially as shown in Table A-2.

Ethanol From Sugar Cane

A block flow diagram showing the steps in the manufacture of ethanol from sugar cane is presented in Figure A-2. The process energy and materials requirements for this process are summarized in Tables A-4 and A-5. The material and energy balance were based on a design by F. C. Schaffer and Associates for a plant processing 9,000 tons of cane per day, which can produce 140,000 gallons of anhydrous ethanol per day. Since the fuel requirements are presented as a ratio of the lower heating value of fuel to the lower heating value of ethanol produced, the scale does not significantly affect the results.

The first step in the process is the cutting and grinding of the sugar cane. Juice is then extracted from the cane in maceration units. The mechanical energy required for these feed preparation steps is supplied by running high pressure steam through a turbine. The exhaust low pressure steam is then available for process heat in other operations (see Table A-4). The raw juice is then treated with lime and purified in clarifiers. The energy associated with the small quantity of lime used is insignificant. The solids, which are known as "mud" in the sugar industry, are concentrated by filtration, segregated, and eventually returned to the cane fields. The filtrate from the "mud" filters is added to the clarified cane juice.

The cane juice is then concentrated from about 4 percent to 20 percent in a triple-effect evaporator. Heating and evaporating the cane juice are significant energy consumers.

After concentration, the cane juice is pumped to fermentation tanks where it is mixed with yeast and ntrients. After fermentation, the fermentation broth is centrifuged to remove yeast. Part of the yeast is recycled to fermentation and the rest is dried for sale as animal feed. The centrifuged fermentation broth is sent to a series of distillation towers where the alcohol is concentrated. In the design used for analysis, which is typical of modern sugar mill practice, the fermentation beer is first distilled in a stripping tower to take a mixture of alcohol and water overhead. The "bottoms" from this tower contain water and dissolved nutrients from the fermentation. These still bottoms are known as stillage. They are concentrated in a triple-effect evaporator, dried, combined with excess yeast from the fermentation centrifuge and sold as dried distillers grains.

The alcohol water mixture is separated in a rectifying and stripping tower. Alcohol is concentrated to about 95 percent in the rectifying tower and then sent to a benzene tower for final concentration to anhydrous alcohol by azeotropic distillation. The small benzene losses which occur are not included in the energy balance. We believe much of the lost benzene will be in the alcohol product and will therefore be used as fuel.

Solvents other than benzene may be used for the azeotropic distillation if OSHA and EPA regulations prohibit benzene. This would have little effect on overall energy consumption.

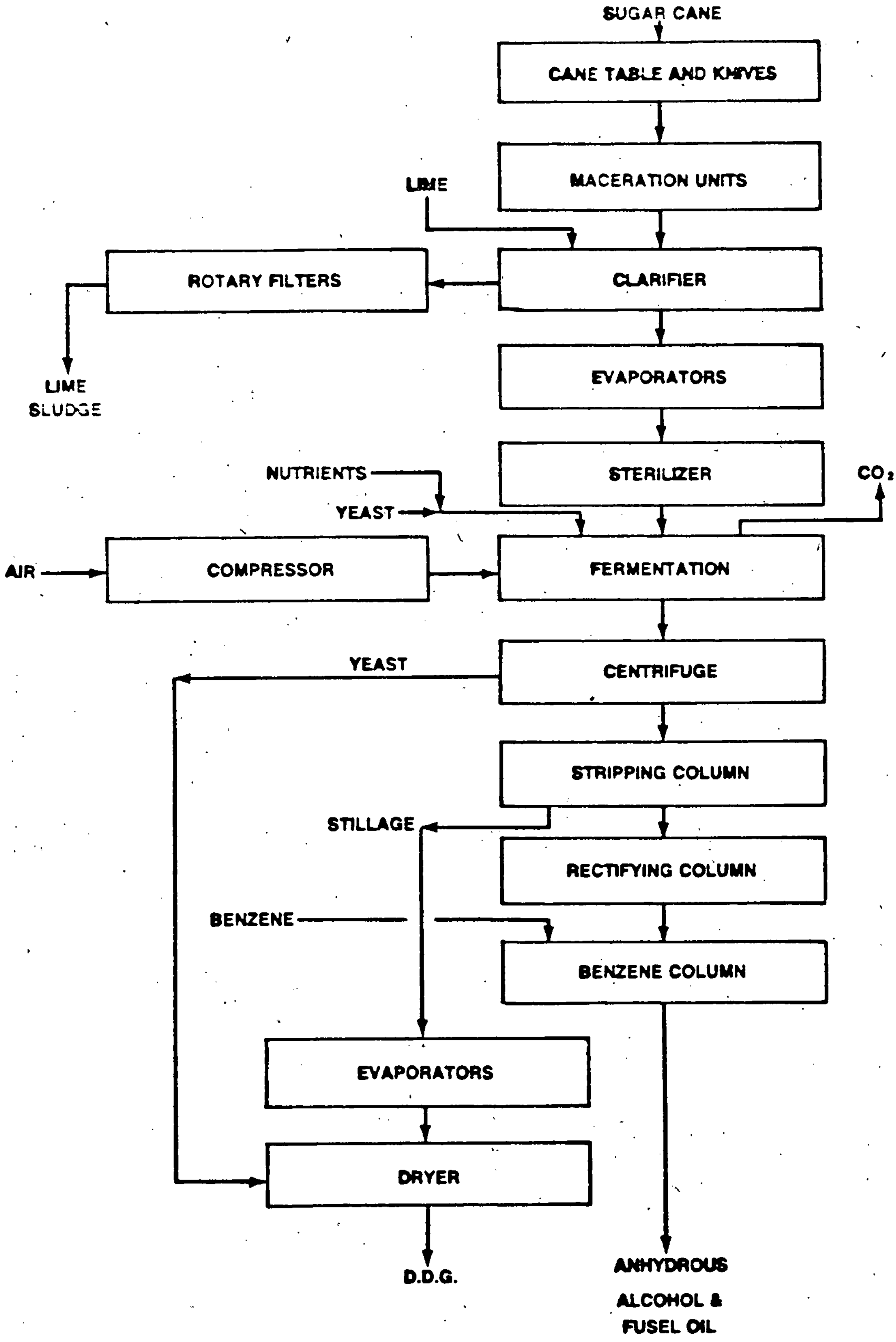

FIGURE A-2 ETHANOL FROM SUGAR CANE, BLOCK FLOW DIAGRAM.

TABLE A-4.—ETHANOL FROM SUGAR CANE. PROCESS ENERGY BALANCE

Basis: 9,000 tons cane/day, 24 hr/day
140,000 gal/day anhydrous ethanol
with LHV = 75,670 Btu/gal

Unit Operations	Direct Energy		Conversion Assumptions	Fuel Requirements Btu/LHV Btu EtOH	Fuel Type
	Amount lb/hr	Steam Pressure			
Feed Preparation					
Knives, shredder, mill	205,744 lb/hr	hp steam(a)	1134	0.822	bagasse
Turbine exhaust	(205,744)	42 psig	956(a)	(0.693)	
Process					
juice evaporator	314,622 lb/hr	42 psig	976 Btu/lb	1.095	
juice evaporator	2000	hp	1134 Btu/lb	0.008	
20 psig steam from evaporator	(280,653 lb/hr)	20 psig	967	(0.956)	
juice heaters	150,558	20 psig	967	0.512	
Separation and Recovery					
reboilers	60,750	42 psig	976 Btu/lb	0.208	
reboilers	130,095	20 psig	967	0.442	
Byproduct Recovery					
stillage evaporator	75,360	hp	1134	0.300	
stillage dryer	9,476	hp	1134	0.038	
Auxiliary and Misc.					
turbines	265,521	hp	1134	1,060	
live steam	10,000	hp	1134	0.039	
exhaust steam	(265,521)	42 psig	956(b)	(0.894)	
misc. uses and heat loss	72,329	42 psig	976	0.249	
Heat loss				0.037	
Total Process Fuels				2.267	

(a) hp steam 420 psig, 200 F superheat
(b) exhaust isentropic average enthalpy.

A fusel oil-alcohol-water mixture is removed from the middle of the rectifying tower and separated into organic and aqueous phases by decantation. The fusel oil would then be combined with the ethanol fuel.

As can be seen from Table A-4, the total process energy consumption is 2.27 Btu per Btu of ethanol. All of this energy is supplied by burning the bagasse recovered from the feed preparation stages.

TABLE A-5—ETHANOL FROM SUGAR CANE. MATERIALS REQUIREMENTS

Basis: 9000 tons cane/day, 24 hr/day
140,000 gal anhydrous ethanol/day

Material	*Amount*	*Fuel Equivalent Btu/Btu EtOH*	*Use*
Sugar Cane	*9000 tons/day*	*0.372*	*process feed*
Bagasse	*3146 tons/day*	*(2.27)*	*boiler fuel*
Ethanol	*140,000 gals/day*	*(1.0)*	*liquid fuel*
DDG	*136.4 tons/day*	*(0.042)*	*animal feed*

Improvements in process efficiency would result in excess bagasse or excess steam. It is unlikely that such excess energy could be economically exported from an alcohol fuel plant. It might be possible, however, to integrate another process with the plant at some locations.

Ethanol From Corn Stover

The manufacture of ethanol from corn stover is a process currently under development by the Department of Energy. The net energy balance is based on a conceptual design which in turn is based upon laboratory scale research and analogies to similar processes. In the process, corn stover or other cellulosic material is hydrolyzed to sugars, which are then fermented to ethanol which can be recovered in the conventional manner. Cellulose decomposes primarily to glucose which can be converted to ethanol by fermentation, while hemicellulose decomposes primarily to xylose and other five-carbon sugars which cannot be converted to ethanol using conventional fermentation technology.

In the conceptual design chosen for analysis, the pentoses (or five-carbon sugars) are converted to furfural which would be the precursor of another liquid fuel. Because of its tendency to polymerize, furfural would not be suitable for direct inclusion in gasoline. Rather, mild hydrogenation would be required to convert it to a more suitable chemical for use as a liquid fuel. Energy for this hydrogenation has not been included in the energy analysis.

The simplified process flow diagram is given in Figure A-3. For the conceptual design it was assumed that the plant scale would be 20 gallons anhydrous ethanol per year, operating 330 days per year. This is the same scale used in the ethanol from corn design. It was further assumed that the problems of storing corn stover for long periods of time could be solved, so that the plant could operate on a year-round basis. As noted before, the scale of operation has little effect on the net energy balance.

The first step in the corn stover process is grinding or chopping the stover. This would be done in hammer mills. For the energy analysis, it was assumed that the corn stover would be dried in the field to a rather low moisture content (20 percent or less). If additional drying were required at the plant, the energy needed would be increased.

After size reduction, the corn stover is treated with dilute acid at about 250 F. This dilute acid leaching converts hemicellulose in the stover to soluble pentosans (five-carbon sugars and their precursors). These pentosans are then sent to a furfural plant where the solution is heated, contacted with high pressure steam, and a mixture of surfural and steam taken overhead. The furfural is then recovered by a combination of distillation and decantation. As can be seen in Table A-6, the furfural manufacture and recovery is

TABLE A-6.—ETHANOL FROM CORN STOVER. PROCESS ENERGY BALANCE

Basis: 20 MM gallons anhydrous ethanol/yr,
330 day/hr, 24 hrs/day.
Lower heating value 75,760 Btu/gal @ 68 F

Unit Operations	Direct Energy		Conversion Assumptions	Fuel Required Btu/Btu EtOH	Fuel Type
	Amount	Form			
Feed Preparation					
Material Handling	49.2 kw	Electricity	10,000 Btu/kwh	0.002	Coal
Process					
Pretreatment	103 kw	Electricity	10,000 Btu/kwh	0.005	Coal
Heater	21 MM Btu/hr	Steam	63.5 Boiler Efficiency	0.173	Residue
Vacuum Filters	322 kw	Electricity	10,000 Btu/kwh	0.015	Coal
Pentosan Washing & Filtering	130 kw	Electricity	10,000 Btu/kwh	0.006	Coal
Dryer	76 MM Btu/hr	Fuel	—	0.40	Fuel Oil
Material Handling & Pumping	92 kw	Electricity	10,000 Btu/kwh	0.004	Coal
Reprecipitation With Methanol, Washing & Filtering	228 kw	Electricity	10,000 Btu/kwh	0.011	Coal
Hydrolysis, Neutralization Washing & Filtering	238 kw	Electricity	10,000 Btu/kwh	0.012	Coal
Heater	53.5 MM Btu/hr	Steam	83% Boiler Efficiency	0.143	Coal
Material Handling & Pumping	49 kw	Electricity	10,000 Btu/kwh	0.002	Coal
Separation and Recovery					
Ethanol Stripping, Rectification, and Dehydration	54.3 MM Btu/hr	Steam	63.5% Boiler Efficiency	0.447	Residue
Methanol Rectification	21.1 MM Btu/hr	Steam	63.5% Boiler Efficiency	0.174	Residue
Acid Mixture Evaporators	8.4 MM Btu/hr	Steam	83% Boiler Efficiency	0.044	Coal
By-Product Recovery					
Furfural Plant	293 MM Btu/hr	hp Steam(a)	83% Boiler Efficiency	1.53	Coal
DDG Evaporators & Dryers	76 MM Btu/hr	Steam	83% Boiler Efficiency	0.067	Coal
			63.5% Boiler Efficiency	0.426	Residue
Residue	223 MM Btu/hr	Residue		(1.22)	Residue
Ester aldehyde	78 gal/hr			0.03	Boiler fuel
Auxiliary					
Boiler Feedwater Heating	63 MM Btu		83% Boiler Efficiency	0.33	Coal
Plant Building Services	25 MM Btu		83% Boiler Efficiency	0.13	Coal
Total Process Energy				2.671	

(a) Hp steam 680 psi 500 F. All other is low pressure steam.

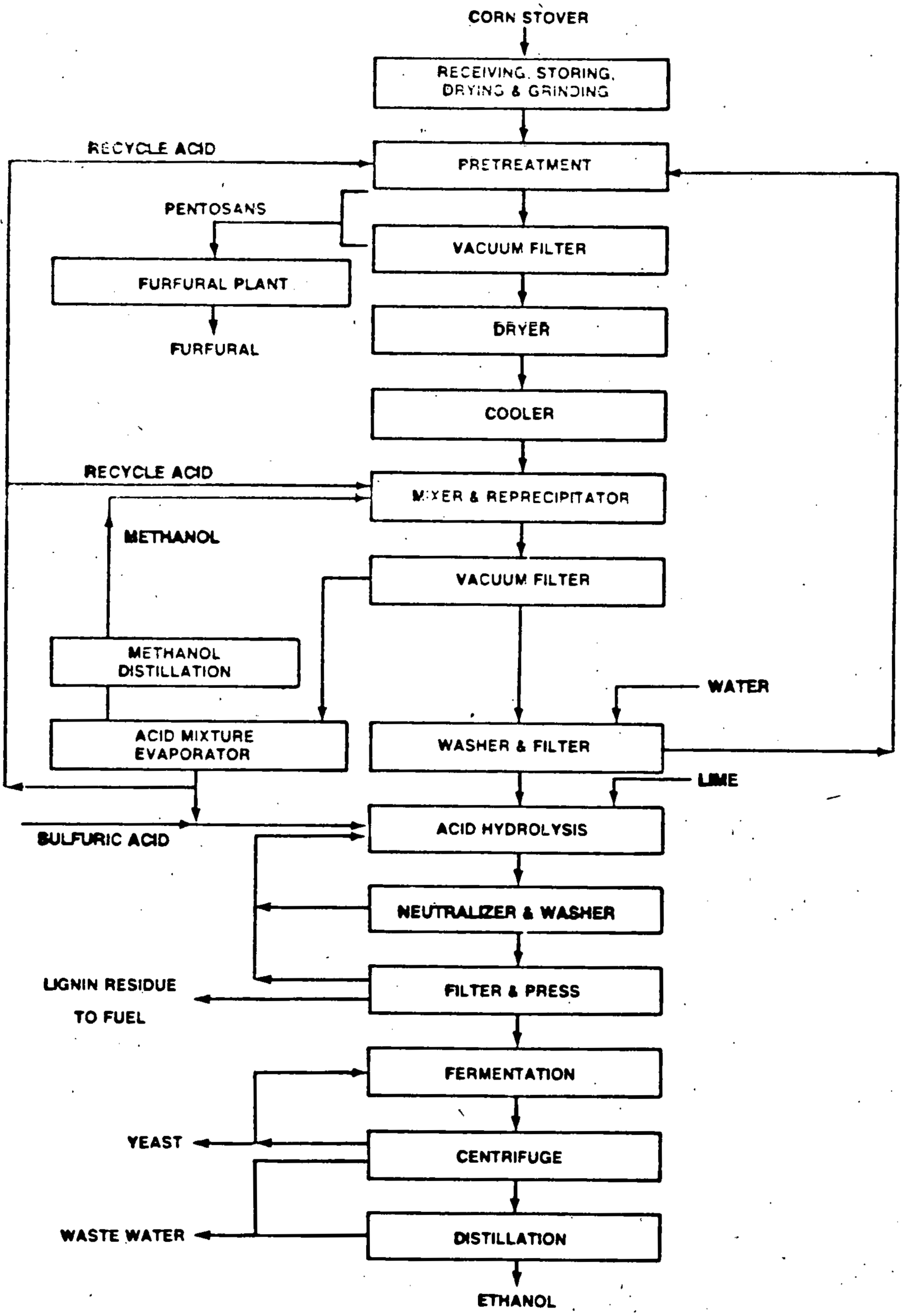

FIGURE A-3. ETHANOL FROM CORN STOVER, BLOCK FLOW DIAGRAM.

a very energy-intensive process, requiring approximately 1.5 Btu/Btu ethanol. Although the manufacture of furfural does consume considerable energy, it also converts between one-third and one-half of the corn stover to a useful liquid fuel precursor. This increase in overall yield of liquid fuel is believed important for the overall process economics.

The solid residue from the dilute sulfuric acid leach is dried to reduce entrapped moisture, cooled, and mixed with concentrated (79 percent) sulfuric acid. The concentrated acid dissolves or solubilizes the cellulosic portion of the stover. The solution is then mixed with methanol, which reprecipitates the cellulose in an amorphous form. This amorphous cellulose is then recovered by vacuum filtration and sent to the acid hydrolysis section.

The purpose of the solution and reprecipitation of the cellulose is to increase the reaction yield in the hydrolysis. Research at Purdue University has shown that this procedure can double the yield of ethanol.

The filtrate containing methanol and sulfuric acid and water is separated by a combination of evaporation and distillation. A two-effect evaporator is used to conserve energy. Although additional energy could be conserved by the use of additional evaporation efects, the corrosive nature of the acidic solution would make this uneconomic. The recovery and recycle of acid and methanol is another energy-intensive step.

The solid from the concentrated acid treatment section is washed with water and sent to the acid hydrolysis section.

TABLE A-7.—ETHANOL FROM CORN STOVER. MATERIAL REQUREMENTS

Basis: 20 MM Gallons Anhydrous Ethanol Per year, 330 days/hr, 24 hrs/day, LHV 75,670 Btu/gal, EtOH @ 68 F

Material	Amount	Fuel Equivalent(a) Btu/Btu EtOH	Use
Corn Stover	1427 Dry TPD (148,646 lb/hr., 20% wet)	0.001	Raw Material
Ethanol	2,525 gal/hr	(1.0)	Liquid Fuel
Furfural	13,460 lb/hr	(0.71)	Liquid Fuel or Chemical
Fusel Oil	12 gal/hr	(0.01)	Liquid Fuel
Distillers Dried Grains	2.46 ton/hr	(0.042)	Animal Feed
Ester Aldehyde	78.7 Boiler Fuel	(1.22)	Boiler Fuel
Lignin & Ash Residue	746 wet tons/day	(1.22)	Boiler Fuel

(a) Fuel equivalents taken at lower heating value, corn stover at fuel to grow and harvest. The conversion effieincy of the cellulosic material to furfural is about 20%.

The dilute acid hydrolyzes the amorphous cellulose to glucose at about 260 F. The reaction mixture is then cooled, neutralized with lime, and filtered. The solids recovered in the filtration consist primarily of lignin and ash. These solids are used as boiler fuel.

The sugars are contained in the filtrate and are sent to a fermentation section. The remainder of the process is similar to the other ethanol processes.

Methanol Via The Purox Process

A simplified process flow diagram for the manufacture of methanol from wood using the Purox Process is illustrated in Figure A–4. The Purox Process employs a vertical shaft furnace for converting a mixture of oxygen and wood chips into synthesis gas. Oxygen used to combust wood residue in the lower part of the furnace, and the heat of combustion partially gasifies the wood in the upper portion of the reactor. Significant energy in the form of electricity is consumed in the separating of the oxygen from the air (Table A–8).

The gas leaving the reactor contains 30 to 40 percent moisture. The moisture, along with ash, tars, and other condensable liquids are removed in a gas cleaning step. On a dry basis, the gas from the reactor is reported to have the following composition:

H_2	37.%
CO	25.
CO_2	23.
CH_4	6.
C_2H_2	9.
C_2H_4	2.0
C_2H_6	0.2
C_3+	6.2

The high percentage of propane and higher hydrocarbons gives the gas a surprisingly good heating value. This gas composition has been reconfirmed with Union Carbide.*

Following cooling and cleaning, the gas is compressed to about 200 psi and sent to an acid gas removal section. For the purposes of analysis, a Benfield hot carbonate system was used to remove carbon dioxide from the gas. In this system, acid gases are absorbed in a hot potassium carbonate system. The absorbant is then regenerated by a combination of reduced pressure and the application of heat (which is supplied by low pressure steam). The acid gas removal section consumes about 0.72 Btu/Btu methanol.

After acid gas removal, the gas is compressed to about 500 psi, heated, and passed over a hydrogenation catalyst to saturate the olefinic compounds which would have an undesirable effect on the shift catalyst. The gas is then cooled in a waste heat boiler to recover heat of hydrogenation before sending to a water-gas shift reactor.

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* Mr. R. S. Paul, Union Carbide Corp., private communication (July, 1978).

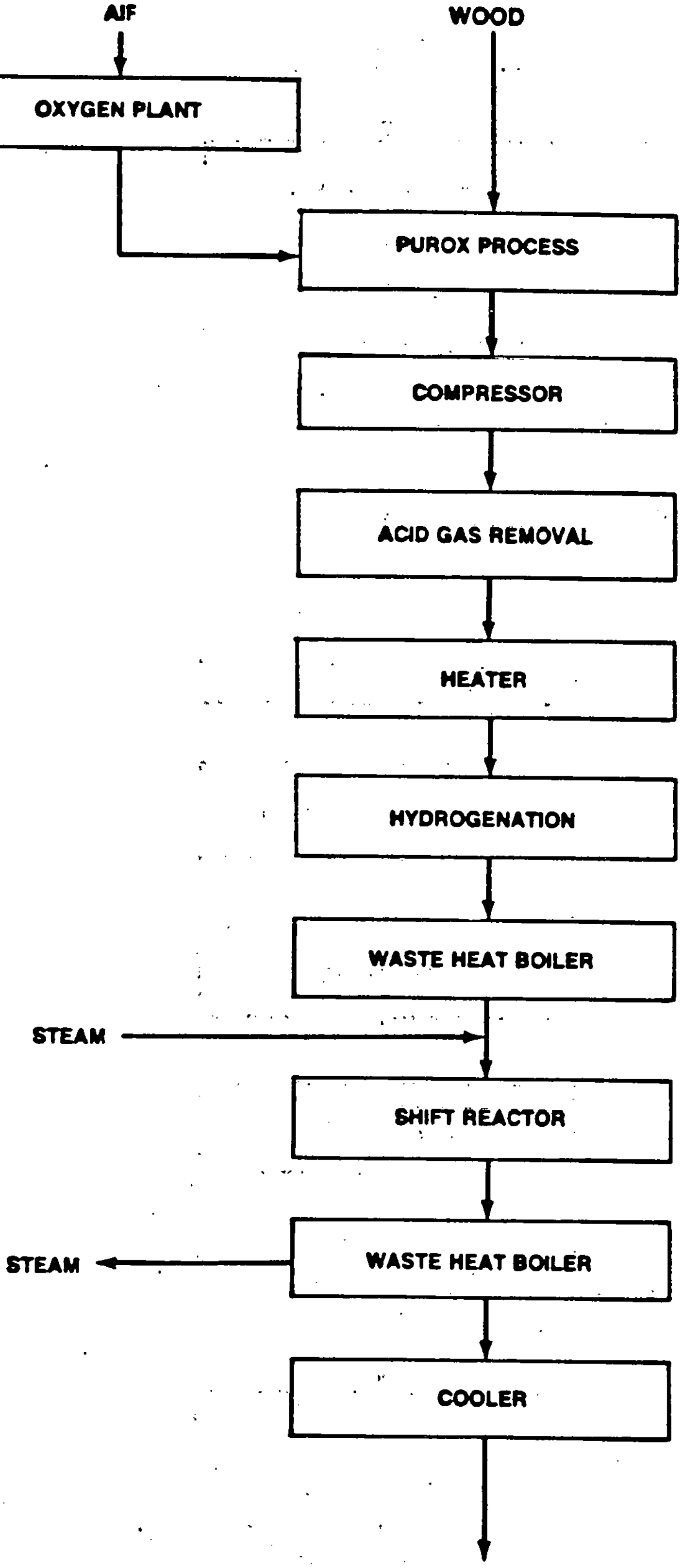

FIGURE A-4. METHANOL FROM WOOD (PUROX PROCESS), BLOCK FLOW DIAGRAM (CONTINUED ON NEXT PAGE)

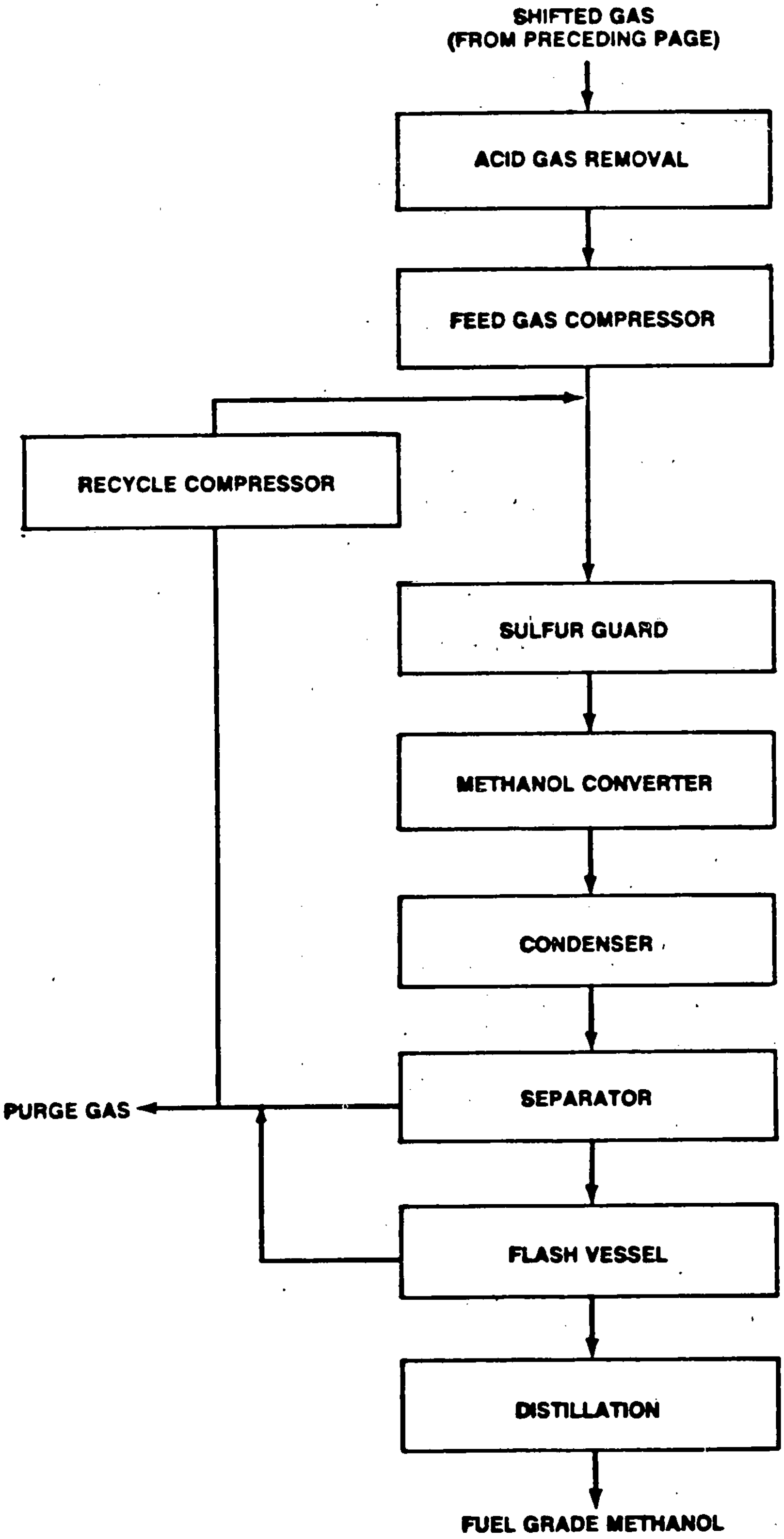

FIGURE A-4. CONT'D. METHANOL FROM WOOD (PUROX PROCESS), BLOCK FLOW DIAGRAM.

TABLE A-8.—METHANOL FROM WOOD (PUROX PROCESS). ENERGY BALANCE

Basis: 1000 tons/day bone dry wood (1428 tons/day green wood)
205 tons/day methanol, LHV 8570 Btu/lb

Unit Operation	Direct Energy Amount	Direct Energy Form	Conversion Assumptions	Fuel Btu/Btu MeOH	Fuel Type
Gasification	7140 kw	electricity			
Oxygen Plant		or equivalent	10,000 Btu/kwh	0.488	coal
Acid Gas Removal					
compressor	6946 hp	electricity	10,000 Btu/kwh	0.354	coal
pumps	774 kw	electricity	10,000 Btu/kwh	0.053	coal
regen tower	38,347 lb/hr	lp steam[a]	83% boiler eff.	0.315	coal
Hydrogenation and Shift					
gas heating	6.9 MM Btu/hr	process heat		0.047	process
hydrogenation WHB	(23.8 MM Btu/hr)	hp steam		(0.163)	process
process team	38.6 MM Btu/hr	hp steam		0.263	process
shift WHB	(15 MM Btu/hr)	hp steam		(0.102)	process
WHB	(11.3 MM Btu/hr)	300 psi steam		(0.077)	process
gas cooling	(6.9 MM Btu/hr)	process heat		(0.047)	process
compressor	961 hp	hp steam		0.195	process
compressor	664 hp	electricity	10,000 Btu/kwh	0.034	coal
turbine exhaust	(24,506 lb/hr)	lp steam	1000 Btu/lb	(0.167)	process
Methanol Synthesis					
compressors	899 hp	electricity	10,000 Btu/kwh	0.046	coal
waste heat boiler	(17.1 MM Btu/hr)	hp steam		(0.116)	process
purification	24.5 MM Btu/hr	lp steam		0.167	process
	4.55 MM Btu/hr	lp steam	83% efficiency	0.037	coal
Total process before purge gas credit				1.327	
Purge gas	(405.8 MM Btu/hr)			(2.772)	fuel gas
Net Process Energy				(1.445)	

(a) hp steam is 550 psi 500 F, h = 1223 Btu/lb
lp steam is 50 psi saturated

The gas is combined with steam, and sent to a water-gas shift reactor where the carbon monoxide reacts with steam to form hydrogen and carbon dioxide. The ratio of hydrogen to carbon monoxide is adjusted to 2:1 for the methanol synthesis. The shifted gas is then cooled, and carbon dioxide is then removed in a second Benfield unit.

The gas is then compressed to about 50 atmospheres, combined with recycled gas and sent to a methanol converter. The ICI low pressure methanol synthesis was the basis for the process energy estimates. This process is used in many commercial applications throughout the world. There were some critical areas where the process details on the methanol synthesis are proprietary. Energy requirement for the methanol synthesis was estimated from fundamentals and from the data available in the literature. These numbers were checked by consultation with ICI licensors.

The unreacted gases are separated from the methanol in a series of flash vessels and the methanol product is purified by distillation. Most of the gas is recycled to the methanol

TABLE A-9.—METHANOL FROM WOOD (PUROX PROCESS). MATERIALS REQUIREMENTS

Basis: 1000 tons/day bone dry wood (1,428 tons/day green wood, 205 tons/day methanol, LHV 8570 Btu/lb.

Material	Amount	Fuel Euivalent[a] Btu/Btu MeOH	Use
Wood	1000 tons/day	0.425[b]	Raw Material
Methanol	205 tons/day	(1.0)	Liquid Fuel
Purge Gas	282 tons/day	(2.772)	By-Product Fuel Gas

(a) Fuel equivalents taken at lower heating value, wood at fuel to grow and harvest.

(b) For a typical low yield area (Wisconsin, 5 dry tons/acre–yr). A high yield area like Louisiana would need only about 0.30 Btu/Btu methanol.

synthesis and a purge gas with a high fuel value is removed. Because of the high amount of hydrocarbons in the gas from the Purox gasifier, the purge gas has a heating value sufficient for use as pipeline quality gas. Credit for this purge gas was taken in the net energy balance. It would be possible to increase the methanol yield and greatly decrease the energy content of purge gas by incorporating a steam reforming step in the process. While increasing the yield of methanol, a reforming step would decrease the net energy produced.

Methanol From Wood (Battelle Process)

The manufacture of methanol from wood chips consists of three steps: (1) gasification, (2) gas purification and shift, and (3) methanol synthesis and purification. Whereas the technologies for gas purification and shift and for methanol synthesis and purification are well-developed and are practiced commercially, the technology for the gasification of wood is in its early stages of development. In the conceptual design used to estimate the net energy of methanol from wood via the Battelle gasification process, an experimental technology under development at Battelle Columbus Laboratories was selected. A simplified process flow diagram is shown in Figure A-5 and energy and material requirements are given in Tables A-10 and A-11.

The first step in the process is feed preparation. The Battelle process requires that the wood chips be reduced in size by milling. The wood particles are then conveyed through a lock-hopper system to a dryer where the green wood is dried by hot flue gases exiting the gasifier. The wood particles then are transferred to a fluid bed gasifier. A unique multi-solid fluid bed design permits high gas rates in the gasification section, but this has little impact on the overall energy balance. Heat for gasification is supplied by recirculating hot sand from a combustor. In the combustor, wood char which is not converted in the gasifier is burned with air to provide heat which is then converted to sensible heat of the recycling fluid sand. From a net energy viewpoint, the use of recirculating sand as a heat transfer medium eliminates the need for an oxygen plant and significantly reduces the energy required for the gasification section compared to a Purox system.

Another advantage of the fluid bed gasifier compared to a fixed bed gasifier like Purox is that there are negligible

TABLE A-10.—METHANOL FROM WOOD (BATTELLE PROCESS). ENERGY BALANCE
Basis: 1000 tons/day bone dry wood
492 tons/day methanol, LHV 8580 Btu/lb

Unit Operation	Direct Energy		Conversion Assumption	Fuel Btu/Btu/MeOH	Fuel Type
	Amount	Form			
Feed Preparation	2237 kw	electricity	10,000 Btu/kwh	0.064	coal
Gasification					
process steam	21.8 MM Btu/hr	50 psi steam			
compressor	1820 hp	hp steam	60% turbine eff.	0.062	process
compressor	3042 kw	electricity	10,000 Btu/kwh	0.122	process
turbine exhaust	(36,175 lb/hr)	50 psi steam	960 Btu/lb	0.086	coal
steam superheater	(2.76 MM Btu/hr)	process heat		(0.099)	process
waste heat boiler	(21.8 MM Btu/hr)	50 psi steam		(0.008)	process
BFW heater	(ample)	process heat		(0.062)	process
Acid Gas Removal					
compressor	3335 kw	electricity	10,000 Btu/kwh	0.095	coal
pumps	1068 kw	electricity	10,000 Btu/kwh	0.030	coal
regen. tower	30,593 lb/hr	50 psi steam	960 Btu/lb	0.083	process
Methanol Synthesis					
compressors	3583 kw	electricity	10,000 Btu/kwh	0.102	coal
heat recovery	(40 MM Btu/hr)	650 psi steam	984 Btu/lb	(0.114)	process
purification	69.7 MM Btu/hr	50 psi steam	83% boiler eff.	0.221	coal
purification	5582 lb/hr	50 psi steam	960 Btu/lb	0.015	process
Subtotal before purge gas credits				0.597	
Purge gas	(248.8 MM Btu/hr)			(0.707)	fuel gas
Total process energy				(0.110)	

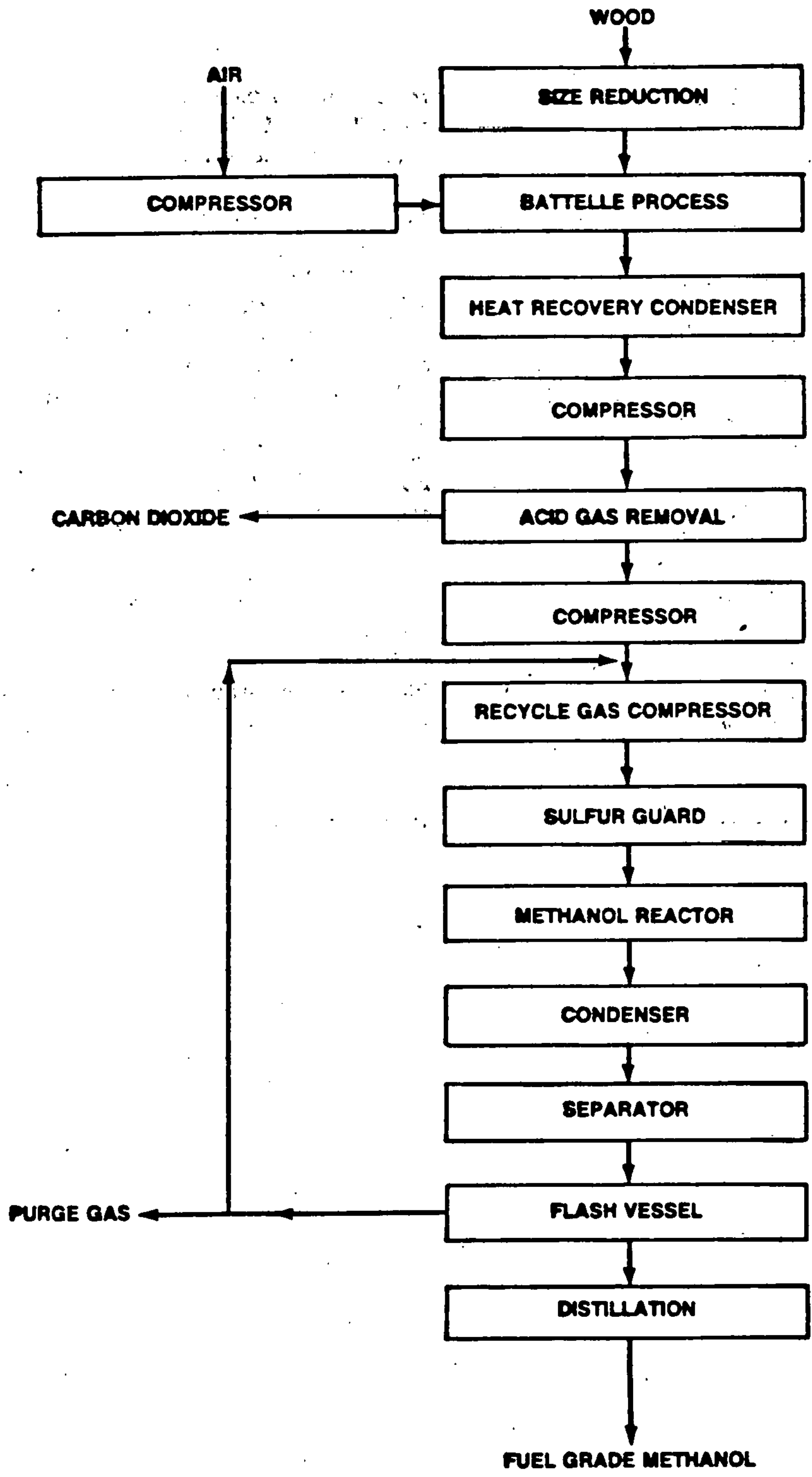

FIGURE A-5. METHANOL FROM WOOD (BATTELLE PROCESS) BLOCK FLOW DIAGRAM.

TABLE A-11.—METHANOL FROM WOOD (BATTELLE PROCESS). MATERIALS REQUIREMENTS

Basis: 1000 tons/day bone dry wood. 492 tons/day methanol, LHV 8580 Btu/lb

Material	Amount	Fuel Equivalent[a] Btu/Btu MeOH	Use
Wood	1000 tons/day	0.777[b]	Raw Material
Methanol	492 tons/day	(1.0)	Liquid Fuel
Purge Gas	234 tons/day	(0.707)	By-Product Fuel Gas

[a] Fuel equivalents taken at lower heating value, wood at fuel to grow and harvest.

[b] For a yield of 5 dry tons/acre expected in Wisconsin.

tars and condensable materials in the gas. This facilitates heat recovery from the hot gasifier gases.

The gasifier operates at low pressure (about 50 psi). Much of the energy required for the gasification is to compress air for the combustion section.

Following the gasifier and dryer, the gases are further cooled, filtered through a sand filter, and compressed to about 200 psi. Carbon dioxide is then removed by a Benfield system. The Benfield consists of an absorption tower, which removes the carbon dioxide and other acid gases, and a regeneration tower where the acid gases are released from solution through a combination of pressure drop and application of steam.

With the Battelle process, the gasifier conditions can be adjusted to give a 2:1 ratio of hydrogen to carbon monoxide so that no water-gas shift reaction is required prior to methanol synthesis. The gas is then compressed, heated to about 480 F through heat exchange with hot process gases, combined with recycled gases from the reactor, and sent through a sulfur guard (which removes traces of sulfur) to the methanol synthesis reactor. The reactor effluent is then cooled, methanol is condensed and sent to a distillation column for purification, and the unreacted gas is recycled. The purge gas stream is removed from the recycle. This purge gas contains hydrogen and carbon monoxide as well as minor amounts of methane and other hydrocarbons. It has a heating value of approximately 615 Btu per cubic foot and can be used as a clean-burning fuel.

APPENDIX B*

ENERGY INPUTS FOR SELECTED BIOMASS RESOURCES

This section of the report indicates the estimated quantity of energy required to produce, harvest, and transport biomass "raw material." Data are based on published research for energy inputs associated with four agricultural crops (sugar cane, sugar beets, corn, and soybeans) and for a silvicultural farm supplying "woody" biomass for energy production.

Agricultural Crops

Various species of agricultural crops grown in the United States are candidates for, or are affected by, any large-scale biomass-for energy plan. Sugar cane and sugar beets produce sugars which can be fermented to produce ethyl alcohol for use in motor fuels or as an industrial chemical. Other fuels and chemicals could also be made from these sugars, instead of ethyl alcohol. Also the residues from these crops contain cellulose and lignin which would provide fuel for direct combustion. Corn grain has a high starch content and can be fermented to produce ethyl alcohol. Soybeans are not a likely source of biomass for energy but are included since they would be affected by any large-scale production of ethyl alcohol from corn grain. Distillers grains are a high-protein by-product of alcohol production from corn. These distillers dried grains could replace a portion of the soybean meal, which is now used extensively as a protein supplement in livestock and poultry feeds.

The energy inputs for the agricultural crops are based on data supplied by a comprehensive investigation of energy used in agricultural production undertaken by the Economic Research Service (ERS) of the U.S. Department of Agriculture.** These energy inputs include energy used in tillage practices, irrigation, harvesting, and crop drying. Also included is the energy required to manufacture and transport fertilizers and pesticides. As will be noted, this invested energy comprises a significant portion of total energy requirements for crop production where there are heavy applications of nitrogen fertilizers.

Sugar Cane

Data on the utilization of fuel in U.S. sugar cane production are shown in Table B-1. A wide distribution in the number of Btu's needed to produce a ton of sugar cane is evident (from 220,000 Btu/ton in Hawaii to 629,000 Btu/ton in Louisiana). Yield differences are the major contributing factor to this dispersion since, except for Hawaii, all states require a total of 13,000 to 14,000 Btu's per acre. These yield differences can be attributed to climate, soil, and technical variations. Hawaiian sugar cane has the highest yield per acre and also the highest total amount of Btu's used per acre, since the sugar cane crops there have a two-year growth period as opposed to approximately 12 months on the Gulf Coast. Hawaii uses electricity as its most prevalent input. Electricity contributes 46% of all energy inputs in Hawaii unlike the mainland states where diesel fuel is the primary input (contributes over 50% in these states as opposed to 13% in Hawaii). This is closely followed by invested energy (34% on the Gulf Coast and 28% in Hawaii).

In Table B-2, data on the energy content of fertilizers applied to sugar cane is provided. Fertilizers account for more than 85% of invested energy for sugar cane. Hawaiii, Texas, and Louisiana use approximately the same ratio (15:1:1) and quantity, with nitrogen being the primary component. Florida, however, uses an insignificant amount of nitrogen, slightly less phosphate, but more potash (requiring less energy than nitrogen) than the other states.

Figures on fuel utilized by types of operation in sugar cane are presented in Table B-3. Fertilizers comprise about 28% of all energy used in sugar cane growing. The operation which requires the most energy is irrigation (20% of total inputs). Irrigation here includes conventional irrigation and drainage since water is withdrawn from most of Florida's fields to control water table levels. Irrigation takes place in Florida (over 97% of all state acreage) and Hawaii (over 30% of all state acreage). Most of the energy in irrigation is consumed via electricity, which is used almost exclusively in Hawaii (see Table B-1). Diesel and liquid petroleum gas pumps tend to be used in Florida. The next most energy consuming activities are harvesting and preplanting, which use 15% and 8%, respectively, of all energy inputs. Transportation and pesticides compose most of the remaining energy input use.

Sugar Beets

Data on the consumption of energy in the production of sugar beets in the U.S. and four selected states is provided in Table B-4. These four states were chosen on the basis of location, with each state representing a major sugar beet

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* Note: The data in this appendix are based on higher heating values.

** *Energy and U.S. Agriculture:* 1974 Data Base; Volume 2: Commodity Series of Energy Tables, U.S. Department of Agriculture and Federal Energy Administration; Washington, D.C.; April, 1977.

TABLE B-1.—UTILIZATION OF FUEL IN U.S. SUGAR CANE PRODUCTION

		Gasoline		Diesel		LP Gas		Electricity		Invested Energy[a]	Total	Tons	
	Acres (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Kwh/A	Btu/A (1,000)	Btu/A (1,000)	Btu/A (1,000)	Cane Per Acre	Btu's Per Ton
Florida	272	17.04	2,131	52.13	7,298	3.75	357	63	213	2,911	12,910	30.0	430,333
Hawaii	224	21.63	2,703	19.60	2,744	—	—	2,799	9,553	5,830	20,831	94.8	219,736
Louisiana	340	11.28	1,410	45.99	6,439	—	—	6	20	5,341	13,210	21.0	629,048
Texas	29	15.97	1,996	45.51	6,372	—	—	—	—	5,276	13,643	37.0	368,730
Total U.S.	865	15.93	1,991	41.07	5,750	1.18	112	747	2,549	4,248	14,650	34.5	424,637

SOURCE: Calculated by BCL based on data from *Energy and U.S. Agriculture: 1974 Data Base*: Volume 2: Commodity Series of Energy Tables, U.S.D.A., U.S. Government Printing Office, April, 1977.

[a] Invested energy includes the energy required to manufacture fertilizers and pesticides (including carrier solution).

region. California typifies the Southwest, Idaho the northern rockies, Minnesota the Red River Valley, and Nebraska represents the Great Plains. The Southwest and northern Rockies are dry but very fertile areas for sugar beets. The Red River Valley represents a more humid climate with a short growing season. The Great Plains region is very dry and requires irrigation.

In the states chosen, the Btu's used per ton of sugar beets ranged between 428,000 Btu-ton in California to 1,124,000 Btu-ton in Nebraska with a U.S. average of 678,000 Btu ton. Reasons for this large variation may be assumed to be due to soil and climate conditions which influence the technology involved in growing sugar beets. Without involving invested energy inputs, which are major discerning factors, an analysis of Table B-4 indicates a high quantity of fuel input in all states except Minnesota. One reason for this may be the use for irrigation. In California, Idaho, and Nebraska 52%, 64%, and 98%, respectively, of state sugar beet acreage is irrigated. The energy costs of irrigation are reflected in the number of Btu's per acre provided in the form of electricity, natural gas, liquid petroleum gas, and diesel fuel in the three states needing irrigation.

In Table B-5, a breakdown of fertilizer use is presented. Fertilizer generally accounts for over 90% of the invested energy. As can be determined by comparing the final column of this table with the total invested energy figures of Table B-1, Minnesota has a higher percentage (22%) of its invested energy in the form of pesticides than most other states. The pesticides, or perhaps the predators they are meant to repel, may be the cause of the low yield in that state, along with the relatively short growing season.

The breakdown of fertilizer energy shows a variety of mixtures, which are due to the variations in state soil fertility. California and Minnesota require only nitrogen, though Minnesota requires much larger quantites per acre. Nebraska soil requires both nitrogen and phosphate on about a 5:1 ratio. Idaho requires all three types, including potash, in a 19:7:1 ratio. Total U.S. Figures show similar results, though in lesser quantites. Using this final figure as a min-

TABLE B-2.—ENERGY CONTENT OF FERTILIZERS APPLIED TO SUGAR CANE

		Nitrogen		Phosphate (P_2O_5)		Potash (K_2O)		Total Invested Energy
	Acres (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Btu/A (1,000)
Florida	272	—	—	50	278	150	642	920
Hawaii	224	150	4,665	60	331	67	289	5,285
Louisiana	340	134	4,167	60	336	68	290	4,793
Texas	29	133	4,125	60	333	67	287	4,745
Total U.S.	865	96	2,984	57	318	93	398	3,701

Source: Calculated by BCL based on data from *Energy and U.S. Agriculture, Vol. 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office

TABLE B-3—U.S. SUGAR CANE PRODUCTION, FUEL UTILIZED BY TYPE OF OPERATION

Operations-Crops	Gasoline Gal/A	Diesel Gal/A	LP Gas Gal/A	Electricity (1,000) Kwh/A	Invested Energy (Million) Btu/A	Total (Million) Btu/A
Preplant	—	8.76	—		—	1.23
Plant	—	3.71	—	—	—	0.52
Cultivate	—	5.60	—	—	—	0.78
Fertilizer Application	—	0.77	—	—	—	0.11
Fertilizers	—	—	—	—	3.70	3/70
Pesticide Application	—	0.67	—	—	—	0.09
Pesticides	—	—	—	—	0.55	0.55
Irrigation	1.22	1.93	1.18	—	—	3.07
Harvest	—	15.96	—	0.74	—	2.23
Farm Pickup	2.38	—	—	—	—	0.30
Farm Auto	11.05	—	—	—	—	1.38
Elect. Overhead	—	—	—	0.01	—	0.02
Miscellaneous	1.27	3.68	—	—	—	0.67
Total Crops	15.93	41.07	1.18	0.75	4.25	14.65

SOURCE: Calculated by BCL based on data from *Energy and U.S. Agriculture, Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

imum, it can be determined that at least 79% of fertilizer energy is provided in the form of nitrogen.

The fuel utilized by type of operation is shown in Table B-6. As was determined earlier, fertilizers and irrigation are the major users of energy inputs in raising sugar beets in the U.S. They account for 40% and 27% respectively. The only other major energy consuming operation is preplanting, which utilizes 11% of all energy inputs.

Corn

The fuel inputs for the production of corn in the U.S. and selected states are presented in Table B-7. These states were chosen on the basis of acres devoted to corn and climatic difference. Illinois and Iowa are the heart of the corn belt, and together account for 35% of total U.S. corn production. Nebraska, the fourth state in terms of value of product, is included to exemplify the plains states, which have less fertile soils and less moisture than the corn belt states. Finally, New Mexico was chosen to show the implications of intense fertilization and irrigation.

As can be determined from Table B-7, there is a wide range in the amount of Btu's needed in each state to produce

Table B-4—UTILIZATION OF FUEL . IN U.S. SUGAR BEET PRODUCTION, SELECTED STATES

		Gasoline		Diesel		Fuel Oil		LP Gas		Natural Gas		Electricity		Invested Energy[a]	Total	Tons Beets	Btu Per
	Acres (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Gal-A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Ft^3/A	Btu/A (1,000)	Kwh/A	Btu/A (1,000)	Btu/A (1,000)	Btu/A (1,000)	Per Acre	Ton (000)
California	234	9.47	1,184	16.07	2,250	—	—	—	—	154	162	598	2,042	5,500	11,136	26.0	428
Idaho	94	14.77	1,846	11.14	1,559	—	—	3.20	304	319	335	1,245	4,248	8,043	16,335	20.1	813
Minnesota	189	8.64	1,080	9.18	1,285	—	—	1.27	121	—	—	5	18	7,053	9,557	11.4	838
Nebraska	83	20.54	2,568	33.18	4,645	—	—	29.12	2,766	1,735	1,822	265	905	7,639	20,344	18.1	1,124
Total U.S.	1,252	13.04	1,630	15.36	2,150	—	—	3.42	325	970	1,018	501	1,709	5,652	12,400	18.3	678

SOURCE: Calculated by BCL based on data from *Energy and U.S. Agriculture, Volume 2, Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

(a) Invested energy includes the energy required to manufacture fertilizer and pesticides (including carrier solution).

TABLE B-5.—ENERGY CONTENT OF FERTILIZERS APPLIED TO SUGAR BEETS, SELECTED STATES

		Nitrogen		Phosphate (P_2O_5)		Potash (K_2O)		Total Invested Energy
	Acres (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Btu/A (1,000)
California	234	159	4,931	—	—	—	—	4,931
Idaho	94	169	5,251	351	1,951	65	277	7,479
Minnesota	189	208	6,482	—	—	—	—	6,482
Nebraska	83	189	5,873	216	1,203	—	—	7,076
Total U.S.	1,252	139	4,334	103	574	21	88	4,996

Source: Calculated by BCL based on data from *Energy and U.S. Agriculture, Vol. 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office

a bushel of corn (from 87,000 Btu/bushel in Iowa* to 470,000 Btu/bushel in New Mexico). The main component of these energy costs for all of the states selected is invested energy inputs (energy required to manufacture fertilizers and pesticides), which accounts for over 50% of the Btu's used to raise an acre of corn in Illinois, Iowa, and the U.S. The fact that Nebraska and New Mexico are not included in this group is indicative of the different production techniques being used. The primary reason for this different technology is the need for irrigation in Nebraska and New Mexico. In both Illinois and Iowa, the amount of irrigated land is less than 0.5% of the total acreage in each state. However, over 53% of Nebraska's corn acreage and over 99% of New Mexico's corn acreage are irrigated. Natural gas for use in irrigation in New Mexico accounts for almost 60% of total energy used for corn production in that state.

Next to invested energy the next largest energy source for Illinois, Iowa, and the U.S. is gasoline, closely followed by diesel fuel and liquid petroleum gas.

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* 1974 corn yields in the Midwest were reduced approximately 20% due to dry weather. Based on "normal" yields, energy used might range from 70,000-80,000 Btu per bushel in the corn belt.

TABLE B-6.—U.S. SUGAR BEET PRODUCTION. FUEL UTILIZED BY TYPE OF OPERATION

Operation-Crops	Gasoline Gal/A	Diesel Gal/A	Fuel Oil Gal/A	LP Gas Gal/A	Natural Gas (1,000) Ft³/A	Electricity (1,000) kwh/A	Invested Energy (Million) Btu/A	Total (Million) Btu/A
Preplant	1.38	7.79	—	0.51	—	—	—	1.31
Plant	0.30	0.61	—	0.11	—	—	—	0.13
Cultivate	0.13	0.76	—	0.05	—	—	—	0.13
Fertilizer Application	0.14	0.10	—	0.05	—	—	—	0.04
Fertilizers	—	—	—	—	—	—	5.00	5.00
Pesticide Application	0.07	0.08	—	0.03	—	—	—	0.02
Pesticides	—	—	—	—	—	—	0.57	0.57
Irrigation	0.52	2.52	—	2.66	0.97	0.50	—	3.38
Harvest	0.02	3.09	—	0.01	—	—	—	0.44
Farm Truck	2.53	—	—	—	—	—	—	0.32
Farm Pickup	1.66	—	—	—	—	—	—	0.21
Farm Auto	5.79	—	—	—	—	—	—	0.72
Elect. Overhead	—	—	—	—	—	—	—	0.02
Miscellaneous	0.50	0.39	—	—	—	—	—	0.12
Total Crops	13.04	15.36	—	3.42	0.97	0.50	—	12.39

SOURCE: Calculated by BCL based on data from *Energy and U.S. Agriculture, Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

TABLE B-7.—UTILIZATION OF FUEL IN U.S. CORN PRODUCTION. SELECTED STATES

		Gasoline		Diesel		Fuel Oil		LP Gas		Natural Gas		Electricity		Invested Energy(a)	Total	Bushels Corn	Btu
Bushels	Acres/ (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Ft$_3$/A	Btu/A (1,000)	Kwh/A	Btu/A (1,000)	Btu/A (1,000)	Btu/A (1,000)	Per Acre	Per Bushel
Illinois	10,010	12.46	1,557	4.89	684	0.007	1	11.45	1,088	14	15	13	46	4,509	7,900	83.0(b)	95,181
Iowa	11,850	12.04	1,505	5.12	716	0.011	1	8.40	798	20	21	11	39	3,878	6,959	80.0(b)	86,988
Nebraska	5,600	8.47	1,058	18.33	2,566	0.002	—	19.14	1,818	783	822	123	420	4,846	11,530	68.0	169,559
New Mexico	35	20.54	2,568	23.23	3,252	—	—	23.91	2,272	20,029	21,030	543	1,853	5,200	36,175	77.0	469,805
Total U.S.	65,194	10.51	1,314	7.22	1,011	0.173	24	8.97	853	397	417	31	104	3,935	7,658	71.3	107,405

SOURCE: Calculated by BCL based on data from Energy and U.S. Agriculture: 1974 Data Base Volume 2: Commodity Series of Energy Tables, U.S.D.A, U.S. Government Printing Office.

(a) Invested energy includes the energy required to manufacture fertilizer and pesticides (including carrier solution).

(b) Abnormally low yield due to dry weather. Corn yields in Illinois normally average 105-115 bushels per acre; based on "normal" yields, energy use would be about 70,000-75,000 BTU per acre. Nevertheless, widespread use of alcohol fuels will necessitate use of marginal land, which will increase energy consumption per bushel. The 1974 data are considered realistic for net energy analysis.

The differences in invested energy inputs can be further investigated by examining Table B-8, which contains data on the energy content of fertilizers applied to corn for the U.S. and selected states. Approximately 85% of the invested energy per acre due to fertilizers is nitrogen. By comparing total invested energy in Tables B-7 and and B-8, it can be ascertained that over 90% of all invested energy is fertilizers; hence, nitrogen contributes about 80% of all invested energy inputs. State to state variations in total amount of fertilizer energy used per acre and mixture ratios are due to the variety of soil types and precipitation differentials.

This data in the last column of Table B-9 reinforces the fact that fertilizers generally account for about a half of the energy inputs per acre. The next most crucial operations are crop drying and irrigation respectively. These two combined only amount to about 20% of the total amount of Btu's used to raise corn. The preplanting process, harvesting, and pesticides account for another 13%. The remainder of the energy inputs are used by transportation or operations with insignificant energy inputs.

Soybeans

A breakdown of fuel inputs in U.S. soybean production for selected states is presented in Table B-10. The states were chosen on the basis of level of production, yield per acre, and geographic location. Illinois and Iowa are the largest U.S. producers of soybeans. Illinois has a moderate to good yield per acre, while Iowa has a relatively good yield. Mississippi represents a state which has tripled soy-

TABLE B-8.—ENERGY CONTENT OF FERTILIZERS APPLIED TO CORN, SELECTED STATES

	Nitrogen			Phosphate (P_2O_5)		Potash (K_2O)		Total Invested Energy
	Acres (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Btu/A (1,000)
Illinois	10,010	116	3,594	62	347	73	311	4,252
Iowa	11,850	102	3,157	50	277	44	187	3,621
Nebraska	5,600	140	4,355	38	210	11	45	4,610
New Mexico	35	150	4,665	60	331	12	52	5,048
Total U.S.	65,194	102	3,162	55	306	55	235	3,702

SOURCE: Caculated by BCL based on data from *Energy and U.S. Agriculture Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

TABLE B-9.—U.S. CORN PRODUCTION. FUEL UTILIZED BY TYPE OF OPERATION

Operations-Crops	Gasoline Gal/A	Diesel Gal/A	Fuel Oil Gal/A	LP Gas Gal/A	Natural Gas (1,000) Cu ft/A	Electricity (1,000) Kwh/A	Invested Energy (Million) Btu/A	Total (Million) Btu/A
Preplant	0.27	2.72	—	0.10	—	—	—	0.42
Plant	—	0.90	—	—	—	—	—	0.13
Cultivate	0.08	1.06	—	0.03	—	—	—	0.16
Fertilizer Application	0.19	0.22	—	0.07	—	—	—	0.06
Fertilizers	—	—	—	—	—	—	3.70	3.70
Pesticide Application	0.09	0.06	—	0.03	—	—	—	0.02
Pesticides	—	—	—	—	—	—	0.23	0.23
Irrigation	0.13	1.02	—	1.33	0.33	0.02	—	0.70
Harvest	1.34	1.06	—	0.50	—	—	—	0.36
Farm Truck	2.25	—	—	—	—	—	—	0.29
Grain Handling	0.15	—	—	—	—	—	—	0.02
Crop Drying	—	—	0.17	6.91	0.06	0.01	—	0.77
Farm Pickup	4.20	—	—	—	—	—	—	0.53
Farm Auto	1.75	—	—	—	—	—	—	0.22
Elect. Overhead	—	—	—	—	—	0.01	—	0.02
Miscellaneous	—	0.18	—	—	—	—	—	0.03
Total-Crops	10.51	7.22	0.17	8.97	0.40	0.03	3.94	7.66

SOURCE: Caculated by BCL based on data from *Energy and U.S. Agriculture Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

bean acreage over the past two decades, but has a relatively low yield.

As can be inferred from the last three columns of Table B-10, differences in the amount of input energy invested in a bushel of soybeans is predominately due to variations in yields per acre, since the total amounts of input energy are relatively similar in the states selected. The fuel inputs breakdown is similar in all states. Gasoline contributes about 40% of all input energy, closely followed by diesel fuel (about 38%) and invested energy (about 15%). Since it seems that parallel technologies exist, environmental forces such as soil fertility and climate must be the sources of the variations in yield per acre.

An examination of Table B-11, which contains data on

TABLE B-10.—UTILIZATION OF FUEL ON U.S. SOYBEAN PRODUCTION, SELECTED STATES

		Gasoline		Diesel		LP Gas		Natural Gas		Electricity		Invested Energy(a)	Total		
	Acres (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Gal/A	Btu/A (1,000)	Ft^3/A	Btu/A (1,000)	Kwh/A	Btu/A (1,000)	Btu/A (1,000)	Btu/A (1,000)	Bushels Per Acre	Btu Per Bushel
Illinois	8,600	7.87	983	5.61	785	0.61	58	9	9	6	22	347	2,204	24.5	89,977
Iowa	7,200	8.08	1,010	5.71	800	0.64	61	10	11	7	22	181	2,085	28.0	74,467
Mississippi	2,630	7.30	912	6.10	853	1.33	127	11	12	6	19	327	2,251	18.5	121,664
Total U.S.	53,582	7.23	904	6.40	896	0.71	67	37	39	7	23	439	2,368	23.5	100,761

SOURCE: Calculated by BCL based on data from *Energy and U.S. Agriculture: 1974 Data Base, Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

(a) Invested Energy includes the energy required to manufacture fertilizers and pesticides (including carrier solutions).

TABLE B-11.—ENERGY CONTENT OF FERTILIZERS APPLIED TO SOYBEANS, SELECTED STATES

	Acres (1,000)	Nitrogen		P^2O^5/Phosphate		K^2O/Potash		Invested Energy Btu/A (1,000)
		Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	Lb/A	Btu/A (1,000)	
Illinois	8,600	3	93	15	83	19	82	258
Iowa	7,200	1	31	6	35	7	31	98
Mississippi	2,630	1	33	5	26	5	20	79
Total U.S.	53,582	4	128	16	88	19	83	300

SOURCE: Calculated by BCL on data from *Energy and U.S. Agriculture: 1974 Data Base Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

the energy content of fertilizers applied to soybeans, would help answer the question of which environmental factors may be concerned. In the three states chosen, the amount of fertilizers used as a percentage of invested energy varies greatly, from 24% in Mississippi to 74% in Illinois with a U.S. average of 68%.

An important difference in the energy inputs for soybeans as compared to corn is due to nitrogen fertilizer application. Soybeans are a legume and can "fix" their own nitrogen; hence, little or no nitrogen is applied. This reduces the energy input associated with fertilizers (about 52,000 Btu's per bushel of corn compared to 13,000 Btu's per bushel of soybeans).

The data in Table B-12 show a breakdown of energy inputs by operation. The primary energy user is the farm pickup which uses 21% of all input energy. This is followed by the preplanting operation, which utilizes 17%. The other major energy consuming operations are cultivating (11%), harvesting (8%), and planting (5%). Fertilizers and pesticides comprise a total of 19% of all energy inputs.

TABLE B-12.—U.S. SOYBEAN PRODUCTION, FUEL UTILIZED BY TYPE OF OPERATION

Operation-Crops	Gasoline Gal/A	Diesel Gal/A	LP Gas Gal/A	Natural Gas Ft³/A (1,000)	Electricity Kwh/A (1,000)	Invested Energy Btu/A (Million)	Total Btu/A (Million)
Preplant	0.32	2.54	0.12	—	—	—	0.41
Plant	0.03	0.92	0.01	—	—	—	0.13
Cultivate	0.24	1.58	0.09	—	—	—	0.26
Fertilizer Application	0.01	0.23	—	—	—	—	0.03
Fertilizers	—	—	—	—	—	0.30	0.30
Pesticide Application	0.21	0.19	0.08	—	—	—	0.06
Pesticides	—	—	—	—	—	0.14	0.14
Irrigation	0.01	0.02	0.04	0.02	—	—	0.03
Harvest	0.31	0.92	0.12	—	—	—	0.18
Farm Truck	0.73	—	—	—	—	—	0.09
Grain Handling	0.03	—	—	—	—	—	—
Crop Drying	—	—	0.25	0.02	—	—	0.04
Farm Pickup	4.01	—	—	—	—	—	0.50
Farm Auto	1.24	—	—	—	—	—	0.15
Electric Overhead	—	—	—	—	0.01	—	0.02
Miscellaneous	0.09	—	—	—	—	—	0.01
Total Crops	7.23	6.40	0.71	0.04	0.01	0.44	2.37

SOURCE: Calculated by BCL based on data from *Energy and U.S. Agriculture: 1974 Data Base Volume 2: Commodity Series of Energy Tables*, U.S.D.A., U.S. Government Printing Office.

Corn Residues

Table B-13 indicates the estimated energy input for collection and transportation of corn residues or "stover". The corn residues represent a source of cellulose which could be converted into ethanol like corn grain (see description of Purdue process). In making these estimates, it is assumed that all the energy necessary for corn production would be allocated to the grain portion, which was discussed earlier in this section. In other words, the only energy input requirements noted in Table B-13 include going through the field after the grain has been harvested and collecting the residues. This might be accomplished by several methods, such as chopping, baling, or compressing the residues into stacks. In estimating the energy required for collection, it was assumed that energy usage would be similar to that required for harvesting corn silage, in which the entire plant material is chopped and blown into a wagon.

The residues then would have to be transported and, in some instances, dried. The moisture content of corn residues will vary significantly according to the weather conditions, such as humidity, rainfall, snow cover, etc. In order to store the residues over any period of time, the material presumably would have to contain no more than 20% mositure. If, for example, a heated air dryer analogous to those used for drying grain was used, a sizable volume of fuel would be required. It is possible that all or a portion of this requirement could be supplied through the waste flue gases generated during the processing the corn residues into ethanol.

TABLE B-13.—ESTIMATED ENERGY INPUT REQUIREMENTS FOR COLLECTION AND TRANSPORTATION OF CORN RESIDUES

	Btu Per Acre (000)	Residue Per Acre (tons)	Btu Per Dry Ton (000)
Harvest	1,513	—	—
Transport	743(397)[a]	—	—
Dry from 57% H_2O to 20% H_2O	7,338	—	—
Total with in-plant drying to 20%	9,594	4.00	5,578
Total with field drying to 20%	1,910	2.14	1,110

(a) 743,000 Btu/acre at 57% H_2O; 397,000 Btu/acre at 20% H_2O.

If the residues do require supplemental drying (other than that provided by solar radiation and natural air movement), the total Btu utilized per ton of residue would be roughly 2.4 million. This assumes approximately 4 tons of residue on a fresh-weight basis, which is the amount of residue that might normally be produced on an acre of corn yielding 100 bushels of grain. If the residues were sufficiently dried by solar radiation and natural air currents and no supplemental drying was necessary, total energy usage would be only about 900,000 Btu/Ton.

Silviculture

For the purposes of this study it is assumed that wood for the gasification processes would be grown on silviculture farms. These would consist of plantings selected from rapidly growing tree species at close spacings which would be harvested at appropriate intervals. The succeeding crops would be grown by coppicing (sprouting from the stumps). Intensive crop management, including fertilization, irrigation during the first 3 years of each crop, and weed control, would be practiced.

Whereas the energy required to grow agricultural crops is based on data collected by the Department of Agriculture, the energy required to grow and harvest small trees is based upon projections by MITRE.* These estimates are believed to be the best currently available, but it must be recognized that they have not been demonstrated in practice.

For the purpose of the present analysis, two sites were selected. The Wisconsin site was selected as typical of a low-yield area (producing five dry tons of wood per acre per year). A Louisiana site capable of producing 12 dry tons per acre per year was selected as representative of a high yield area. (Both sites would have low agricultural and forestry value, but both have sufficient rainfall if supplemented by irrigation.) The sites are relatively flat land with slopes averaging 3 to 4 percent. Hybrid poplars would be selected as representative biomass candidates for the Wisconsin site, while eucalyptus would be a more likely candidate for the Louisiana site.

The estimated energy consumption for silviculture farms producing 250,000 dry tons of wood per year are summarized in Table B-14. For the lower yielding Wisconsin site, the energy consumed is 149,300 Btu per dry ton compared to 103,800 Btu per dry ton in Louisiana. These energy consumptions are on a lower heating value basis. Most of the energy consumed is for irrigation and fertilizer manufacture. The higher energy consumption for the Wisconsin site reflects the lower yields. Transportation costs are fairly low because it was assumed that the gasification facility would be located near the center of the planted area.

It would be possible to reduce energy to grow trees if less

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* Inman, R.E., Silviculture Biomass Farms, MITRE technical report 7347, Vol I and IV, report to ERDA (May, 1977).

TABLE B-14.—ENERGY CONSUMPTION AND BALANCES AT WISCONSIN AND LOUISIANA SITES: 250,000 dry tons/yr (all as higher heating values)[1]

		Energy Consumed (10^9 Btu/yr)	
Operation	Material	Wisconsin	Louisiana
Supervision	Gasoline	1.67	1.67
Field Supply	Diesel/Gasoline	0.53	0.53
Harvesters	Diesel	9.43	7.87
Tractor Haul	Diesel	5.45	5.49
Loading	Diesel	3.32	3.29
Transporation	Diesel	28.83	17.32
Irrigation Move	Diesel	1.30	0.65
Irrigation Pumping	Diesel	223.63	111.83
Manufacture	Urea	99.36	102.32
Manufacture	P_2O_5	8.03	8.17
Manufacture	K_2O	15.42	17.08
Ground Operations	Diesel	1.16	0.06
Aircraft Operations	Gasoline	0.15	0.16
Fertilizer Transport	Diesel (Rail)	0.98	0.64
Energy per dry ton, HHV Btu/ton		1,597,000	1,110,500
LHV Btu/ton		1,493,000	1,038,000

[1] Energy Content:
Gasoline - 124,000 Btu/gal
Diesel Fuel - 138,690 Btu/gal
Urea - 27,730 Btu/lb N
P_2O_5 - 6,019 Btu/lb
K_2O - 4,158 Btu/lb
Rail - 800 ton-miles per gal

Source: MITRE (1977)

intensive agriculture were used. Nevertheless, fertilization to replace nutrients removed with the wood would be needed.

CHAPTER VII

FORMULATED ALCOHOL FUELS

USE OF ALCOHOL BASED FUELS

Fossil-based liquid fuels such as gasoline, diesel and kerosene, are a disorganized mixture of hydrocarbons. Their basic characteristics are only the average of a mixture of related factors, each factor being provided and controlled by different types of moleculars. Basically, the specifications of any liquid fossil fuel are defined by its average molecular behavior.

To the contrary, alcohols are well defined chemical substances, The characteristics of these substances are totally related to their molecular arrangement as well as to the physical and energy contributions of their atomic structure.

These well known and defined characteristics of alcohols, as a pure substance are of paramount importance in determining the expected behavior of biomass-based formulated fuels. (See Table).

TABLE A-1

SELECTED LIQUID FUEL CHARACTERISTICS

	GASOLINE	ETHANOL	METHANOL
THERMAL PROPERTIES			
Lower Heating Value			
BTU/lb	18,900 (Avg)	11,500	8,600
BTU/gal	115,400 (Avg)	75,670	56,560
Higher Heating Value			
BTU/lb @ 68°F	20,260	12,800	9,770
BTU/gal	124,800		
Heat of Vaporization			
BTU/lb	150	396	506
BTU/gal	900	3,378	3,340
Octane Ratings:			
Research	91-105	106-108	106-108
Pump (RON+MON)/2	87-98	98-100	99-101
Flammability Limits (% by Vol. in Air)	1.4-7.6	4.3-19.0	6.7-36.0
BTU/ft^3 @ Stoich. A/F; 60°F; one Atm; Gaseous Reactants:			
BTU/ft^3	95	93.8	87.3
BTU/lb	210		1150
Specific Heat			
BTU/lb-F°	0.48	0.60	0.60
Autoignition Temp (°F)	430-500	685	878
Flash Point (°F)	-50	70	52
Coefficient of Thermal Expansion @ 60°F & one Atm	0.6×10^{-3}	1.12×10^{-3}	1.2×10^{-3}
GENERAL PROPERTIES			
Costs (Average Plant Gate)			
\$ Per gal	0.40	1.20	0.50
\$ Per 10^6 BTU	3.46	15.80	8.85
Typical Vehicle Fuel Tank Equivalent (energy basis)			
Gal	20	30.5	40.8
lb	119	195	261
ft^3	2.59	3.95	5.28

TABLE A-1

SELECTED LIQUID FUEL CHARACTERISTICS

	GASOLINE	ETHANOL	METHANOL
CHEMICAL PROPERTIES			
Formula	C_4-C_{12} Mixture	C_2H_5OH	CH_3OH
Molecular Weight	Varies	46.1	32.0
% Carbon	85-88	52.1	37.5
% Hydrogen by weight	12-15	13.1	12.6
% Oxygen	∿0	4.7	49.9
C/H Ratio	5.6.7.4	4.0	3.0
Combustion Reaction Equation	$C_nH_{2n}+1.5O_2+5.66nN_2=nCO_2+nH_2O+5.66nN_2$	$C_2H_5OH+3O_2+11.3N_2=2CO_2+3H_2O+11.3N_2$	$CH_3OH+1.5O_2+5.66N_2=CO_2+2H_2O+5.66N_2$
Stoichiometric A/F Ratio	14.2 - 15.1	9.0	6.4
Fuel volume % of vaporized stoichiometric mixture	2.1	6.5	12.3
Moles Product Per Mole Charge	1.047	1.065	1.061
Moles Product Per Mole (O_2+N_2)	1.070	1.140	1.209
PHYSICAL PROPERTIES			
Specific Gravity	0.70-0.78	0.794	0.796
Liquid Density (lb/ft^3)	∿43.6	49.3	48.8
Vapor Pressure			
psi @ 100°F (Reid)	7-15	2.5	4.6
psi @ 77°F	∿ 0.3	0.85	2.31
Boiling Point (°F)	80-440	173	149
Freezing Point (°F)	∿-70	-173	-144
H_2O Solubility in H_2O	240 ppm	∿ ∞	∞
H_2O in	88 ppm	∿ ∞	∞
Surface Tension (dyne/cm)		23	22.6
Dielectric Constant		24.3	32.6
Viscosity @ 68°F (cp)	0.288	1.17	0.595
Specific Resistivity	$2x10^{16}$	$0.3x10^6$	$0.14x10^6$

EXPECTATIONS

In order to correctly establish the baseline criteria for biofuels, we must recognize that the formulated fossil fuels of today have, in all likelihood, exhausted their capabilities to control pollution and increase efficiency. For the past 10 years, engine design changes such as modifications in compression ratio, timing, and exhaust gas manipulation, restricted formulations (unleaded gas) and add-on equipment (catalyzers, electronic ignition, and computerized fuel supply, and pollution control devises), have significantly deteriorated the primary function of the internal combustion engine -- the transformation of chemical energy into available torque with the maximum of efficiency.

The need to balance energy and environmental requirements is receiving major attention around the world, and the passenger car is in the spotlight here, and in the rest of the world. It consumes a large share of petroleum that is produced; and it emits hydrocarbons, carbon oxide, nitrogen oxides. At one time, when petroleum was cheap and the supply was assumed inexhaustible, the general approach was to mandate emission standards as low as technically feasible. Now, however, with petroleum being expensive, and the supply known to be finite, people around the world are questioning the balance between air quality and fuel utilization.

This has to have an impact on us and it is difficult to see how that impact can be favorable.

FACTORS AFFECTING FUEL CONSUMPTION

Vehicle Weight

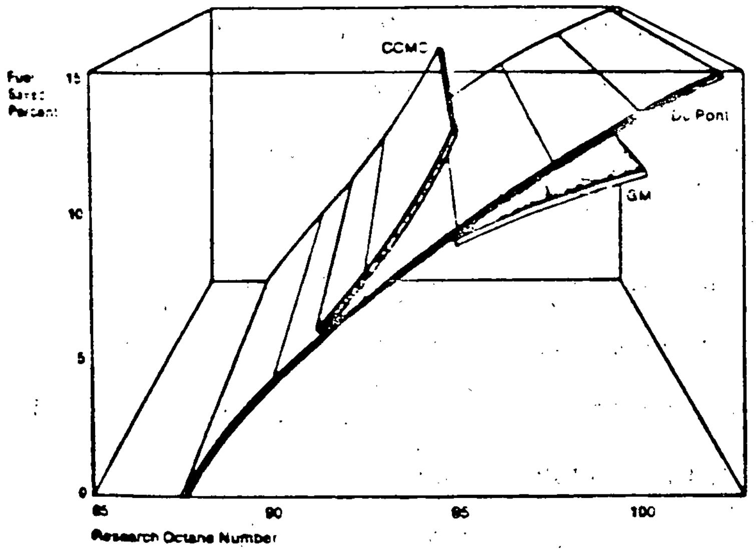
Production Vehicle Performance

Refinery Penalty

Octane Quality

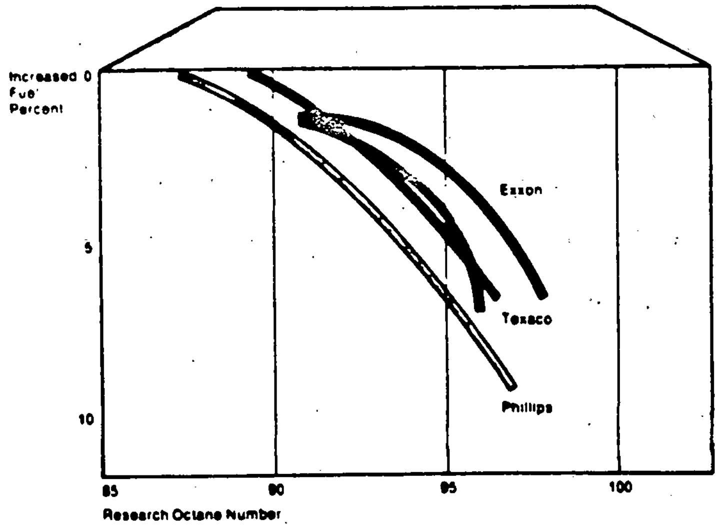
Emission Standards

EFFECT OF OCTANE REQUIREMENT ON FUEL CONSUMPTION



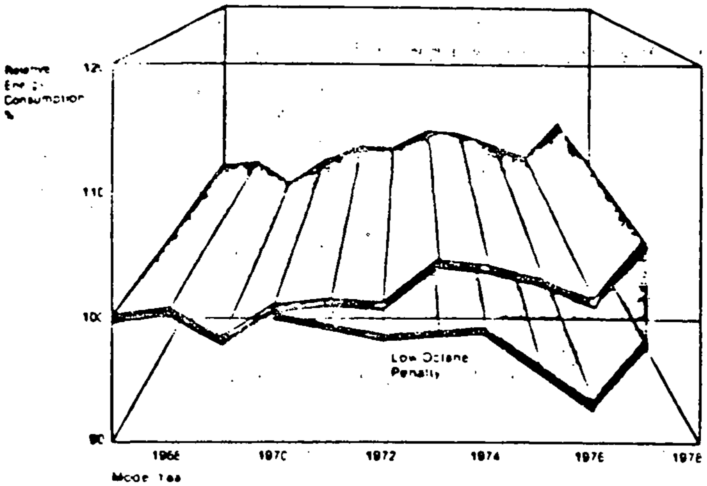
Du Pont, General Motors, and more recently, a committee of European automobile manufacturers (CCMC) have reported reduced fuel consumption associated with higher octane requirement engines

Figure 19
EFFECT OF UNLEADED OCTANE NUMBER ON REFINERY ENERGY CONSUMPTION



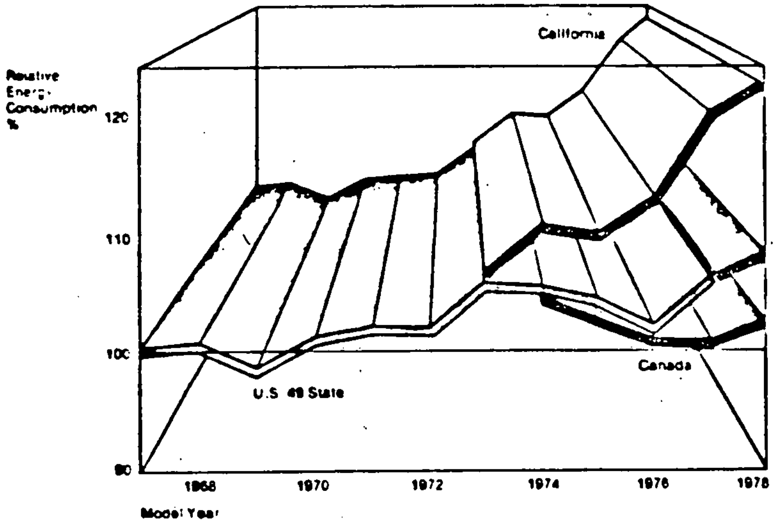
Estimates from three major U S petroleum companies indicate that to increase the average U S unleaded pool octane quality from 87 5 to 95 0 research octane number would consume an average of 5 percent more energy in the refinery

A INCREASED ENERGY CONSUMPTION DUE TO ADAPTATION TO 91 RON GASOLINE



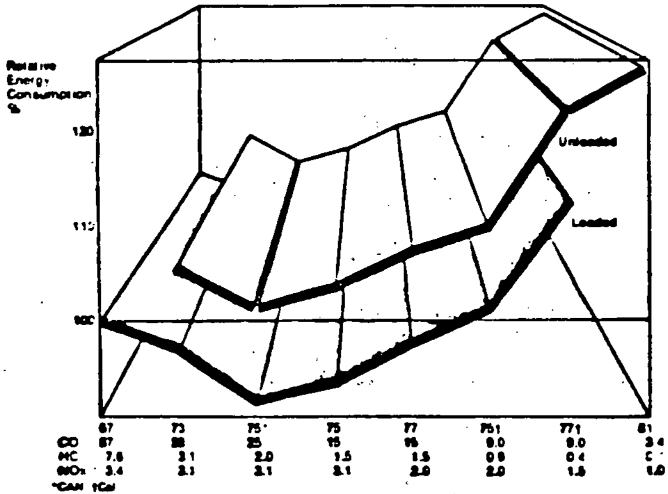
Virtually all of the domestically produced automobiles in the U.S.A. in recent model years have required unleaded fuel because of the use of catalytic emission control devices. Had these cars been designed with other types of emission control systems they could have used leaded fuel and could have given lower fuel consumption due to the higher octane quality of the leaded fuel available in the U.S.A. An energy penalty of about 6.5 percent is incurred due to the use of unleaded rather than leaded fuel in the U.S.A. Thus, the orange area in the above figure represents the energy lost due to operation on lower octane unleaded rather than higher octane leaded fuel.

B ENERGY CONSUMPTION OF VEHICLES



Starting in 1974 the emissions reductions required for cars sold in the State of California have been substantially more stringent than those for the remaining 49 states in the U.S.A. According to the fuel consumption data published by the U.S. EPA, these more stringent standards have resulted in higher fuel consumption for the California cars. This "California penalty" has grown from about 6 percent in 1974 to 12 percent in 1977-78. On the other hand, since 1975 the emission standards for Canada have been less stringent that in the U.S. 49 states. As consequence, the cars in Canada have been retuned to take advantage of these less stringent standards and fuel consumption has been improved by 5-8 percent in 1977-78.

EFFECT OF EMISSION STANDARDS ON ENERGY CONSUMPTION



The data from Figures A and B can be combined with the emissions standards for the corresponding model years to arrive at a relationship between stringency of emission control and fuel consumption penalty. Fuel consumption increases of up to 5 percent apparently have been incurred to meet the U.S 1973-78 emissions standards. Only a very small increase in fuel consumption was incurred to meet the current Canadian emission standards and a significant improvement could have been achieved if vehicles had continued to be designed to operate on high octane leaded gasoline. The more stringent emission standards already being met in California in 1977-78 result in an additional 11-13 percent penalty for a total to date of about 20%. General Motors recently estimated that another 5% penalty would be incurred to meet the U.S 1981 emissions standards

FORMULATION

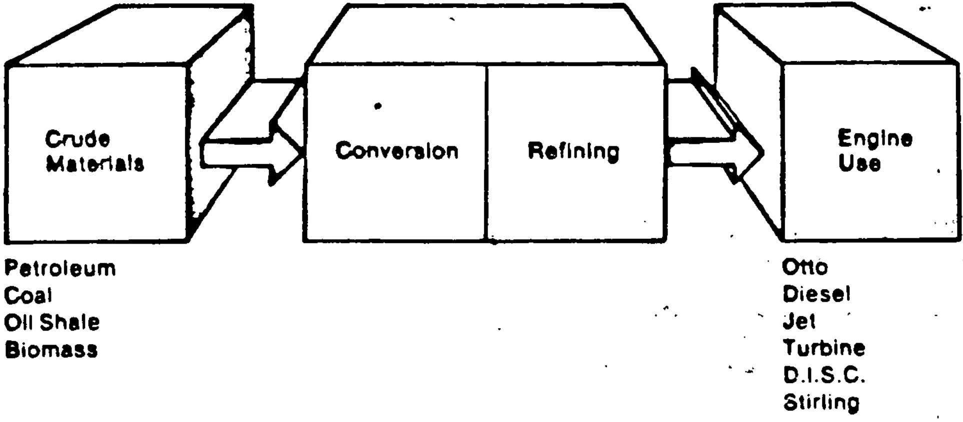
The baseline for a formulated biofuel must consider the fuel and the engine as a complete entity. This combined system -- fuel and the conversion of fuel into torque -- must be considered in any analysis of a formulated fuel.

The entire system -- the contribution of the raw material, the conversion and refining of the fuel, and the engine using this fuel -- must be considered in determining the performance of an engine in meeting its preestablished expectations.

ALTERNATE TRANSPORTATION FUELS

H_2
CH_4
Ch_3.OH. C_2H_5 OH. $(CH_3)_3$ $COCH_3$
Liquids from Oil Shale
Liquids from Coal
78-8284M/4.5

FUEL SUPPLY — MANUFACTURE — USE SYSTEM



In any comparison of fossil and biomass fuels, we must consider the total cost in money and energy of the above described negative remedies. We must, therefore, consider, as part of the baseline criteria, the ability of biofuels to avoid these negative remedies in order to achieve pollution standards and combustion efficiencies.

Use of Alcohol Fuels and Blends

Overview

The subject of alcohol fuels is a popular one and raises lots of questions. The what, why and when of alternatives; the nature and influences of alcohols on performance; the problems and solutions using alcohol fuels;. Fuel extenders as alternative source of high grade fuels.

A reason for concern, of course, is that transportation uses more than half of the U.S. petroleum consumption, and out of that, highway vehicles use about three-quarters. So this means that our highway vehicles use something over a third of the total petroleum in this country. As a result, alternative fuels for highway vehicles are getting a lot of attention and certainly deserve a top priority in our energy program.

The feasibility studies show that to satisfy the U.S. supply from domestic resources, only oil shale and coal are sufficient for transportation. The best candidates for alternatives are fuels from syncrudes, whether it be synthetic shale crude or coal crude, followed by methanol from coal, and possibly, eventually, hydrogen from water. But, state of the art of their technologies and related availability in time need to count.

With hydrogen from water we need a lot of energy from an abundant renewable resource. What we really do is put it in the hydrogen as a carrier and, thus, need nuclear or solar or a combination. But it's going to be a long time before it's applicable to vehicles.

Liquids from coal will not be available in significant quantities, before the year 2000.

Use of oil shale as an alternative faces economic environmental problems, and the question is whether we, as a nation, are going to be able to break that bottleneck for filling the gap between domestic oil and supply and demand.

One way, of course, is by imports, and this is the way we're doing it right now. Another way is to help the situation by increased efficiency and, of course, there is a lot of work going in transportation as well as in other end uses. Another approach is reduced demand, or perhaps, in the case of transportation, shifting from other sectors. A fourth possibility is electrical propulsion, whereby the electrical energy is generated from a non-petroleum resource. And then, finally, we have alternative fuels and engine systems.

The point of all this is that in the transportation area only the last two are permanent solutions. Anything else is a stop-gap. But we really need to be working hard on these permanent solutions.

The situation is recognized, but is often overlooked, "use fuels from syncrudes, and these are at the top of our list, availability in itself does not answer our needs." The reason for this is that conversion of nonpetroleum resources to liquid syncrudes does not assure practical or easy formulation of what the industry calls "finished fuels." Much work is required on the utilization end.

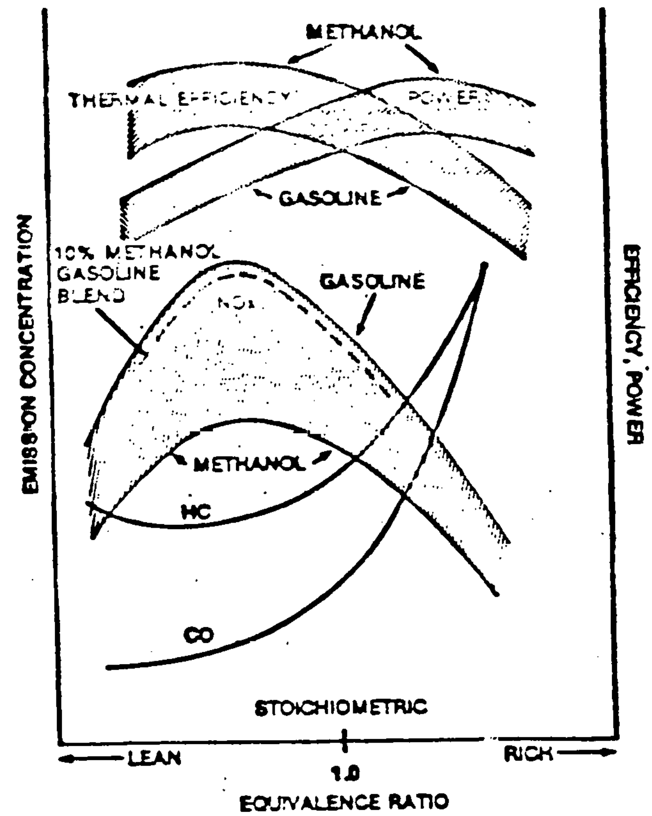
Logic and common sense in the analysis of real facts shows that for increasing the availability of liquid fuels for transportation in the near term, the only candidate are alcohols. Tab 24 shows the prime characteristics of gasoline and the major alcohols that we think of: methanol and ethanol.

Table 24

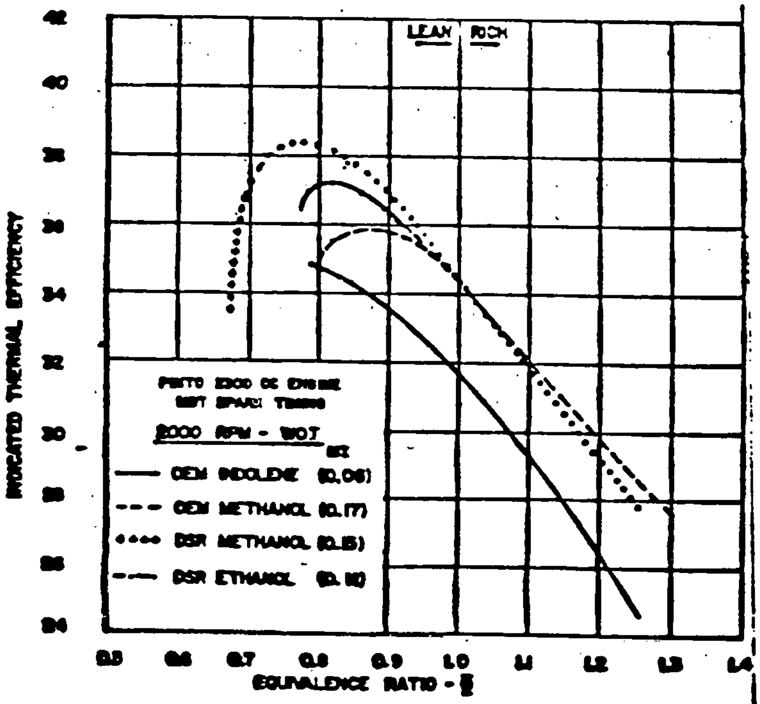
PRIME FUEL CHARACTERISTICS

	Gasoline	Methanol	Ethanol
Energy Btu/ Gal (LHV)	115.400 (Avg)	56.560	75.670
Octane			
Ron	91-105	106-112	106-111
Pump	87-98	99-102	98-102
Stoichiometric A/F	14.55	6.46	9.0
Boiling Point °F	80-440	149	173
Vapor Pressure PSIA	7-15	4.6	2.5

The following figures consolidate the results of the University of Santa Clara of Ford Pinto Engine comparatively operated on gasoline (indolene methanol, and ethanol).



EFFECTS OF ALCOHOL FUELS ON ENGINE PERFORMANCE AND EMISSIONS



COMPARATIVE WOT THERMAL EFFICIENCY AT 2000 RPM FOR ETHANOL, METHANOL, AND INDOLENE

Operative Characteristics

The subject of alcohol fuel is a popular one and raises lots of questions. We're briefly going to cover these aspects: the what, why, and when of alternatives; the nature and influences of alcohols on performance; the problems and solutions using alcohol fuels.

First of all, alcohols can be used straight or in a blend, and this pertains to both methanol and ethanol. The Table shows the prime characteristics of gasoline and the major alcohols that we think of: methanol and ethanol. Some of the major fuel engine considerations shown relate to certain kinds of problems that we have.

On an energy basis, for an equal volume, methanol has about half the energy that gasoline has. Ethanol has about two-thirds of that of gasoline.

From an applications point of view, this means that we need to put more fuel into our engine with alcohol than with gasoline. Alcohols have high octane numbers and this can be very helpful. This is the basis for our being able to use engines with higher compression ratios and, therefore, higher efficiencies. On a systems basis, this is rather important. If you go to straight alcohols, you can improve the efficiency of the engine above and beyond that which you have with gasoline.

Also, of course, alcohols can serve as an octane booster, and this is helpful to us because it might possibly be a solution to lead, MMT, and things of this sort.

When we burn these fuels, the ratio of the air to the fuel is different with the alcohols than with gasoline, because you have some oxygen in the alcohols. And so, in addition to having to meter a different amount of fuel into the engine, we also have to handle air in proportion to it in a different manner, which gets us back into the management system of our engine.

The next two points, boiling point and vapor pressure, combine in a sense, in that there are some combination portions that relate to starting problems. On the latter item, the vapor pressure of the alcohols is lower, but there is an anomaly there. When alcohol is added to gasoline, you get a disproportionate increase in vapor pressure. And this gives us potential vapor lock problems.

Other effects of alcohol fuels:

. We need more heat to vaporize alcohols, and this gives us some problems as far as cold starting is concerned.

. Alcohols burn cooler. Here's a place where we get some advantages. As a result, we can get a greater charge into our cylinder and, get more power. The formation of oxides of nitrogents (NO_x) is very heavily temperature-dependent. And since the alcohols burn cooler, we automatically get lower combustion and lower NO_x.

. Another feature that gets us into some of the fine points is that we can burn leaner. There are some problems because alcohols react differently with some materials than gasoline does. Present systems are designed for gasoline; they are not designed for alcohol.

. Also, a gasoline-alcohol-water combination gives us problems. We will touch on all of these things in a little more depth.

Use of straight alcohols involves modifying the fuel management system to provide a greater fuel flow and to operate in which we term a desirable air-to-fuel regime. We also must change the materials in at least the fuel supply system and possibly in the engine system. It's highly desirable to increase the compression ratio to give the added power and efficiency which is permitted by the higher octane that is available from the alcohols.

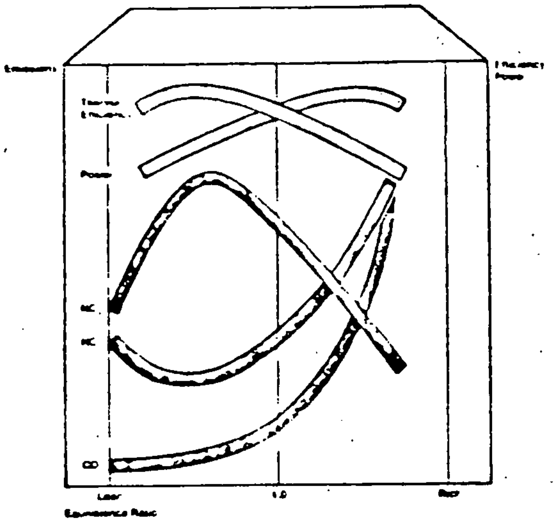
Fuel management is important to the use of any fuel, so let's lay some groundwork. Figure A shows the influence of the fuel-to-air ratio for any fuel. If the chemically correct ratio between fuel and air exists to completely burn all the fuel, the so-called "equivalence ratio" is unity. The center of the graph is the general region of operation of gasoline-powered engines.

Now, you can see what happens to the various characteristics as you shift to the rich fuel side or what happens if you go to the lean fuel side. If one could go far enough in the lean direction, without too great a loss in power, the emission problem would not be as severe. If you go a little bit lean, the NO_x keeps going up. But once you get over the hump of that, it starts coming down and all of the emissions are coming down. However, as the mixture is made leaner, the misfire limit is approached and performance suffers. As we approach this limit, the fuel doesn't burn completely. The hydrocarbon emission starts going up. The thermal efficiency comes down. The power continues to come down.

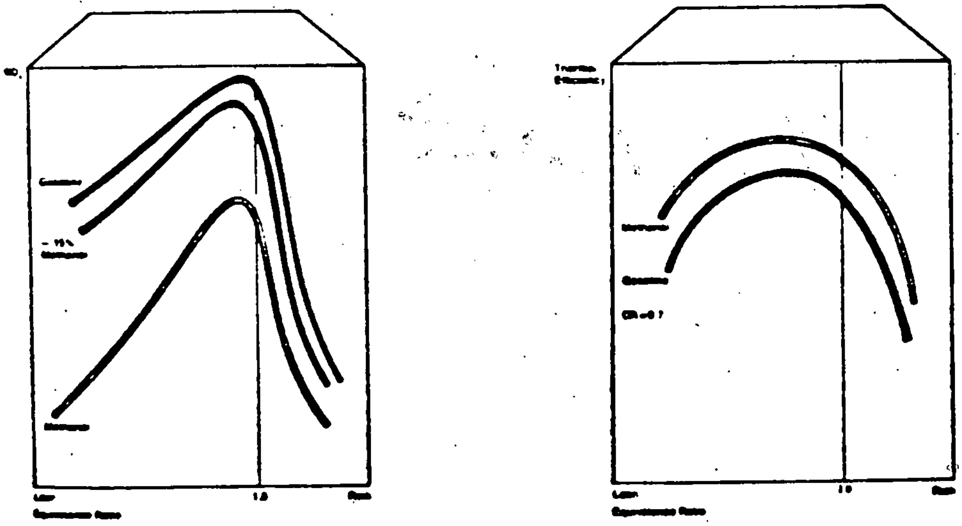
One of the benefits of the alcohol fuels is that they burn leaner than gasoline burns. And so we can push further out into the lean regime if we use straight alcohol.

When an engine is set for gasoline, it operated, say, at an equivalence ratio of one, as represented by a vertical line right through the center of the chart.

Figure A
FUEL-TO-AIR RATIO FOR ANY FUEL



FUEL-TO-AIR RATIO FOR GASOLINE, METHANOL, AND BLENDS



Blank

Now let's change the fuel to an alcohol-gasoline blend. The alcohol has oxygen in it, and we automatically lean out the mixture, so that the operating line moves over to the lean side. As a result, you are going to find differences in the performance of the vehicle, as shown by these curves.

Now, one item that is now shown is that of aldehyde emission. Aldehydes are part of the hydrocarbons, and they are only a small part of it. However, they are chemically reactive and they are responsible for the eye irritation that you get from smog. With straight alcohols, aldehyde emissions are four to ten times as great as they are with gasoline. The level is still very low and your exhaust catalysts reduce them even further so we do not feel that they are a problem. But certainly they are something that we have to face up as part of our considerations.

Due to lower combustion temperatures, the use of methanol reduces NO_x by a third to a half of that obtained with gasoline. The cooling effect of methanol also provides a greater density change, so that power is increased. And the lower combustion temperature means less lost heat so the thermal efficiency increases. As you can see from the curve on the right, we get something in the neighborhood of eight to ten percent better thermal efficiency with the methanol.

Now, another of the problems that we have with straight alcohols is cold starting. Straight methanol will not start at below about 15 degrees centigrade. It just doesn't vaporize sufficiently to do so. The addition of other hydrocarbons will help start at lower temperatures.

About 5 percent pentane in the methanol will permit starting at about minus 10 degrees centigrade. And about 8 percent of it will achieve starting at about minus 30 degrees centigrade.

The addition of about 12 percent gasoline to methanol will provide starting at minus 10 degrees centigrade. And 30 percent gasoline drops this down to about minus 30 degrees centigrade. Also we can mix the two of them together, so we can have combinations of these. And so we do have fuels solutions to cold starting when we use straight alcohols.

Gasohol and Blended Fossil Fuels and Alcohols

If we use alcohol-gasoline blends, present engine designs in principle are suitable. Minor changes or adjustments can accommodate a switch to the blends, although it is essential that we do the same thing with an ethanol blend.

One of the benefits of the alcohol fuels is that they burn leaner than gasoline burns. And so we can push further out into the lean regime if we use straight alcohol.

When an engine is set for gasoline, it operated, say at an equivalence ratio of one, as represented by a vertical line right through the center of the chart.

Now let's change the fuel to an alcohol-gasoline blend. The alcohol has oxygen in it, and we automatically lean out the mixture, so that the operating line moves over the lean side. As a result, you are going to find differences in the performance of the vehicle, as shown by these curves.

Due to lower combustion temperatures, the use of methanol reduces NO_x by a third to a half of that obtained with gasoline. Now, if we use a blend, the reduction is roughly proportional to the blend percentage. So, if you have a 10 percent alcohol blend, you only move that NO_x curve down 10 percent of the difference. And that is still in the noise level, as far as measurements are concerned.

So even though people talk about getting lower emissions with alcohol blends, so far as NO_x is concerned, the change is really in the noise level.

Figure 3
VAPOR PRESSURE EFFECT

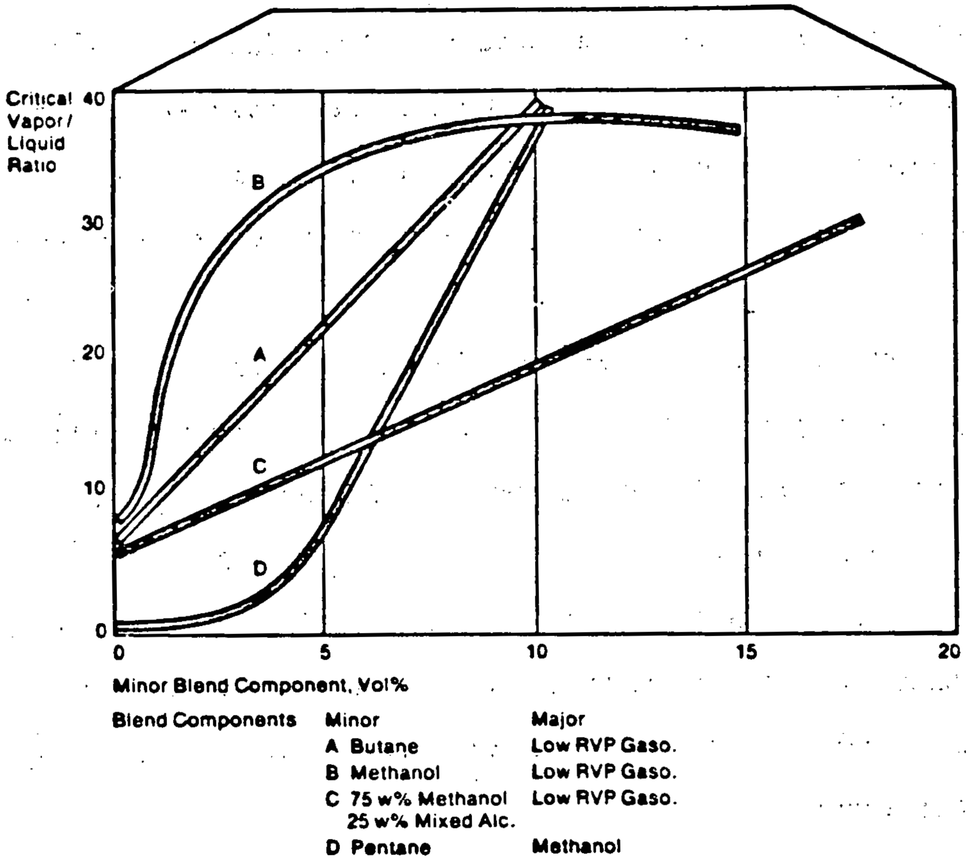


Figure B looks at some other problems. Vapor pressure is of great concern to us. This is the effect when the gasoline heats up and some of the liquid changes to vapor. Your fuel pump can't pump as much fuel and, as a result, you don't get the proper fuel flow, so your car stalls. It may even stop completely. There's been a lot of work done on correcting this. The "critical vapor-liquid ratio" of Curve B shows that the addition of a little methanol to the gasoline increases the vapor pressure a great deal. And this rather dramatic change is the thing that gives trouble.

Now ethanol is not as marked in this regard. Here's one of the cases where it's better. Its effect on vapor pressure is only about a third as much as that obtained with methanol. Curve A shows the influence of butane which is used in our gasolines. And it also has a marked effect.

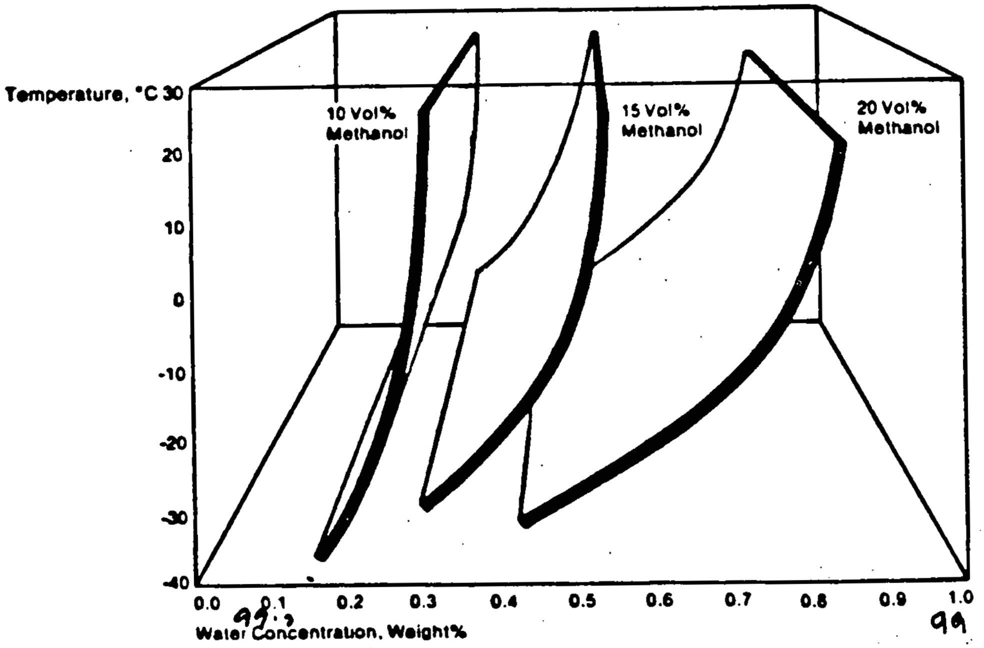
However, Curve C shows an interesting aspect. In the graph, the percentage of blend goes across the bottom. Curve C represents the result with addition of alcohol where three-quarters of it is methanol, and the other quarter is mixed alcohols of a little higher order. Now the increase in vapor pressure is not anywhere near as great and, indeed, offers an opportunity to manage this particular problem.

There's a Curve D which applies to the use of straight methanol, where we might want to add some pentane into gasoline to help us with cold starting problems but that I'll get to in a little bit. And it shows, in essence, that we can add a pretty fair amount of pentane to the gasoline before the vapor-liquid ratio increases to the point of concern.

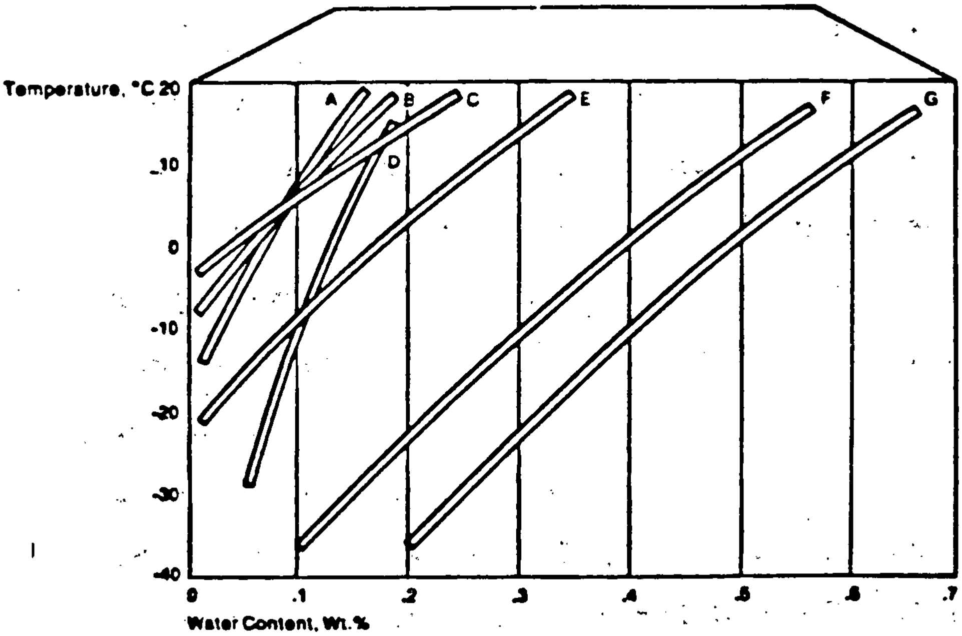
Now, to put this into perspective. Today's automobiles and fuels are designed so that the critical vapor-liquid ratio is about 15.

Figure C shows the sensitivity to water of various blend levels of methanol in gasoline. If we put methanol in gasoline and include some water, at some lower temperature the methanol and gasoline separate. And as you can see from these curves, it's a very, very complex type of situation. Now, the problem stems from the fact that the alcohol has less energy than an equal amount of gasoline. And this so-called "phase separation" when we operate the vehicle, we wind up feeding alcohol into the engine when it's adjusted for gasoline, so we're going to get a stall, hesitation, or power fade. The curves for ethanol are similar to this. Ethanol will handle water a little better, so the curves are not so severe.

SENSITIVITY TO WATER OF METHANOL/GASOLINE BLENDS



AMOUNT OF WATER TOLERATED IN BLENDS



	Alcohol in Blend V%	Cosolvent in Alcohol Wt.%	Gasoline Aromatics V%
A	10	0	26
B	15	0	26
C	20	0	26
D	10	20	26
E	20	20	14
F	20	20	26
G	20	20	38

In Figure 44 we have some of the same kind of curves, together with those showing some potential solutions. This graph shows the amount of water that can be tolerated in a blend. Curves A, B, and C were the type that I just showed.

Now, if you look at Curve A and at Curve D, they show that use of a selected co-solvent accommodates appreciably more water in the blend at a set temperature, or put another way, reduces the temperature at which separation will occur for any given amount of water.

Curves E,F, and G are data taken with the same percentage of cosolvent in each, but with difference in the aromatic content of the gasoline. So this water situation is very, very complex. The bottom line is that if we're going to go to commercial fuels, we have to formulate those fuels just like we formulate gasolines; we have to adjust formulations with climatic corrections, geographic location, and seasons. We are not under any set of circumstances going to just dump alcohol into gasoline and expect it to work to the degree that we would like to have it.

MATERIALS INCOMPATIBILITY

Alcohol Attacks:

- Zinc
- Terne Alloy
- Aluminum
- Magnesium
- Polyester-Bonded Fiberglass

Alcohols Causes Shrinkage or Swelling

- Cork Gasket
- Leather
- Viton
- Polyurethane

Alcohols does attack various metals. It also attacks polyester-bonded fiberglass, and that's pretty important because it's used in some gas tanks and it's used in all kinds of underground storage tanks in the fuel distribution system. Methanol also causes a shrinkage or a swelling invarious plastics and leather, and so on and so forth. And similarly, ethanol is a solvent for some plastics, including some of those that are used in the fuel system. And, as a result, we do have to make vehicle changes.

Now, there's nothing magic about this. It's straightforward engineering. It can be done, but it isn't being done now because we're building automobiles to run on gasoline.

DRIVEABILITY

Carburetion Deterioration
Volatility, Leaning, Combination
Fuel Injection Unaffected
Aldehydes Minimized

Driveability is, of course, the bottom line. All other things being equal, for vehicles with carburetion, deterioration occurs due to the volatility, to the leaning effect, and to the combination thereof. Now, it is found that problems with driveability are essentially accommodated totally by retuning the engine. So there is a combination of things that happen, but in essence, they happen because we run leaner.

For vehicles with fuel injection and a three-way catalyst, the so-called "Lambda System," in Volvo's California cars driveability is unaffected. Also aldehydes are minimized, and perhaps even eliminated.

TOXICOLOGICAL ASPECTS OF ALCOHOL FUEL UTILIZATION

COMPARATIVE TOXICITIES

In any consideration of methanol as a replacement fuel for gasoline, some assessment of its toxicity relative to gasoline must be made. Concern has been expressed about the fuel use of methyl alcohol, as it has resulted in blindness and death on oral ingestion and serious effects following topical exposure and inhalation. Any product containing more than 4% methanol is required to carry the 'skull and cross-bones' poison insignia. It has been suggested that if methanol is added to gasoline, the resultant fuel would require such labelling.

Many methanol-containing products have been available over the years.

1. 'Sterno' - for many years contained up to 50% methyl hydrate
2. Automobile radiator antifreeze - until supplanted by ethylene glycol
3. Windshield washer antifreeze
4. Model airplane fuel
5. Denatured alcohol preparations

Grain alcohol, variously denatured with methyl alcohol, has been widely available for topical use, without obvious complications attributed specifically to cutaneous exposure.

Therefore, in any relative assessment of the toxicities of methanol and gasoline, one must weigh differing circumstances. Present label warnings for methanol are based on the fact that these products are commonly in our home and certain segments of the population are prone to drink anything labelled 'alcohol'. Gasoline is not so labelled, not because it is less toxic, but because it is altogether too hazardous to keep in the house and except for the bizarre and growing practice of gasoline 'sniffing', people are not tempted to use it pharmacologically. The very serious explosion hazard associated with gasoline is well known. Methanol does not present the same explosion liability and in case of fire or spill, is much more readily contained with almost universally available water.

Injuries and fatalities related to methanol have been reported on exposure to higher concentrations, almost always in closed spaces. Exposure to 800-1000 ppm for 4 hours has been reported to produce headache, as has exposure to 300 ppm associated with the use of duplicating machine fluid. A fatal case has been reported following exposure to 4-13,000 ppm for 12 hours. Dogs exposed to 450-500 ppm for 379 days were without toxicity. Generally, industrial exposure is conceded as safe if the concentration does not exceed 200 ppm.

Clinical signs of acute toxicity relate to mucous membrane irritation, headache, roaring in the ears, nervousness, trembling, nausea and vomiting. Numerous deaths have been reported following the oral ingestion of methyl alcohol. 'Epidemics' or clusters of deaths have usually occurred following a change in the source of 'moonshine' or other non-regulated alcoholic beverage.

Alcohol containing methanol as a denaturing agent was used for many years as a rubbing compound. It is, however, generally conceded that toxic levels can only be attained in man by inhalation or gastrointestinal absorption. Only under exceptional conditions can toxic percutaneous absorption be demonstrated in animals.

The pharmacologic and toxic properties of ethanol are too well documented to repeat. It should be remembered that ethanol has been used intravenously in man, to produce anaesthesia and while responsible for much social misery, is considered to be less toxic than methanol on chronic administration. Workers in biological product plants, such as insulin and blood fraction facilities, have been exposed to relatively high concentrations of ethanol fumes, on a chronic basis and without serious long-term effect. A recent report from Sweden has indicated that chronic use of alcohol can possibly result in direct bone marrow toxicity - even in the absence of liver disease.

Gasoline is a most extensively used hydrocarbon and being a mixture, no single toxic level can be clearly defined. The Threshold Limit Value is described as 500 ppm, but this will depend on benzene and other aromatic content.

Acute exposure results in mucous membrane, central nervous system and gastrointestinal side effects. A recent report of gasoline 'sniffing' illustrates the type of hazard that can be associated with the handling or misuse of such products. Of a group of Indian children that had misused gasoline for some years, two were burned to death through careless handling, two developed serious mental problems related to the gasoline sniffing and two developed organic lead poisoning as a complication of their 'gasoline addiction'

Massive exposure to gasoline can result in sudden collapse, coma and death with tissue changes characteristic of a lipophilic solvent. Severe acute exposure results in convulsions and tremors. In most cases, the patients recover. Repeated exposure at relatively low concentration is usually without effect. However, exposure to 2000 ppm is reported as unsafe for man for even a brief period and prolonged exposure at levels greater than 300 ppm should not be allowed.

Gasoline is a primary skin irritant and the topical use of gasoline blends containing benzene or toluene are especially hazardous. Two cases of bone marrow toxicity have recently been reported and specifically relate to the use of benzene containing fuel. With the increased availability and more widespread use of unleaded gasolines, bone marrow toxicity must be anticipated more frequently. Recent hearings on a proposed benzene standard in the United States, considered a retrospective report on the possible occurrence of acute leukemia among industrial workers exposed to the agent.

High solubility of methanol makes its mechanical removal from environmental systems more difficult. However, the lower alcohols are plant growth stimulants and their water solubility facilitates dispersion, dilution and biodegradation.

Fire and explosion hazards associated with the use of methanol and methanol gasoline blends should be studied further. Flash-point and ignition temperatures must be determined for each proposed mixture. Because alcohol fires are 'clean' and therefore difficult to see, consideration should be given to the use of appropriate additives to enhance visibility. With regard to ethanol, new and better methods should be devised to reduce palatability.

The more commonly used gasoline engine emission monitoring devices will require re-design if unburned alcohol forms a large part of the hydrocarbon exhaust. Additional sampling techniques will be required to monitor aldehydes.

Because environmental exposure to alcohol, whether methanol or ethanol, will substantially increase, synergistic effects with commonly used drugs must be studied carefully.

CONCLUSIONS

All available information to date indicates that the biomedical and environmental issues associated with the use of alcohol fuels are not critical - in fact, the relative impact is clearly less than that for gasoline.

For the internal combustion engine, it is obvious that alcohol fuels can be part of the short-term solution when blended with gasoline and the basis for a longer-term solution when used alone as the alternative fuel. Full benefits of neat alcohol will only accrue with re-design of the engine for use of alcohol-water mixtures--where their superior lean combustion characteristics will allow for more efficient operation, with extremely low emissions.

Alcohols provide a certain flexibility offered by no other fuels. Whether produced from urban garbage or agricultural wastes, low grade coal or remote natural gas, they can fire a boiler, drive a 'rabbit', fuel gas-turbines or be regasified to meet emergency pipe-line requirements - in addition to facilitating interpersonal communication, nurturing single cell protein and powering fuel cells.

As in the historic context, 'wood alcohol' bridged the gap between a wood fuel economy and the modern petroleum era, so methanol may now provide that clean liquid bridge between fossil fuels and a renewable resource-based/ultimate electrical economy. A combination of escalating world market prices for gas and oil and rapidly dwindling reserves make it essential that we examine the 'alcohol option' as an interim alternative. And accurate quantification of the biomedical and environmental impact is an essential part of this examination.

PART THREE

Compilation of Crossreferences on the State-of-the-Art on Handling and Combustion of Fuels in Internal Combustion Engines and Presentation of Basic Evaluations of Events Leading to the Use of Alcohols as Motor Fuels.

Overview of Today's Applications of Alcohols as Motor Fuels.

The Formulation of Alcohol Fuels for the Engines and the Modification of the Engine and Fuel Handling Hardware for Using the Alcohol Fuels.

Introduction to Multifuel Engines Concept, Today's Approaches, Their Practical Results and Expectations.

PART THREE

TABLE OF CONTENTS

PAGE

A-11* CHAPTER I

USE OF ALCOHOL AS A MOTOR FUEL

CHAPTER II

DESCRIPTIVE SUMMARY OF THE INTERNAL COMBUSTION ENGINES - SPARK IGNITION (SI) AND COMPRESSION-IGNITION (CI)

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* Denotes source document - see Bibliography

PART THREE - continued

PAGE

CHAPTER III
FUEL METERING IN THE SI AND CI ENGINES

CHAPTER IV
ENGINE CONVERSION FOR ALCOHOL FUELS

CHAPTER I. USE OF ALCOHOL AS A MOTOR FUEL

INFORMATION REVIEW

The first serious attempt to examine the possibility of alcohol as a fuel in competition with petroleum seems to have been made in 1894 at Leipzig, Germany, by Professor Hartman for the Deutschen Landwirtschafts Gessellschaft. German alcohol distillers, seeking to enlarge their market, succeeded in interesting the German Government. They pointed at the significance of having available a source of fuel for power, production within the nation from yearly crops, while the supply of crude oil may ultimately become exhausted.

By Acts of U.S. Congress for June 7, 1906, and March 2, 1907, denatured ethanol became exempt from internal revenue taxation when used in the industries. The U.S. Department of Agriculture in 1907 published Farmer's Bulletin No. 277, "The Use of Alcohol and Gasoline in Farm Engines" by Charles Edward Lucke and S.M. Woodward.

In 1909 the United States Geological Survey published a bulletin, No. 392, called "Commercial Deductions from Comparisons of Gasoline and Alcohol Tests on Internal Combustion Engines." This thirty-eight page bulletin by Robert M. Strong is the result of careful observation of 2,000 tests conducted at St. Louis, Missouri, and Norfolk Virginia. The tests were under technical supervision of R.H. Fernald, engineer in charge of the producer-gas section of the technological branch.

No Shortage of Fuel

In an interview in 1929 with M.K. Wisehart, author of "The Marvels of Science," Henry Ford predicted no shortage of fuel for internal combustion engines of the future. "We can get fuel from fruit," Ford said, "from that sumach by the roadside, or from apples, weeds, sawdust almost anything. There is fuel in every bit of vegetable matter that can be fermented. There is enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the field for a hundred years."

"And it remains for someone to find how the fuel can be produced commercially better at a cheaper price than that we now know!"

On May 7 and 8, 1935, Ford hosted the Dearborn Conference of Agriculture, Industry and Science at his famous airport hotel, the Dearborn Inn. A major topic of the proceedings was the production and use of alcohol as motor fuel. He did this again May 12-14, 1936, and in September 1937. These meetings led to the organization of the farm Chemurgic Council and the first attempt to market an alcohol-gasoline blend in the United States. The blend sold under the trade name of "Agroll" at Atchison, Kansas, where a plant opened for that purpose October 1st, 1936. Dr. Leo M. Christensen was instrumental in this effort.

At about the same time Cleveland Petroleum Products Co., was selling an alcohol-gasoline blend in Britain called "Cleveland Discol."

Truck and Tractor Running on Alcohol

At this time Koppel (Phillippines) Incorporated claimed that they had 82 Plymouth Alcohol Locomotives in operation and under order for operation in the Philippine Islands. International Harvester Co. of the Philippines was selling motor trucks powered with engines especially designed to burn Philippine alcohol. Sugar cane in Manila was delivered in Studebaker trucks built to use alcohol instead of gasoline. In 1933 this was to save the sugar planter 45% on fuel costs. Baldwin Locomotive Works and General Motors also offered the alcohol burning option.

April 28, 1936, Harry J. Woolson, Chrysler Corporation engineer, said that Detroit-made automobiles equipped for using alcohol are being shipped to New Zealand. The only changes required, he said, are a different carburetor jet and the use of more heat on the mainfold.

Alcohol as motor fuel has the unique quality of having a practically unlimited potential market, and it can be made from so many raw materials. As such, any study of the subject is entering into an enormous jungle of competing economic, political, and ideological interest groups.

American Petroleum Institute published in July 1976 a thirty-two page report called "Alcohol, a Technical Assessment of their Application as Fuels." No better reference can be found to magnify every smallest limitation of alcohol as motor fuel.

The Use of Alcohol as Fuel in the Past

Brazilian history has shown that attempts to introduce ethanol as fuel have been made for a considerable time.

We have reports available on research and the use of ethanol as early as in the 20's. Already in 1923 automobiles with pure-ethanol-powered engines were used to travel from Rio de Janiero to Sao Paulo (430 Km) and from Rio to Petropolis.

A pioneering group of sugar-cane planation owners in the state of Pernambuco can be credited for having made a significant step toward the broad application of alcohol as fuel. These people formed an alcohol-engine cooperative in 1927. The product was named AXULINA and was successfully put on the market. It was a carbon compound based on a alcohol. The composition was as follows:

85% alcohol purified to 90%
10% ethyl ether
5% gasoline.

ALCOHOL AS AN ALTERNATIVE FUEL

Alcohol as motor fuel was studied very carefully by the Society of Automobile Engineers of Paris, France, in a series of lectures starting on November 10, 1942.

For many years, in France, alcohol (ethanol) was mixed with gasoline to get rid of surplus alcohol production and, thus maintain price stability in the beverage market. Gasoline alcohol blends were found to be less than satisfactory because water tended to contaminate the mixture causing separation. Also, some ions found in denaturing agents and in poor quality gasolines would react with water of the alcohol to form corrosive chemicals.

Most automotive engines today were never designed to use straight alcohol as fuel and, therefore, they can't be. expected to run on alcohol efficiently. The properties of alcohol are completely different from those of gasoline and there are difficulties mixing the two. Pure ethanol and methanol, as well as other alcohols and alcohol derivatives, mix well with each other and with water.

The Brandt System

The National Experiment Station at Bellevue, France, in September of 1941, tested a four-cylinder internal combustion engine modified to burn straight alcohol according to what is called the Brandt System. Compression ratio of the engine was twelve to one. The ethanol fuel was injected at high pressure directly into the cylinders using a lubricated fuel pump and specially lubricated injectors. The alcohol was thus mechanically pulverized into a fine mist which evaporated instantly in the cylinder as it absorbed the heat developed in the compression stroke of the engine. An ordinary spark plug was then used to ignite the air fuel mixture.

Fuel consumption using ethanol in the above engine was 94% of what it had been when using gasoline before the conversion. It had been a carburetor type engine with a compression ratio of 5.65 to 1. After the Brandt conversion, available power was increased by 18%, using neat ethanol, although the fuel consumption by volume was lower.

Methanol in this engine gave the highest thermal efficiency at 45.5%. Ethanol yielded a very respectable thermal efficiency of 42%.

Within limits, the power and efficiency were not affected by water content of the alcohol, only the fuel consumption varied inversely with the energy content of the fuel.

Exhaust temperature was reduced by 150 degrees C, using ethanol, and by 200 degrees C with methanol as compared to gasoline operation.

Diesel engines are the easiest to convert to the Brandt System because all engine components are already designed for a high compression ratio. The experimental results from Bellevue were verified by road tests of a converted diesel truck. Over the same route, with the same load, the truck used 24 litres of diesel oil in 100 kilometers compared to 32 liters of ethanol. Note that here is not a comparison with gasoline. The energy content of the fuels used is different by nearly 100%.

"ALCOHOLS-A TECHNICAL ASSESSMENT OF THEIR APPLICATION AS FUELS"

American Petroleum Institute

SUMMARY AND CONCLUSIONS

In the search for an independent energy base for transportation in the United States, alcohols are being proposed as fuels to supplement domestic oil and natural gas supplies.

In today's economy, synthetic fuels, including alcohols, would be considerably more expensive than petroleum fuels. This differential is expected to remain as long as petroleum is generally available. Longer term, if synthetic fuels were to become cheaper than petroleum, alcohols should have to compete against hydrocarbon liquids from coal and shale, both in cost and in raw material utilization. Should alcohols become competitive, their best use at the start would appear to be as gas turbine fuels forland-based peak power generation, and in other premium fuel applications, where their clean-burning and low nitrogen oxide formation characteristics can be used advantageously. Following this, their use in automobiles could be considered. Here the use of straight alcohols in appropriately modified engines would be preferable to the use of alcohol-gasoline blends.

The chemical and physical properties of alcohols, particularly those of methanol and ethanol, differ considerably from those of conventional hydrocarbon fuels. Energy contents of alcohols per unit volume are substantially lower than those of hydrocarbons. Solubilities in most petroleum fuels are limited, the exception being in aromatic gasolines. Even here, only very small amounts of water cause the alcohol blend to separate into two phases. Alcohol-gasoline blends also exhibit disproportionately high vapor pressures which, if not corrected, would greatly increase the risk of vapor lock in automobiles.

Alcohols also differ from petroleum fuels in corrosivity towards metals, compatibility with plastics and rubbers, toxicological properties and fire hazards. Their application as fuels would therefore require the use of different materials in fuel handling systems, and at least a comprehensive review, if not an extensive revision, of current safety codes.

If the levels of performance and reliability currently expected of petroleum fuels are to be ensured, alcohols - either straight or in blends - cannot be interchanged with gasoline in conventional vehicles without costly modifications to both vehicles and fuel distribution systems. Moreover, with prices of methanol and ethanol substantially higher than those of gasoline, there exists no economic incentive to make these modifications.

Straight Alcohols as Automotive Fuels

If used to fuel vehicles specifically designed for optimum use their properties, straight alcohols offer potential advantages that could outweigh disadvantages in cern situations. As example might be a large fleet, where both vehicles and fuel distribution facilities could be justified by the local supply pattern of raw materials and energy. In this case, performance relative to gasoline compares as follows:

o Thermal efficiency economy. Thermal efficiency is potentially better with alcohols because they have more favorable thermochemical properties, can be burned leaner, and can operate at higher useful compression ratios. However, to the general public, the most evident difference would be significantly fewer miles per gallon, which is a direct result of the lower energy contents of the alcohols. Methanol has about half the energy content per unit volume of gasoline, and ethanol about two-thirds.

o Exhaust emissions of hydrocarbons (or unburned fuel) and of carbon monoxide are practically the same when methanol and gasoline are compared at the same relative mixture strength (equivalence ratio). Aldehyde emissions are higher with methanol. Emissions of nitrogen oxides are generally lower with methanol, especially at very lean mixtures where operation without misfire would not be practical with gasoline. However, with these lean mixtures, the other emissions would not be low enough to meet projected emission standards without emission controls like those required with gasoline.

o Driveability, except for starting quality, has not received sufficient attention to date. Starting methanol-fueled, carbureted engines below 50-60°F requires a special staring aid, such as a volatile additive in the fuel or an auxiliary volatile fuel. Even with aids, starting below 10-20°F is extremely difficult.

o Durability of some components of engines and fuel systems may be impaired with alcohols, especially with methanol Terneplate (a common fuel tank material), copper and brass show evidence of increased corrosion, and some plastics and rubbers show increased softening or swelling.

Supplying straight alcohols as automotive fuel would also require new and separate distribution systems designed to deal with the different materials compatibility and corrosion characteristics, the different fire, explosion, and health hazards encountered in handling and storing alcohols, and the necessity of preventing deliberate or accidental adulteration with water.

Alcohol-Gasoline Blends as Vehicle Fuels

Alcohol-gasoline blends have been seriously proposed for use only in conventional automobiles. Their characteristics in unmodified cars are predictable from the relatively leaner fuel-air mixtures they produce:

o Thermal efficiency/Fuel economy. Thermal efficiency increases somewhat, particularly in those cars with rich mixture calibrations (mainly pre-1968 models): however, fuel economy measured in miles per gallon generally decreases, approximately in proportion to the alcohol content of the blends. The offsetting improvements in thermal efficiency are of lesser magnitude than the reduce energy content of the blends.

o Exhaust emissions change to the same extent they would have changed using gasoline, were the carburetor adjusted to an equivalently leaner mixture strength. Hydrocarbon and carbon monoxide emissions are reduced somewhat (particularly in older cars originally set rich) but the improvement is not enough to obviate the need for emission controls With emission controls, alcohol offers no advantage in this regard NO_x emissions are not much different with alcohol blends, being somewhat higher for cars set rich and somewhat lower for cars set lean. Aldehyde emissions increase somewhat.

o Driveability suffers significantly, just as it would if gasoline alone were used with equivalently lean carburetion.

o Durability of fuel system components is impaired with alcohol-gasoline blends, although not as severely as with straight alcohols.

If cars were operated on alcohol-gasoline blends, the chief advantage would be a reduction in knock and after-running in those afflicted with these symptoms. The chief disadvantage would be (1) the risk of phase separation at winter temperatures, or if water contamination were present; (2) the corrosion or deterioration of sensitive fuel system parts; and (3) a directional deterioration in vehicle driveability, not only because of leaner operation, but also because of the higher vapor locking tendency of the blends.

Avoiding these problems would require (1) modifying fuel distribution systems to exclude water, (2) replacing sensitive fuel system materials, (3) re-calibration of engine fuel metering systems asneeded to offset the leaning effect and/or modifying engine fuel systems or reformulating base gasolines to avoid vapor locking and maintain driveability. In the case of methanol, reformulating the base gasoline would exclude from the gasoline pool a quantity of butane and pentanes about equal to the methanol added. Although these components could find a fuel use elsewhere, it would make more sense to find an alternative use for the methanol.

Fire, Explosion and Health Hazards

Handling requirements for alcohols are generally the same as those for gasoline except for two crucial differences.

o The alcohols have much wider flammability limits. As a result, their vapors in storage tanks, including vehicle tanks, are explosive at ambient temperatures while those of gasoline are too rich to ignite.

o Methanol, in addition to its generally known toxicity when ingested, presents an insidious health hazard in its ability to induce blindness when inhaled, or absorbed through the skin. For methanol-gasoline blends, the health hazards are such that under current law they would require the skull-and-crossbones label.

Conclusions

Short range, as indicated in the Preface, alcohols are too expensive to be considered for large-scale fuel use. Longer range, when synthetic fuels from coal, shale, wastes, or agricultural products become economically competitive with petroleum, the use of alcohols as fuels should be re-examined.

reexamined. The most attractive of such uses would be in land-based gas turbines, or as a straight fuel in automobile engines specially designed to take advantage of methanol's special properties. Use of alcohol-gasoline blends is the least attractive alternative because of the handling problems associated with them and because the potential advantages of straight alcohols are lost and not realized in blends.

CHAPTER V
DEVELOPING THE MULTIFUEL CAPABILITY OF THE INTERNAL COMBUSTION ENGINES

PART THREE - continued

CHAPTER VI
REFINING THE SCIENTIFIC ASSUMPTIONS OF THE INTERNAL COMBUSTION ENGINES TECHNOLOGY - THE BETA CYCLE

USE OF ALCOHOL FUEL

Ford Motor Company

In general, Ford Motor Company supports consideration of possible governmental actions which would provide incentives for the development of alternative energy sources. However, we would urge that such proposals provide sufficient flexibility to exploit whichever technology is most effective in meeting the overall energy goals of the country.

For example, we believe that equal consideration should be given to the use of any alcohol, be it methanol, ethanol, or other. Which alcohol should be favored is not yet known.

Similarly, if a governmental incentive is found desirable, it should apply equally to the direct use of alcohol and to the use of alcohol after conversion to gasoline. Recent reports indicate that alcohol can be converted to high quality gasoline efficiently and at low cost.

Any proposed incentives should apply equally to the use of alcohol produced from sources such as grain, sugar cane, and beets as well as to liquid fuels produced from cellulose and other materials present in agricultural and forestry wastes, and from any other currently unexploited source.

Finally, the incentives should apply equally to fuels produced from solar energy, both by the agricultural product route and by other means such as non-biological photochemical reactions.

This flexibility is essential in view of the unsolved problems and open issues connected with the prospective use of alcohols and alcohol-gasoline blends as automotive fuels, including, for instance:

- potential adverse impact on air quality;
- potential driveability problems;
- potential corrosion and other material compatibility problems.

As I stated in my opening remarks, although probably not insurmountable, these problems are sufficiently serious to demand careful consideration.

In closing, I express my support for the examination of possible means to encourage the production of liquid fuels from sources other than petroleum, but I urge you to broaden any legislative proposals so as to apply not only to Gasohol, but also to all other liquid fuels which could be made from abundant domestic resources.

PREPARED STATEMENT OF DR. SERGE GRATCH

Director, Chemical Sciences Laboratory
  Ford Motor Company

THE USE OF ALCOHOLS AS FUELS

(Excerpt General Motors Research Laboratories)
Joseph M. Colucci

Use of alcohol as fuel in automobiles is technically feasible although the result in the case of an alcohol gasoline blend would be some degradation in driveability.

There are two forms of alcohols currently being considered as substitutes for gasoline: ethanol and methanol. They are distinct chemically but are both clear liquids that look and almost smell alike.

Ethanol, the alcohol in beverages, is produced by fermentation of grains, while methanol, the poisonous wood alcohol, is currently produced by a catalytic process from natural gas. Both can be produced from other feedstocks, such as coal, field and forest residues, etc. Ethanol is more soluble in gasoline than methanol. Both will freeze (but not at practical temperatures) and boil, but in each case methanol before ethanol. Both react in an automobile in much the same way, but the disadvantages when compared to gasoline are less with ethanol than with methanol, while the advantages are greater with methanol than with ethanol. (See Table on page 3.)

Development of a production and distribution system for alcohol fuels would take a large investment and long lead times. During this lead time period, any necessary vehicle modifications could be accomplished.

Automotive Use of the Alcohol Fuels

Clearly, alcohols could be used as an automotive fuel as a strategy to reduce petroleum consumption in the U.S. But questions of availability and usual priorities are of paramount importance.

General Motors testing of these fuels, primarily methanol, has indicated the following changes in cars that would be necessary if methanol were to be used as an automotive fuel:

1. To operate on 100% methanol.

Cars currently on the road cannot operate with 100% methanol. Methanol is more corrosive than gasoline, and specially formulated plastic, rubber and metal linings would have to be developed for use in the fuel system to resist chemical attack by alcohol fuels. For example, the thin lead alloy coating that lines all metal gasoline tanks is readily corroded by methanol. For practical purposes, this means that retrofit of used cars to operate on pure methanol is not practical.

Obtaining satisfactory driveability on 100% methanol for new cars would require significant engine modifications, but these problems appear solvable through design changes on cars to be built in the future, as indicated below:

Performance Characteristics of Methanol Use as an Automotive Fuel

A table showing the advantages/disadvantages of using a blend of pure methanol follows. The basis for comparison is today's commercial unleaded gasoline.

A. Emissions	90/10% Gasoline Methanol (no change to carburetor)	Pure Methanol (redesigned car)
1. MC	about the same	considerably less
2. CO	decrease	about the same
3. MO_2	slight decrease	considerably less*
4. aldehydes**	slight increase	great increase
5. unburned methanol**	increase	great increase
6. evaporative	may increase	may decrease
B. Fuel Economy		
1. Volume Basis (miles per gallon)	slight decrease	about 50% less
2. Energy Basis (miles per Btu)	about the same	slight increase
C. Driveability		
1. hesitation, stumble, surge	worse	about the same
2. vapor loss	potential problem	no problem

---

* Could meet .4 g/m NO_x standard without converter. Much higher aldehyde and methanol emissions could be controlled through simpler oxidation catalyst.

** These emissions are not now regulated. This may be partly due to the fact that the volume of these pollutants presently emitted is negligible.

3. cold start	no problem	problem-probably can be eliminated with hardware or fuel modifications
D. <u>Corrosion</u>		no problem
E. <u>Fuel Separation</u>		no problem

F. <u>As a Fuel for Alternate Power Plants</u>

1. <u>diesels</u>: it is not a good fuel for diesels

2. <u>gas turbine</u>: it is an excellent fuel for automotive and other gas turbines.

3. <u>To operate on 100% ethanol</u>

Modification of fuel system needed to permit operation on 100% ethanol would be approximately the same as those graphically presented for use of pure methanol. The operating characteristics of pure ethanol when compared with unleaded gasoline are also approximately the same as those represented for pure methanol in the table above; however, the magnitude of advantages and disadvantages in general will be slightly less.

4. <u>To operate on a blend of 90% gasoline, 10% methanol</u>.

Some of the same type of new car modifications required for use of 100% methanol would be desirable for use of the 90%/10% blend. However, very little retrofit would be absolutely required in used cars if owners would be willing to overlook the gradual corrosive attack on the fuel system parts and some degradation in performance. To retain approximately the same performance, the carburetor jets would have to be changed, costing about $25 to $75.

5. <u>To operate on a blend of 90% gasoline, 10% ethanol</u>.

Use of ethanol as a 90%/10% blended fuel would create the same driveability problems, including vapor lock, as are true to methanol as a blend, but again, to lesser degree. This is also true with fuel separation problems, where the use of ethanol would present fewer problems than with methanol.

Methanol-Gasoline Blends

GM researchers ran tests with a fleet of 14 employe-owned cars ranging from 1966 to 1974 model years. All of the cars had been driven in normal service. The fuel was a blend of 10% methanol in unleaded gasoline. This proportion of methanol is most practical—less doesn't save enough gasoline, more involves driveability problems.

DRIVEABILITY. Driveability was measured in terms of total weighted demerits (TWD). To arrive at these numbers, trained test drivers subjectively rated various operating difficulties, such as hesitation, stumble, surge, on a scale of 1 (trace) to 4 (heavy) demerits. Weighting factors were assigned to these difficulties; higher numbers for more serious problems. Then TWD were derived by multiplying the demerits by their weighting factors and totaling the results. So, the higher the TWD, the worse the driveability.

In studies of the test fleet, with 10% methanol added to the gasoline, demerits ranged from 427% more to 12% less and averaged 104% more than with pure gasoline. Reports Norman Brinkman, the associate senior research engineer who's been running GMR's car programs with methanol, "This poor driveability is a direct result of methanol's leaning effect."

By "leaning effect" Brinkman refers to the fact that, because oxygen accounts for about half the weight of a molecule of methanol (CH_3OH), adding methanol to gasoline essentially reduces the amount of fuel, increases the amount of oxygen, and makes the engine run leaner.

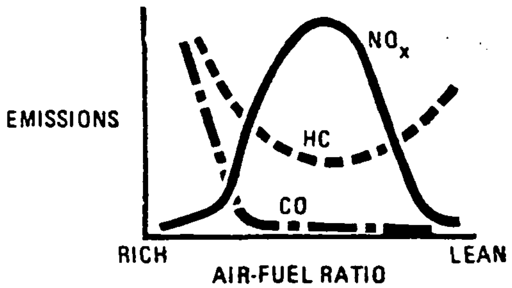
Vapor lock developed in some tests with the blend at high ambient temperatures. This is one of methanol's peculiarities. By itself it has a lower vapor pressure and higher heat of vaporization than gasoline. So, when you add it to gasoline, you'd expect it to lower the fuel's volatility. But the volatility of the blend goes up. Why? To simplify a complicated chemical story, methanol is polar, gasoline is nonpolar. Molecules of methanol, left alone, cling to each other with hydrogen bonds. This keeps them earthbound, reduces their volatility. Dilution in large volumes of gasoline spreads the molecules about and breaks these bonds, freeing the methanol to vaporize more readily and, when conditions are right, to cause vapor lock.

EMISSIONS. Hydrocarbon (HC) emissions from the methanol blend varied in the cars from an increase of 41% to a decrease of 26% in comparison with gasoline. The average change was a 1% increase. Adding methanol to gasoline decreased carbon monoxide (CO) emissions (in all but one car) an average of 38%. Nitrogen oxide (NO_x) emissions were scattered from a 20% increase to a 36% decrease, averaging an 8% decrease. Although several factors affect this emission picture, the primary one is methanol's leaning effect.

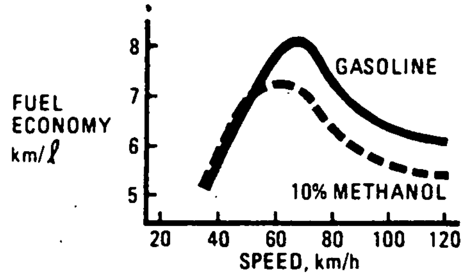
The simplified graph (see Graph I) of well-established trends of emissions vs air-fuel ratio helps explain the variation in emission results. Adding methanol to gasoline moves the air-fuel ratio to the right (in the leaner direction) on the curves. So, whether emissions increase or decrease depends primarily on the initial carburetion of the car.

FUEL ECONOMY. As you would predict from methanol's lower energy content (see box), adding it to gasoline generally reduces fuel economy when you consider it in volume terms (km/ℓ). In energy terms (km/million joules), however, methanol can increase fuel economy.

In tests run in an unmodified passenger car, GM researchers observed that constant speed, level road load, volume-based fuel economy was almost the same for both gasoline and 10% methanol-gasoline blends at 48 km/h (30 mph) and lower speeds. At higher speeds, fuel economy with the methanol blend was considerably less (see Graph II).



Graph I. Typical relationship between exhaust emissions and air-fuel ratio.



Graph II. Effect of adding 10 percent methanol to gasoline on level road load fuel economy (volume basis).

Fuel economy with the test fleet was measured on a chassis dynamometer. Using the 1975 Federal Test Procedure (FTP), the change in volume-based fuel economy from addition of methanol ranged from a 6% increase to a 9% decrease, averaging a 3% decrease. At steady speeds of 48 and 64 km/h, methanol addition to gasoline decreased volume-based fuel economy by 5% and 4%, respectively.

Pure Methanol Fuel

Before it can be fueled with straight (neat) methanol, the car will have to be modified (see cover diagram). And materials that come into contact with neat methanol must be corrosion resistant (see photograph). "We aren't really sure whether the corrosion we see is caused by the methanol or by the water inevitably associated with it," says Brinkman. "But it really doesn't matter, since we can't keep them apart."

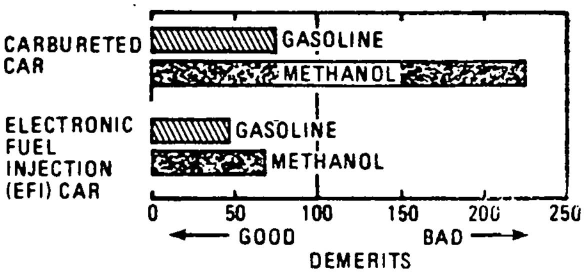
Brinkman has recently completed tests using two cars fueled with pure methanol. One car was a carbureted 1974 Chevelle; the other, a 1975 Oldsmobile Cutlass with an electronic fuel injection (EFI) system. Since about twice as much methanol as gasoline must reach the combustion chamber to provide the same energy, both the carbureted system and the EFI system had to be redesigned to provide higher flow rates with methanol.

DRIVEABILITY. "Driveability with the production Chevelle was totally unacceptable," reports Brinkman. "We had starting problems and poor warm-up performance; it stalled frequently and wouldn't respond when the throttle was depressed. Methanol's low vapor pressure and high heat of vaporization are part of the problem here," he explains. "It vaporizes very little and remains a liquid in the ordinary engine. So it is sluggish moving through the intake manifold and getting into the cylinders."

The answer? In part, redesign the engine to heat the intake manifold and intake air enough to give satisfactory vaporization. On an equal fuel energy basis, about nine times more heat is required to vaporize methanol than gasoline. These changes, plus use of a commercial aluminum intake manifold, improved warmed-up driveability of the Chevelle fueled with methanol to nearly equal that of a gasoline-fueled production car. Cold-start driveability, however, was still considerably worse than that of the gasoline-fueled car (see Graph III).

Driveability with the Cutlass was considerably better than with the Chevelle. The EFI system eliminates, in large part, the need to heat the fuel to vaporize it and move it through the manifolds.

Warmed-up driveability of the Cutlass was equivalent to that obtained with gasoline. But it, too, had a cold start problem. Neither vehicle could be started below about 7°C (45°F). This problem might be solved by either adding more volatile fuel components to the methanol, or adding a preheat system to the engine.

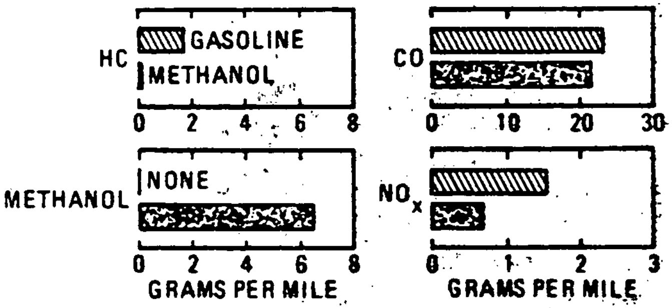


Graph III. Driveability – CRC Procedure. Includes cold start and warmed-up maneuvers.

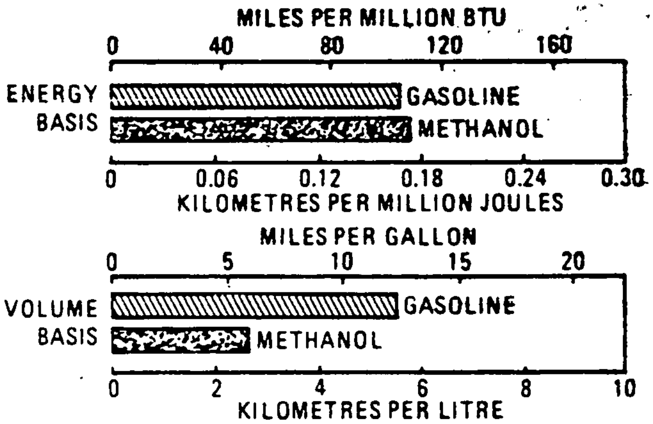
EMISSIONS. In the EFI-equipped Cutlass, exhaust NO_x and HC emissions from pure methanol were less than from gasoline (see Graph IV). But other organic emissions, mainly unburned methanol, were greatly increased.

Drs. Dave Hilden, senior research chemist, and Fred Parks, senior research engineer, ran emission tests with an unmodified single-cylinder CFR engine. They observed that unburned fuel emissions were four times greater with neat methanol than with gasoline. Methanol's low volatility was the problem here. When they modified the engine's intake system by heating the fuel mixture to improve vaporization, unburned fuel emissions were reduced 80 to 90% with methanol and 30 to 50% with straight gasoline. Aldehydes were significantly reduced, too, but were still three to four times greater with methanol.

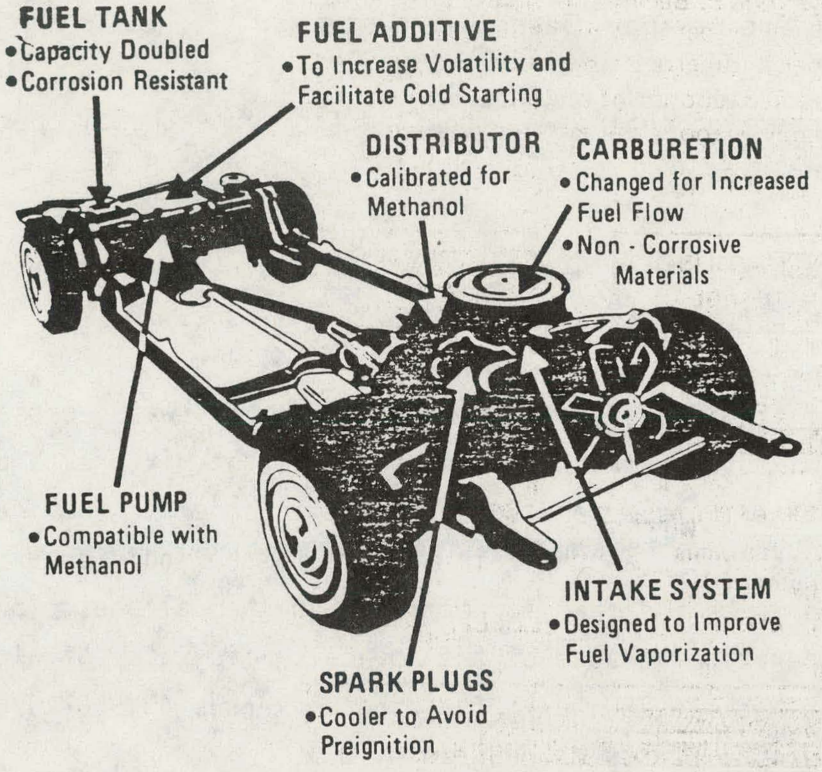
FUEL ECONOMY. Because methanol gives about half as much energy per litre as gasoline, the volume of fuel burned per kilometre is approximately doubled. Using this doubled amount of methanol, though, the energy efficiency is about the same as gasoline (See Graph V).



Graph IV. Emissions – 1975 FTP-EFI Car (No Catalytic Converter)



Graph V. Fuel Economy – EPA City Cycle – EFI Car.


FUEL TANK
•Capacity Doubled
•Corrosion Resistant
FUEL ADDITIVE
•To Increase Volatility and Facilitate Cold Starting
DISTRIBUTOR
•Calibrated for Methanol
CARBURETION
•Changed for Increased Fuel Flow
•Non - Corrosive Materials
FUEL PUMP
•Compatible with Methanol
INTAKE SYSTEM
•Designed to Improve Fuel Vaporization
SPARK PLUGS
•Cooler to Avoid Preignition

Practical Experience with Pure-Ethanol Engines - Brazil

Operating Behavior

Air-and water-cooled, pure-ethanol engines were developed under a cooperative ethanol research program. The development of the 1.6-liter, 4-cylinder, opposed-piston VWB engine took place in two steps:

1. The gasoline-operated engine was modified for pure-ethanol operation. The compression ratio was kept at 7.2:1.

2. The compression ratio was raised to 11:1 in order to increase the efficiency and performance and to improve emissions.

Intense heating of the intake system by hot exhaust gas was necessary in order to improve mixture distribution and increase the mixture temperature. Intake system modifications were also necessary in order to provide for optimum distribution of the alcohol/air mixture to the individual cylinders. The carburetor was to be modified to permit 65% higher alcohol flow-through versus gasoline operation because of the low calorific value of alcohol compared with gasoline (26,780 kJ/kg for ethanol versus 43,950 kJ/kg for gasoline). The airflow had to be reduced by 38%.

Experimental Results

Mixture distribution posed most of the problems during the engine test-stand phase of the experimental program. Additional problems were posed by the ignition system. Intense mixture heating, ignition retard, higher ignition voltage (26 KV) and longer sparks solved most of the problems.

Fuel and Energy Consumption during Normal Driving

Alcohol-powered engines had 4% less fuel consumption when the compression ratio was raised from 7.2:1 to 11:1 (Figures 11 and 12) (6).

It is obvious that the low calorific value of ethanol leads to a higher volumetric fuel consumption in terms of liters per 100 km in road traffic at a normal compression ratio of 7.2:1.

Figure 13 shows that general energy savings of roughly 20% is obtained for alcohol-powered engines versus gasoline-powered engines (6).

Engine Behavior

A comparison between gasoline and ethanol operation revealed that the ethanol-operated engine produced only slightly higher engine output at high speeds in full-load driving when the compression ratio remained unchanged. However, an increase in the compression ratio from 7.2:1 to 11.0:1 resulted in an increase of the maximum output from 35.5 KW (48HP) to 41.8 KW (57HP), i.e. an 18.7% improvement. The use of ethanol may also result in an increase of the maximum torque from 101 Nm to 122 Nm (20.5%). It is known that race drivers make use of these very important properties of alcohol engines, i.e. the capacity for higher output and torques compared with gasoline engines. The primary effects are a better internal cooling of the engine, higher volumetric efficiency of the fuel/air mixture, and improved combustion at higher compression ratios.

Energy savings of up to 30% were obtained with high compression-ratio ethanol engines. Improved energy utilization was obtained at higher compression ratios during full-load operation.

Driveability

Driveability tests were performed on vehicles equipped with 1.5-liter, air-cooled VW ethanol engines. The results showed that minor hesitation may occur during acceleration from low speeds. Driveability is good at high engine speeds and vehicle velocities and at ambient temperatures around 15°C. Higher ignition voltages and longer sparks were found to result in substantially improved driveability. Test vehicle driveability was significantly improved when 5 or 10 volume percent of gasoline was added to the ethanol (we call this blend ethylfuel).

Start-up Behavior

High performance ignition systems were used to improve the cold-start behavior of ethanol engines. This was demonstrated by the increase in ignition voltage from 19.5 to 26 KV during the tests. An excellent way to improve cold-start behavior is the blending of 5 or 10 volume percent gasoline into the ethanol. Low ambient temperatures (below +5°C) require straight gasoline for cold start. Therefore, we developed a simple cold-start system consisting of a 2-liter gasoline tank, an electric pump, a solenoid valve, an injection nozzle, and the necessary injection lines.

Other Results

During the early stages of our work, ethanol-powered engines always were destroyed when the intake air was heated excessively and engine-knock occurred. The problem was solved when pre-heating was reduced, especially under full-load operation, and when a sufficiently safe margin from the knock-limit was reached. The highest temperature of engine parts was 290° at the cylinder head during full-load operation. Volkswagen do Brazil and Volkswagen Research are carrying out endurance tests on three test vehicles with air-cooled engines (in Brazil) and on one test vehicle with water-cooled engine in Germany. While the present results are very promising, work continues on some problems such as better mixture distribution, avoidance of high-speed knocking, improved cold-start behavior and warm-up phase driveability. Nevertheless, we are quite optimistic and feel that these remaining problems can be solved by using the engineering know-how that VWB and the Wolfsburg research division have acquired by now.

THE CONGRESSIONAL

ALCOHOL FUELS CAUCUS

PRESENTS AN

ALCOHOL FUELS — ENGINE EXHIBIT

ON THE GROUNDS OF THE

UNITED STATES CAPITOL

JUNE 18, 1980

IN COOPERATION WITH THE

DEPARTMENT OF ENERGY'S

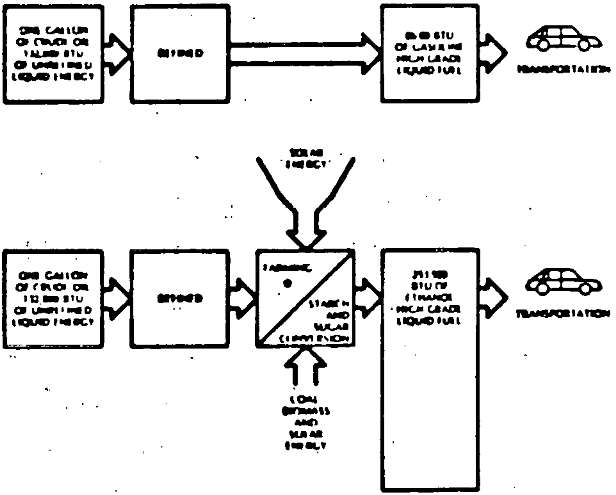
OFFICE OF ALCOHOL FUELS

AND

OFFICE OF CONSUMER AFFAIRS

REMEMBER!

Each gallon of ethanol used for transportation saves us more than 1.5 gallons of imported crude, thus reducing our dependence on foreign countries for our energy supplies. (The savings are displayed on the chart below.)



- Fourteen pounds of seed corn planted in an acre of soil and treated with 3,702,000Btu of fertilizers (API study) will yield about 100 bushels (5,600 lbs.) of corn, which will convert into 250 gallons of ethanol or 18,900,000 Btu of high-grade liquid fuel. In addition, the co-products include 1,700 lbs. of high quality distillers meal, 1,500 lbs. of CO_2, as well as 20,000,000 Btu of crop residue available for a variety of purposes, including fertilizers. The sun has paid a mighty dividend.

EXHIBIT	FUEL	EXHIBITOR	CONTRACTS
Beta modified 350 cubic inch General Motors engine in a Chevrolet pick-up truck	Can be switched from gasoline to alcohol (ethanol or methanol)	Students and Faculty Delta Vocational Technical School Marked Tree, Arkansas	Mr. Bill Stanley Delta Vocational Tech College P.O. Box 279 Marked Tree, Arkansas
Beta modified 400 cubic inch diesel engine in a John Deere tractor	Blend of ethanol with vegetable oil, castor oil, or linseed oil		
Modified 404 cubic inch diesel engine mounted for display	Blend of ethanol and vegetable oil		
Modified 350 cubic inch General Motors engine mounted for display	Multi-fuel		
Modified 505 cubic inch diesel engine in a Case tractor	Ethanol	Engine retrofit project of the Southern Ilinois College with the participation of the educational branch located in Vienna Correctional Center	Mr. Hartzel Black Vienna Correctional Center Vienna, Illinois 62995
Modified 3.5 horsepower engine in a go-cart	Ethanol, gasoline, or vegetable oil		
Beta modified 301 cubic inch 1979 Pontiac engine mounted for display	Multi-fuel		
Standard 350 cubic inch Chevrolet engine mounted for display	Ethanol		
Alcohol Fuel engine conversion kit for standard automobile engines	Switchable from gasoline to alcohol (ethanol and methanol)	Dr. Bill Harris and Dr. R.R. Davidson Texas A&M University	Dr. Bill Harris/Dr. R.R. Davidson Chemical Engineering Dept Texas A&M University College Station, TX 77840
Modified six cylinder Plymouth engine in a 1979 Plymouth Volare	Ethanol	Ashland Oil Company	Harold Messick Ashland Oil Company 222nd St. & Front St Ashland, KY 41101
Standard four cylinder Ford Model A engine in a restored 1929 Ford Model A truck	Ethanol	Robinson Secondary School Fairfax, Virginia	George Price Robinson Secondary School 5035 Sideburn Road Fairfax, VA 22032
(2) modified six cylinder Chrysler engines in 1979 Chrysler unmarked police cars	Methanol	New York City Police Department	Eugene Masci New York Police Department 1 Police Plaza New York, NY 10038
Modified 250 cubic centimeter Yamaha motorcycle engine in a Yamaha motorcycle	Ethanol	National Park Service U.S. Park Police	Officer Mike Foster U.S. Park Police (202) 523-0056
Hybrid alcohol-electric powered lawn tractor	Ethanol/battery	National Park Service National Capitol Region Brentwood Maintenance Facility	John Hoke (202) 282-7192/426-3760 (For any questions on hybrid technology)

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CHAPTER II

Overview of Internal Combustion Engines Technology

BASIC ENGINE TYPES AND THEIR OPERATION

In an external combustion engine, the products of combustion of air and fuel transfer heat to a second fluid which then becomes the motive or working fluid for producing power; in an internal combustion engine,† the products of combustion are, directly, the motive fluid. Because of this simplifying feature and a resulting high thermal efficiency, the combustion engine is one of the lightest (in weight) power-generating units known, and therefore its field of greatest application is that of transportation. Today the manufacture of combustion engines for automobiles, boats, airplanes, and trains, and for small power units, is one of the largest industries in the world.

At the turn of the century, the automobile was powered by either a steam engine with boiler, or by an electric motor with storage battery. Internal combustion engines even then had a long history from gunpowder engines of the Abbe Jean de Hautefeuille (1678) and Chritian Huyghens (1791), the gas turbine of John Barber (1791) (with water injection!), and the piston engines of Street (1794) and Philippe Lebon (1799). The first practical gas engine, invented by Jean Joseph Lenoir in 1860, ignited the gas and air by electric spark on the intake stroke, without compression. Because of this feature, fuel consumption was high, and costs were not competitive with the steam engine. It remained for Otto in 1876 to build the four-stroke internal combustion engine that compressed the air and gas before ignition.

With the discovery of oil in Pennsylvania in 1859, a petroleum industry was born. Liquid fuels became available because of the demand for lamp oil. This factor and the Otto engine, plus the invention of the pneumatic tire by John B. Dunlop in 1888, were the ingredients that spawned the automotive industry. George B. Selden filed a patent in 1879 for a road vehicle driven "by a liquid-hydrocarbon engine of the compression type." With the granting of the patent in 1895, Selden was in a position to control competition, and an association of licensed manufacturers was formed.

Henry Ford, owner of one of the fifty or more small automobile companies of that time, was sued under the Selden patent, and in 1909 the patent was upheld. On appeal, however, in 1911 the Court construed the patent to be valid only for an automobile powered by a Lenoir engine with the changes set forth by Selden. Since the engine was obsolete, the patent was worthless, and impetus was given to many firms to enter the field.

This beginning chapter outlines the types, construction, and operation of combustion engines; subsequent chapters will examine the processes and components of the various engines.

1-1. The Four-Stroke Spark-Ignition (SI) Engine.†

Most internal combustion engines have the reciprocating-piston principle shown in Fig. 1-1, wherein a piston slides back and forth in a cylinder and transmits power through, usually, a simple connecting-rod and crank mechanism to the drive shaft. For a reciprocating-piston engine, Beau de Rochas had proposed in 1862 a sequence of operations that is, even today, typical of most spark-ignition (abbreviated SI) engines:

1. An intake stroke to draw a combustible mixture into the cylinder of the engine, Fig. 1-1a (intake valve open).

2. A compression stroke to raise the temperature of the mixture, Fig. 1-1b (both valves closed).

3. Ignition and consequent burning of a homogeneous mixture at the end of the compression stroke, with the liberation of energy raising the temperature and pressure of the gases; the piston then descends downward on the expansion or power stroke, Fig. 1-1c (both valves closed).

4. An exhaust stroke to sweep the cylinder free of the burned gases, Fig. 1-1d (exhaust valve open).

In 1876 Nikolaus A. Otto, a German engineer, with the principles of Beau de Rochas, built a four-stroke-cycle engine that became highly successful, and the name of the cycle of events gradually became known as the Otto cycle.

In discussion the reciprocating-piston engine, the terms displacement, clearance volume, and compression or expansion ratio are convenient. The displacement D is the volume swept by the piston in one stroke (and n times this value for an engine with n cylinders); the clearance volume (C) is the volume of the compressed gases, which is also the volume of the combustion chamber; the compression or expansion ratio (r_V and CR) equals

$$r_V = \frac{C + D}{C} = CR \tag{1-1}$$

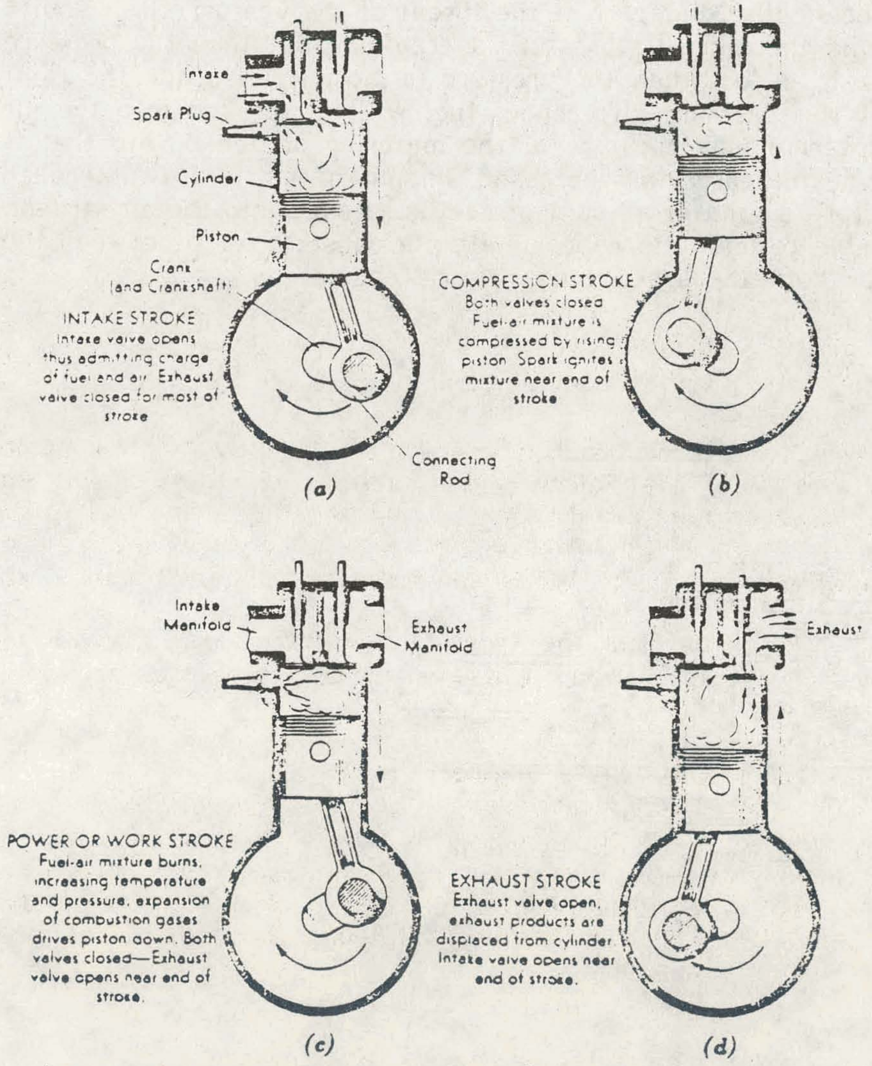


Fig. 1-1. The four-stroke spark-ignition (SI) cycle. Four strokes of 180 degrees of crankshaft rotation each, or 720 degrees of crankshaft rotation per cycle.

In all reciprocating-piston engines, the piston necessarily comes to a complete standstill at two particular positions of the crankshaft before the direction of its motion is reversed. In Fig. 1-1d the piston has just passed the lower limit of the stroke; this position is called the bottom dead center (abbreviated BDC). A similar "dead" or motionless stage of the piston exists at the instant the piston reaches the top dead center (abbreviated TDC). Because of this "dead" position, combustion of the mixture in the Otto engine occurs at, practically, constant volume. Since the power stroke exists for only a part of the total time of the cycle, a flywheel is able to smooth out the power pulses and so obtain, essentially, a uniform rotation of the crankshaft.

1-2. Speed and Load Control in the SI Engine.†

Since a spark can ignite only a combustible mixture, a fairly definite (and homogeneous) mixture of fuel and air (approximately 15 parts of air to 1 part of fuel by mass) must be present in all parts of the combustion chamber, if a flame is to be propagated throughout the mixture. A carburetor is the usual means for obtaining this air-fuel ratio. In Fig. 1-2 are illustrated the basic parts of a simple up-draft carburetor: a venturi, a fuel nozzle with metering orifice, a reservoir of fuel in the float chamber, a throttle and a choke. Air, at about atmospheric pressure, is drawn through the venturi when the piston descends on the intake stroke. Because of the smaller diameter at the throat of the venturi, the velocity of the air increases and therefore its pressure decreases. But then the pressure at the tip of the nozzle is less than the pressure (atmospheric) inside the float chamber. Because of this pressure difference, fuel will be sprayed into the air stream, of amount determine by the size of the metering orifice. Note that if the speed of the engine increases, an increased amount of air is drawn through the venturi and therefore a greater amount of fuel is sprayed into the air stream. A carburetor is thus able to maintain approximately a constant ratio between the air and the fuel throughout the speed range of the engine.

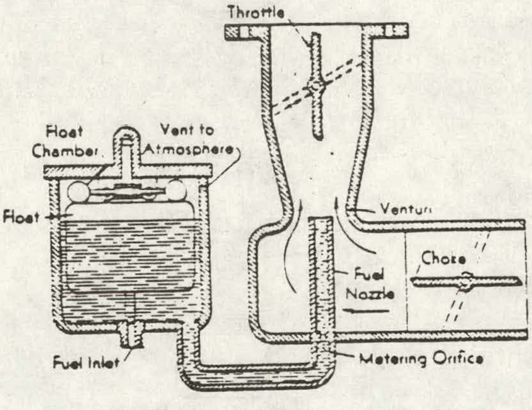


FIG. 1-2. Elements of a simple updraft carburetor.

The turning effort applied to the crankshaft depends upon the mass of mixture burned in each cylinder per cycle and it is controlled by restricting the amount of mixture (but not necessarily the air-fuel ratio) entering the cylinder on the intake stroke. This is accomplished by using a valve, called the throttle, on the carburetor to obstruct the passage way into the intake manifold (Fig. 1-2). On the intake stroke of the engine, if the throttle is almost closed, only a small amount of mixture will enter the cylinder, and the pressure in the cylinder will be far below atmospheric, with corresponding low compression and combustion pressures. The resulting speed of the engine is low and, if the crankshaft is not connected to an external load, the engine is said to be idling. When the throttle is gradually opened, the speed of the engine will increase to a value determined by the external load connected to the drive shaft. (The load is an opposing drag to the rotation of the drive shaft and may be supplied, for example, by the resistance of the driving wheels of a car on the road or of a propeller turning in air or in water.) Thus the speed of the engine is controlled by the throttle position and, also, by the amount of load. A definite speed can be maintained while varying the throttle position in relation to the load; or the throttle position can be held constant, with the load adjusted to maintain various desired speeds.

1-3. The Four-Stroke Compression-Ignition (CI) Engine.†

In 1892 Rudolf Diesel planned a new type of engine that was to be capable of burning coal dust. The diesel cycle was to be similar to the Otto cycle except that a high compression ratio was required and air alone, instead of a combustible mixture, was to be admitted to the engine on the intake stroke. It was well known that rapid compression of air to a high pressure could raise its temperature to such a point that a fuel, if delivered into the combustion chamber, would spontaneously ignite without depending on a spark to initiate combustion, or a homogeneous mixture to propagate the flame. Diesel first proposed to time the injection of the fuel to give constant-temperature combustion, but this was found to be impractical. He next attempted to time the injection of the fuel to achieve constant-pressure combustion and this arrangement was more successful. Diesel soon found that coal dust was an unsatisfactory fuel and that liquid fuels were necessary.

Figure 1-1 can be used to visualize the diesel or compression-ignition (abbreviated CI) engine if the spark plug is replaced by a fuel-injection valve and the compression ratio is increased to about 15. The successful diesel engine embodied the following cycle of events:

1. An intake stroke to induct air alone into the cylinder, Fig. 1-1a (intake valve open).

2. A compression stroke to raise the air to a high temperature—a temperature higher than the ignition point of the fuel (compression ratios of 12 to 18 are used), Fig. 1-1b (both valves closed).

3. Injection of the fuel during the first part of the expansion stroke at a rate such that combustion maintains the pressure constant, followed by expansion to the initial volume of the cylinder, Fig. 1-1c (both valves closed).

4. An exhaust stroke to purge the burned gases from the cylinder, Fig. 1-1d (exhaust valve open).

An early method of injecting the fuel was to use a blast of compressed air to carry it into the combustion chamber. This method gave good atomization and good control of the combustion process. However, air injection is now obsolete, because a large air compressor was a necessary and expensive auxiliary.

1-4. Speed and Load Control in the CI Engine.†

The modern method of injection is to compress and spray the fuel alone into the cylinder and depend upon the high injection pressure (2,000-30,000 psia) for atomizing the fuel. In Fig. 1-3 is a schematic drawing of a mechanical or solid injection system. When the injection plunger is at the bottom of its stroke (not shown), fuel will be forced into the plunger chamber through the inlet port A. At the proper time in the cycle, the injection plunger will rise and seal the inlet port, with consequent compression of the fuel. This fuel will open the check valve and communicate its pressure to the residual fuel trapped in the discharge tubing. The same action is repeated at the check valve near the outlet of the nozzle, with fuel being sprayed from the orifice of the nozzle into the combustion chamber. The end of the injection period will appear after the inlet port is uncovered by the helical groove on the pump plunger, because the high pressure above the plunger will be released through the slot B communicating with port A.

The duration of the injection period is determined by the design of the cam on the injection-pump camshaft, which is driven by the engine, as well as by the position of the helix.

If a lesser load is to encountered, the rack C is moved to the left, thus rotating the injection plunger with its helical groove. Now when the plunger is lifted, injection starts the same as before but the pressure relief occurs at an earlier stage because the helical groove soon meets the port A. Thus the duration of injection is reduced for part loads, along with the quantity of the fuel injected.

When the rack C is moved to its limiting position, the slot B will be aligned with the port A. In this stop position, fuel cannot be compressed or injected.

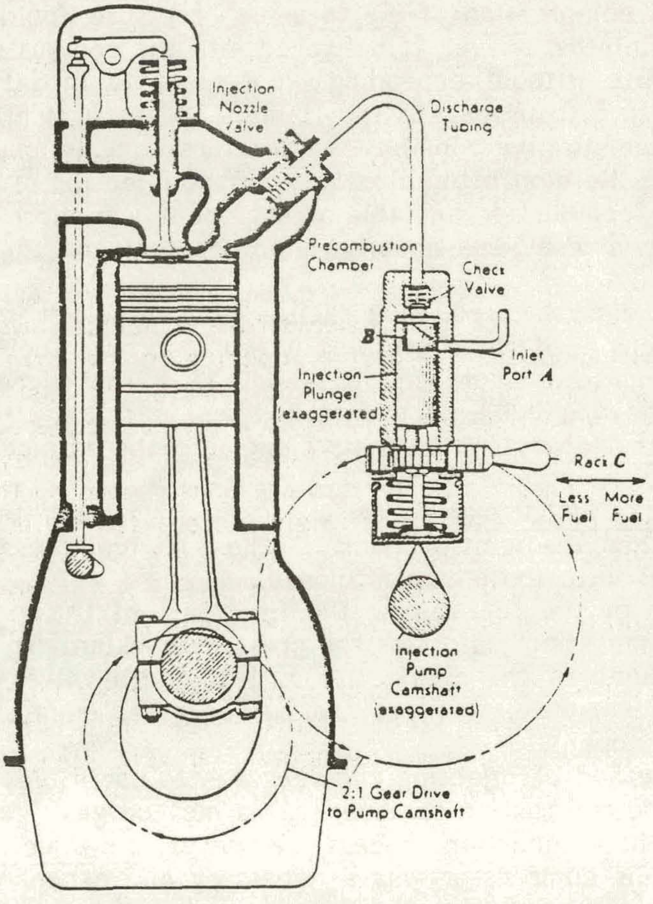


FIG. 1-3. Mechanical or solid injection system on four-stroke CI engine.

Since the control rack C governs the speed and load-carrying ability of the engine, it is called the throttle. Despite this name, note that the CI engine does not throttle the air intake as a means of control. With a multicylinder engine, each cylinder usually has an accompanying injection pump although one rack may be employed for all of the individual units.

Recall that in the SI engine a fairly definite relationship had to be maintained between the amounts of air and fuel to ensure that a flame would be propagated throughout the mixture. In the CI engine, no fixed relationship of air and fuel is required, because the fuel is injected into extremely hot air and ignites at each location where a combustible mixture forms. A flame need not propagate in order to have combustion take place. Thus, at full load it is desired to inject a quantity of fuel such that all of the air (oxygen) in the cylinder can be burned. Practically, this limit cannot be reached because it is not possible for the localized fuel spray to find all of the air, rich and lean regions abound, and the engine exhaust gas may be colored in appearance and pungent in odor. At part load, only a fraction of the fullload fuel quantity is injected; in localized regions, combustion of the fuel occurs at ratios of air to fuel of about 15 to 1, although the overall airfuel ratio is much higher than this (say 90 to 1). At full output of the engine, most of the air undergoes reaction; at part load, only a fraction of the air need be combined with fuel, and because of the localized combustion the air-intake process need not be throttled at any time.

An injection system, such as described above, is quite expensive because of the close tolerances that must be maintained and the production costs that accompany hardened-steel material.

1-5. The Two-Stroke Cycle.†

The four-stroke cycle requires two revolutions of the crankshaft for each power stroke. In order to get a higher output from the same size of engine and obtain some valve simplification, the twostroke cycle was developed by Dugald Clerk in 1878. This cycle is applicable both to compression-ignition operation and to spark-ignition operation, but has been primarily successful only with the former.

Referring to Fig. 1-4, at TDC we have either the spraying of fuel into hot compressed air or the spark ignition of a vapor mixture starting the combustion and liberating the energy for the power stroke which follows. Near the end of this stroke the piston uncovers a port or opening in the cylinder wall at B, and most of the products of combustion escape into the exhaust manifold. Immediately afterward in the stroke, a second port at A is uncovered by the piston and either air or the gasoline-air mixture is forced into the cylinder. This is an example of cross-scavenging. Deflectors are constructed on the piston to prevent the incoming charge from passing straight across the cylinder to the exhaust manifold as the remainder of the burned gases are being scavenged (exhausted) from the cylinder. The return stroke of the piston is the compression stroke of the cycle. It should be noted that the entire cycle is completed in one revolution of the crankshaft.

If the inlet ports are placed near, instead of across from the exhaust ports, the inlet air must pass through a complete "loop" before reaching the exhaust passageway; this is called loop scavenging. In Fig. 1-5, the combination of exhaust valves in the head and inlet ports in the cylinder allow through or uniflow scavenging to be obtained.

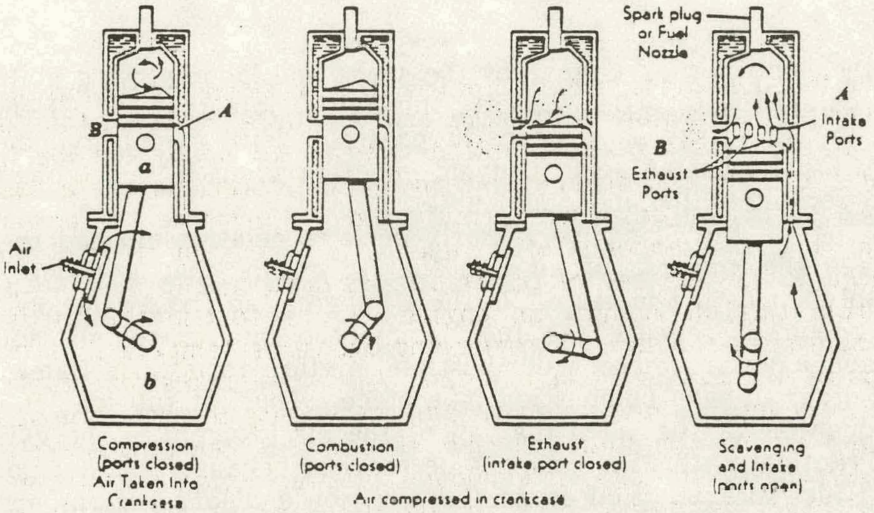


FIG. 1-4. Cylinder events for two-stroke cycle. Cross scavenging.

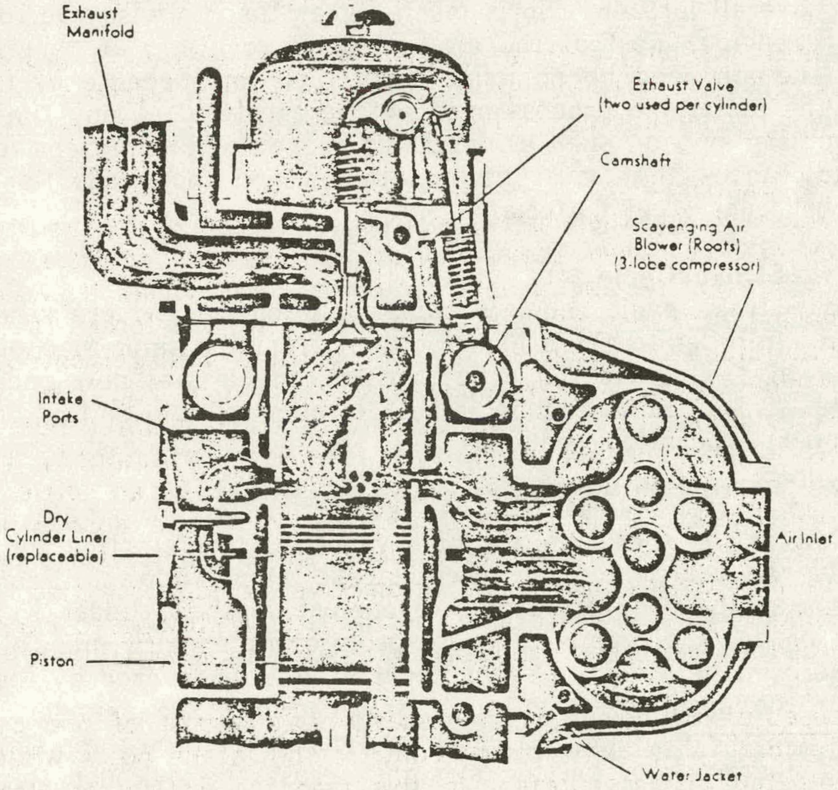


FIG. 1-5. Two-stroke-cycle CI engine. (Courtesy of General Motors Corporation.)

If the two-stroke cycle engine is a carbureted gasoline engine, some of the fresh mixture will be carried away with the exhaust gases.† Efficient charging of the cylinder is hard to achieve without excessive fuel losses. Therefore, two stroke-cycle SI engines are not popular except for small gasoline engines where economy is not a vital factor, as in outboard motorboat engines. In the CI or diesel engine, the disadvantage of loss of fuel does not exist, for air alone is wasted in the scavenging of the cylinder. (See Fig. 14-26.)

Consider that an engine may be limited to slow speeds by reason of its large size. For example, an engine with large and therefore heavy pistons could not be operated at high speed because of the stresses set up by the inertia forces created in accelerating and decelerating the reciprocating parts. In such cases, the two-stroke cycle can be advantageously used to increase the power output. On the other hand, the tendency of an engine to fail from thermal stresses is directly related to the number of power strokes occurring in a definite interval of time. From this standpoint, an engine with a four-stroke cycle can be operated at high speeds without experiencing excessive temperatures that might cause breakdown of lubrication and metals. Also, the two-stroke-cycle engine, with its relatively less efficient exhaust and scavenging process, cannot normally induct as much air on the intake stroke as can the four-stroke-cycle engine, unless a supplementary air pump is employed. Newer-design two-stroke-cycle CI engines do not have the method of compressing the air charge in the crankcase, shown in Fig. 1-4, but have compressors driven from the main engine shaft to put the air under a pressure of 2 to 5 psi for scavenging and delivery to the engine cylinder (Fig. 1-5). However, power must be supplied by the engine to operate such blowers.

The names two-stroke diesel engine and two-stroke CI engine are used synonymously; similarly, the two-stroke SI engine is often referred to by the name two-stroke Otto cycle (although Otto had nothing to do with this development).

1-6. Types of Engines.

Since the speed and therefore the power of an engine can be limited by the inertia forces created when the parts are accelerated or decelerated, it is desirable to subdivide the engine into a number of individual cylinders. By this means the inertia force per cylinder is reduced; also, the forces in one cylinder can be counteracted or "balanced" by an opposing arrangement of the other cylinders. Various cylinder arrangements are shown in Fig. 1-6. The in-line engine offers the simplest solution for manufacture and maintenance. An engine with a shorter length than the in-line type for the same output is the V engine, which consists of two in-line banks of cylinders set at an angle (usually 90 degrees) to each other to form the letter V. Here two connecting rods are fastened to one crank of the crankshaft. Where space problems are present, such as arise with rear-engine drives in automotive vehicles, a flat engine with horizontal cylinders may be preferable. In the horizontal-opposed engine shown in Fig. 1-6, the pistons are offset from one another with a separate crank for each cylinder.

An opposed-piston engine is also shown that consist of one cylinder containing two pistons. The upper piston controls the intake ports while the lower piston controls the exhaust ports. In this manner, uniflow or straightthrough scavenging of a two-stroke engine is obtained. The radial cylinder arrangement with all cylinders in one plane and with equal angular spacing between cylinder axes is popular for air-cooled aircraft engines.

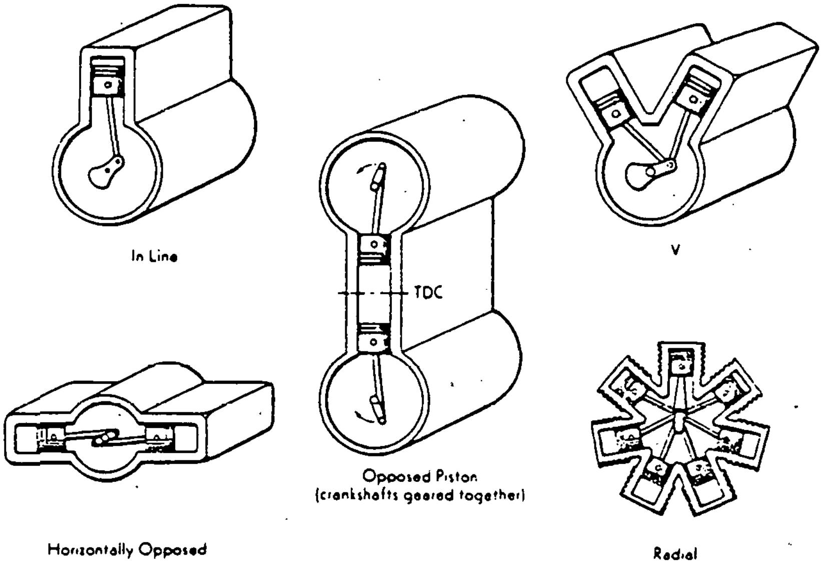


Fig. 1-6. Classification of engines by cylinder arrangement.

The radial engine presents the problem of fastening 3, 5, 7, or 9 connecting rods to a single crank. A master rod is guided by the crank and articulated rods are attached to the master (Fig. 1-7). It should be noted that the master rod executes the same motion as the connecting rod in more usual engines, while an articulated rod follows a slightly different path since the point of attachment is not at the center of the crankpin. When the crankshaft in Fig. 1-7 is rotated 40 degrees from TDC of the master cylinder, the Number 2 piston is not at TDC but is at 3 degrees from TDC. This difference is taken into account by the ignition timing.

The in-line and V engines can be designed to operate with the crankshaft above the cylinders; the engine is then said to be inverted.

All of the above arrangements can be either air- or water-cooled. Water cooling is the more popular method, although where simplicity is desired (motorcycle engines) or light weight is required (aircraft engines), air cooling is found. All heavy-duty truck and bus engines in this country are, at present, liquid-cooled.

1-7. Classifications by Valve Location.†

Another classification for the combustion engine is made by designating the location of the valves, Fig. 1-8. The most popular design is the overhead-valve engine, which is also called an I-head and valve-in-head engine; examples are shown in Figs. 1-5, 1-10, and 1-12. The underhead valve or L-head is illustrated in Fig. 1-11. A combination of these two locations is occasionally made to give an F-head. Here the intake valve is located in the head (overhead) while the exhaust valve is located in the block (underhead).

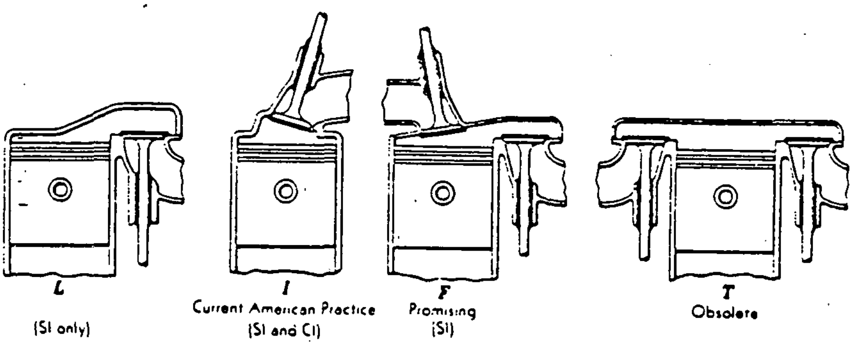


Fig. 1-8. Classification of engines by valve location.

1-8. Supercharging.†

In the SI engine, the maximum load can be carried when the restriction of the throttle is removed from the intake passage of the engine. At wide-open throttle the cylinder is filled with a mixture under approximately atmospheric pressure and the output of the engine is proportional to the energy released by burning that particular mass of fuel and air. To increase the output, a greater mass of mixture must be forced into the cylinder. When this is done by either a blower or some form of compressor, the process is called supercharging (Fig. 1-9). Theoretically, the power could be indefinitely increased by forcing more and more of the mixture into the engine with an auxiliary air (mixture) pump, but overheating of the engine limits the amount of supercharging. It should be noted that an unsupercharged engine at part throttle has a pressure in the manifold less than atmospheric pressure if the throttle is not fully opened. The supercharged engine can have either positive or negative pressures in the manifold, the pressure depending on the position of the throttle and the capacity of the air pump.

The CI engine inducts a constant amount of air, and maximum load is reached when the quantity of fuel injected is too large to be effectively handled by the amount of oxygen in the chamber. This is evidenced by smoke (unburned fuel) appearing in the exhaust gas. An overloaded engine exhibits a black smoke, with the color fading to gray as the load is relieved. To supercharge a CI engine, a greater amount of air must be forced into the cylinder and a correspondingly greater amount of fuel must be injected into the air. An unsupercharged CI engine has approximately the same manifold pressure (atmospheric) at all times, while a supercharged engine will have increasingly greater positive pressures as the amount of supercharging increases.

Many of our larger engines have turbochargers such as that illustrated in Fig.1-9b. Here the "blowdown" energy, arising from the exhaust gases escaping from the cylinder at high velocity, drives a gas turbine which is coupled to a centrifugal compressor.

1-9. Engine Parts and Details.

The parts and components of the internal combustion engine are made of various materials and perform certain functions that will be briefly reviewed in this section (the identifying letters are shown in Figs. 1-10 and 1-11).

1-11. Rotary Engines.†

Literally hundreds of combustion engines have been proposed that substitute a rotary member for the reciprocating

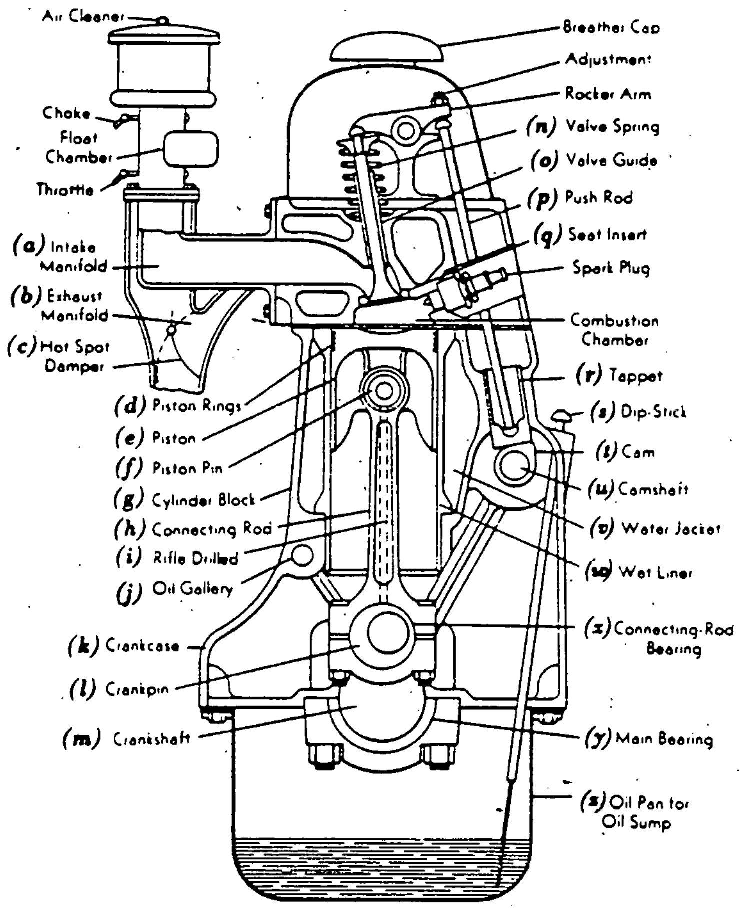
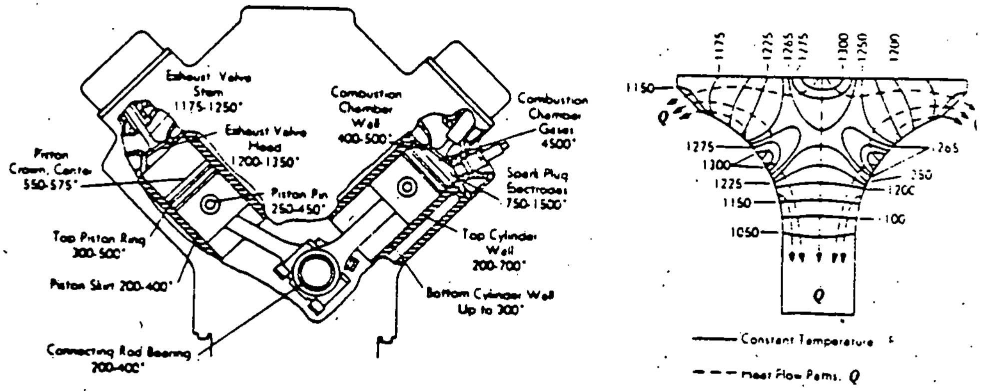
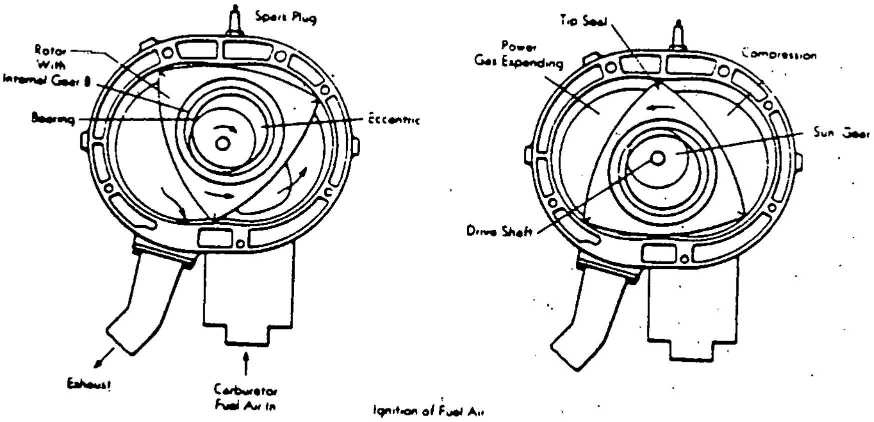


FIG. 1-10. Cross section of overhead-valve four-stroke-cycle SI engine.



(b) (c)

FIG. 1-12. V-8 automotive engine showing usual operating temperatures. (Courtesy of American Oil Company and Thompson Products, Inc.)



(a) (b)

1-12. Trends in Combustion-Engine Development.

Figure 1-16 illustrates the trends in automotive engine design in the United States. The advertised horsepower rose sharply to 1958 and then leveled to some degree because of physical and practical limitations imposed by the size of the engine. In 1955 the smallest engine available in an American car was 42 hp, and the largest, 275 hp; in 1965, the smallest was 90 hp, and the largest, 425 hp (advertised). The increase in horsepower was primarily obtained by increasing the "peaking" speed of the engine from about 3,700 rpm to about 4,700 rpm. Note that the average horsepower and displacement dropped in the period 1959-63 with the advent of "compact" cars.

The use of the V-8 engine keeps the length of the engine small and allows the low hood lines now favored; about 70 percent of American cars are of this type.

A number of U.S. manufacturers supply two- and four-stroke diesel engines for trucks, boats, trains, and power generation. Several companies offer engines developing about 5,000 hp on the four-stroke-cycle, and about 20,000 hp on the two-stroke cycle. All of the large engines have speeds of 500 rpm or less and are supercharged (Chapter 15).

CHAPTER III

Fuel Metering of SI and CI Engines

FUEL METERING - SI ENGINES

The carburetor, or the injection system, of the spark-ignition engine meters fuel into the air stream of amount dictated by the speed and by the load. Proper proportioning of the fuel and air must be within definite limits as prescribed by engine design, Fig. 10-1.

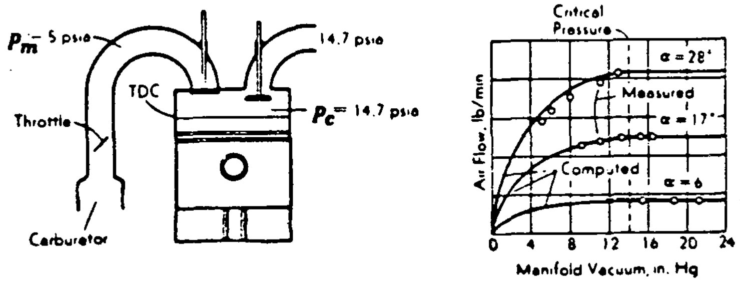
11-1. The Engine Requirements.

The ratios of air and fuel required for various conditions of speed and load are illustrated in Fig. 11-2.

AB Idling and low-load range (throttle almost closed)
BC Economy (cruise) or medium-load range (throttle partially open)
DE Power or full-load range (throttle wide open)

Idling and Low Load. The engine is said to idle when it is disconnected from external load with the throttle being essentially closed. An idling engine demands a rich charge, such as A in Fig. 11-2. Fortunately, as the throttle is opened the AF ratio requirement increases (AB, Fig. 11-2) and the charge can be leaner.

To understand this behavior, note that the pressure of the exhaust gas at the end of the exhaust stroke does not vary much with changes in load, while the temperature, if anything, decreases with either load or speed decrease (because of heat losses). Since the volume of the combustion chamber is constant, the mass of exhaust gas remaining as residual tends to be constant ($m = pV/RT$). On the other hand, the mass of fresh charge inducted on each intake stroke depends upon the manifold pressure and therefore on the throttle opening—reaching a maximum, for each speed, at WOT. It follows that the percentage of residual diluting the fresh charge increases as the throttle is closed (increases with manifold vacuum). The dilution is not serious at most loads and speeds but becomes a problem when decelerating and when idling. Consider the pressures in the engine at idling, Fig. 11-1. Since the pressure in the inlet manifold is much less than that of the residual, exhaust gas will flow from the combustion chamber into the inlet manifold when the inlet valve opens. Then, as the piston descends on the intake stroke, the exhaust gas is drawn back into the cylinder along with a portion of fresh charge, and the overall mixture contains a high percent of exhaust gas. To offset the increasing percentage dilution of fresh charge by residual as the throttle is closed, the carburetor must furnish an increasingly richer charge, B to A, Fig. 11-2, else the engine may misfire.



(a) (b)

FIG. 11-1. (a) Closed-throttle pressure conditions in SI engine manifold. (b) Airflow versus inlet vacuum and throttle position α (Kopa, Ref. 14).

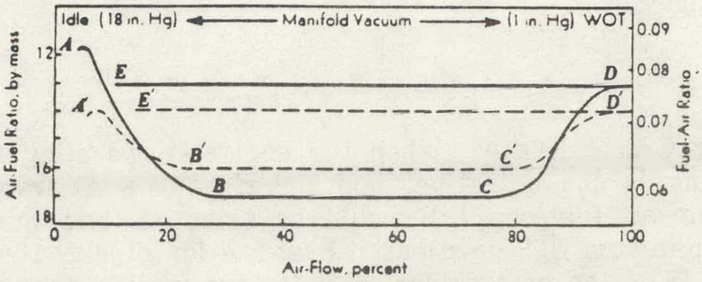


FIG. 11-2. Air-fuel and fuel-air ratios required by the engine at various throttle positions.

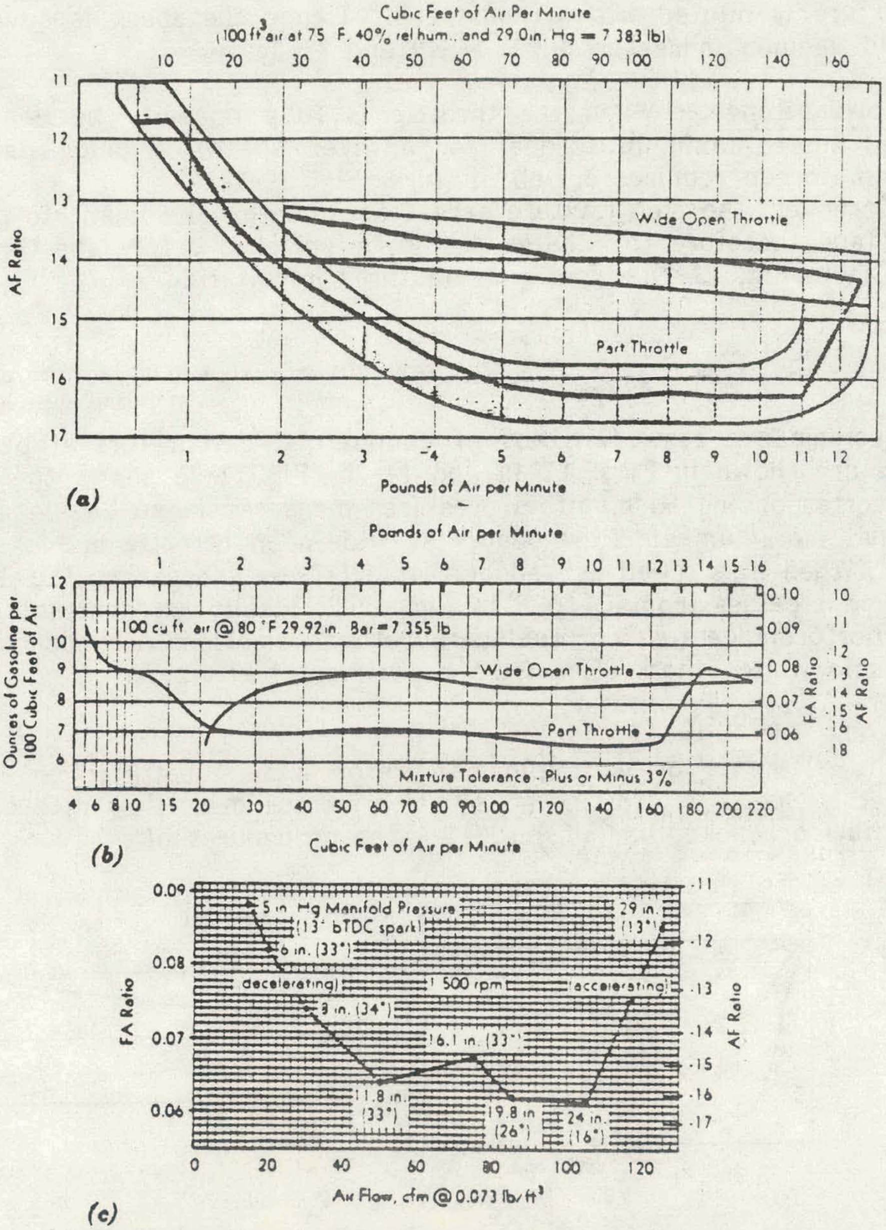


FIG. 11-3. Performance tests of commercial carburetors. (a) Courtesy of Zenith Carburetor Division, Bendix Aviation Corp. (b) Courtesy of Chrysler Corp. (c) Inlet manifold pressures, engine spark advances, and air-fuel ratios at various throttle positions and 1500 rpm. (Car accelerating, decelerating, or cruising with various loads, AF ratios from steady-flow flow box tests.) (Data *precedes* pollution precautions, Secs. 10-10A and 11-1.) (Hagen and Holiday, Ref. 9, Chap. 10.)

* * * * *

Economy or Cruise Range. When the engine is operating at part-throttle, maximum economy is the objective, and therefore the AF ratio for best efficiency (minimum lb fuel/bhp hr) should be selected (and this same ratio is usually that for minimum HC emissions). Examination of Fig. 10-1 indicates that a ratio of about 16 is the best compromise for the various possible part loads of a modern SI engine (and a value of about 18 is a practical maximum in the laboratory with well-mixed gaseous fuel and air).

With lean mixtures the flame speed is relatively slow, and even slower when the mixture is diluted with exhaust gas. Hence the spark is advanced as the manifold vacuum increases, Figs. 14-40 and 11-3c.

Power Range. When the throttle is fully opened, the charge must be enriched since maximum torque (for a given speed) is being demanded (and maximum torque requires a rich mixture, Fig. 10-1).

Moreover, the rich mixture serves as an internal coolant to prevent valve failure (and therefore the charge should be enriched before the throttle is wide open—CD in Fig. 11-2). Too, rich mixtures inhibit NO.

* * * * *

Performance tests (air-box) of commercial carburetors at part- and full-throttle are shown in Figs. 11-3a and 11-3b; Fig 11-3c shows the probable AF ratios corresponding to manifold pressures measured in an engine at 1,500 rpm. Note that maximum air flow occurs at wide-open throttle and a selected high speed. When the speed is reduced at WOT by increasing the load, the AF requirement passes from D to E in Fig. 11-2, ideally, at constant charge ratio. In the performance tests of real carburetors, variations are apparent; some are explainable while others arise from experimental errors.

11-2. The Air Flow.

The elements of a simple carburetor were illustrated in Fig. 1-2 and described in Sec. 1-2. To find an equation for the mass flow rate of air through the venturi or choke tube of Fig. 11-4 the procedures of Sec. 3-14 will be followed: Substitute the steady-flow equation, Eq. 3-3b, into the continuity equation, Eq. 3-3a, and obtain Eq. 3-26. This equation is for ideal gases with reversible (frictionless) and adiabatic flow, but is modified to hold for the real flow process by multiplying by a coefficiant of discharge, C_a (Prob. 11-7):

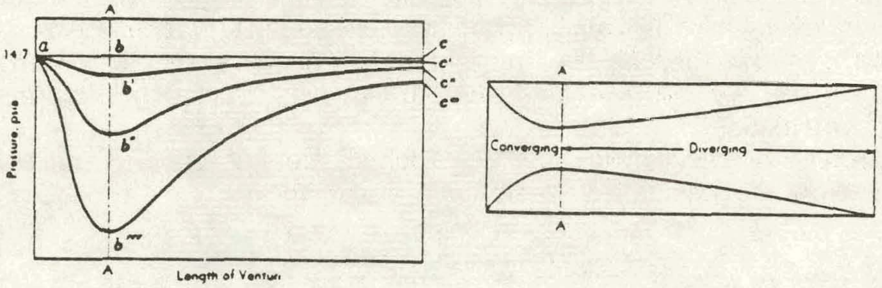


FIG. 11-4. Venturi, and internal pressures.

$$\dot{m}_{air} = \frac{1.62 C_a p_1 d^2}{\sqrt{T_1}} \sqrt{\left(\frac{p_2}{p_1}\right)^{1.43} - \left(\frac{p_2}{p_1}\right)^{1.71}} \quad \left(\frac{lb_m}{sec}\right) \qquad (11\text{-}1)$$

p_1 = inlet pressure, psia d = venturi diameter, in.
p_2 = throat pressure, psia T_1 = inlet temperature, °R

Since the mass-flow rate has the same value at each cross section of the venturi, it follows that the velocity of the air increases in the convergent portion with corresponding decrease in pressure (and the velocity decreases in the divergent portion with corresponding increase in pressure). The changes in pressure with changes in mass-flow rate (or with changes in throat area) are illustrated in Fig. 11-4: As the mass-flow rate increases, the pressure at the throat decreases; this is the basis of the metering principle of the venturi.

The different pressure histories in Fig. 11-4 could also be obtained at constant mass-flow rate by decreasing the throat area. If the venturi has a small throat, a large pressure drop is obtained, b-b''', which would enable the fuel nozzle to deliver a nicely atomized spray of fuel into the air stream. On the debit side, a large pressure drop is accompanied by a large pressure loss, c-c''', and therefore the mass-flow rate of air is reduced from a maximum value (and the indicated power of the engine is controlled by its air consumption). Hence, if power is the objective, the venturi throat should be large to avoid pressure losses that limit the power output; if economy is the objective, the venturi throat should be small to promote atomization with consequent better mixing of air and fuel and better distribution (see Sec. 11-10).

The discharge coefficient has value between 0.94 (low flow rate) and 0.99 (high flow rate) for a plain venturi such as that in Fig. 11-4. In the actual carburetor, the choke, throttle, nozzle, and carburetor body all combine to obstruct the venturi passageway and an overall loss of 2 in. Hg is encountered (high air flow) (about 1.3 in. Hg for two-barrel, 0.8 in. Hg for four-barrel, and 0.4 in. Hg for large four-barrel carburetor).

The problem is complicated further by noting that the derivations assumed that steady flow existed in the venturi. This condition is approached, for a four-stroke-cycle engine, when four or more cylinders are connected to the venturi, because each cylinder begins its intake process near the end of the intake process for a preceding cylinder. However, with less than four cylinders, the flow through the venturi is intermittent; the abruptness of changes in velocity being affected by the volume of intake manifold between venturi and cylinder and the position of the throttle. Unsteady flow is a maximum when only one cylinder is connected to the carburetor, for flow exists, theoretically, only for about half a revolution in every two revolutions of the crankshaft (four-stroke cycle). The interruption of flow through the carburetor of the single-cylinder engine causes a rebound of the air with consequent "blowback" of fuel (and air) from the carburetor entrance.

In calculating the venturi size for four or more cylinders (and a four-stroke cycle), the flow is considered steady and equal to

$$\dot{m} = n_v p \; \frac{D}{1728} \; \frac{rpm}{2 \times 60} \quad (lb/sec) \qquad (11\text{-}2)$$

n_v = volumetric efficiency
D = displacement of n cylinders (in.^{3})
p = density of atmospheric air (unsupercharged engine) (lb/ft^3)

If the four-stroke-cycle engine has only one cylinder, the flow is unsteady with, theoretically, the same maximum flow rate as if four cylinders were present (although this rate would occur only for 1/2 revolution in every 2 revolutions of the crankshaft). Thus the single-cylinder engine should theoretically require the same venturi size as if three more cylinders were present. Commercial practice is to decrease the single-cylinder venturi by about 10 percent from the size required by the four-cylinder engine (displacement of each cylinder equal to that of the single cylinder).

11-3. The Fuel Flow. For simplicity of analysis, suppose that the tip of the nozzle is capped with an orifice and placed in the throat of the venturi, Fig. 11-5. The steady-flow energy equation

$$q - w = (u_2 - u_1) + \frac{p_2 v_2 - p_1 v_1}{J} + \frac{V_2^2 - V_1^2}{2 g_c J} \qquad [3\text{-}3b]$$

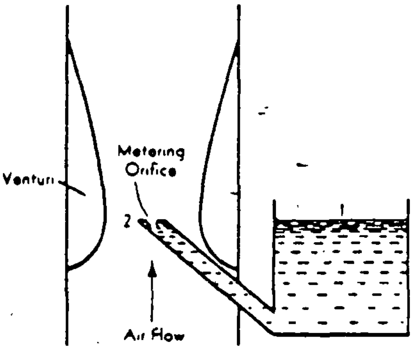


FIG. 11-5. Simple updraft carburetor with metering orifice at tip of main nozzle.

relates the properties of the liquid fuel at sections 1 and 2. For ideal (frictionless) and adiabatic ($q = 0$) flow of an incompressible fluid ($u_2 = u_1$ and $v_1 = v_2$), Eq. 3-3*b* reduces to

$$V_2 = \sqrt{2 g_c v (p_1 - p_2)} \qquad (a)$$

The actual mass-flow rate is formed by substituting Eq. *a* into the continuity equation, Eq. 3-3*a*, with the departures from ideality contained within a discharge coefficient, C_f:

$$\dot{m}_{\text{fuel}} = C_f A_2 \sqrt{2 g_c \rho (p_1 - p_2)} \qquad (b)$$

The pressure difference, $p_1 - p_2$, might be measured with a manometer (in. H_2O) and the area A_2 is invariably circular; therefore Eq. *b* reduces to (Prob. 11-8),

$$\dot{m}_{\text{fuel}} = 0.79\, C_f d_f^2 \sqrt{G\, \Delta p} \qquad (\text{lb}_m/\text{sec}) \qquad (11\text{-}3)$$

G = fuel, specific gravity
Δp = in. H_2O
d_f = orifice diameter, in.
C_f = discharge coefficient

For a "sharp-edged" orifice, the coefficient of discharge is, closely, 0.60. However, the approach edge of the orifice is made slightly rounded so that a coefficient of about 0.75 is appropriate (rounding the approach edge makes the coefficient more reproducible for mass production).

11-4. The Elementary Carburetor.†

That the flow of a liquid (gasoline) does not follow the same law as the flow of a gas (air) is apparent upon comparing Eqs. 11-1 and 11-3. Therefore, it cannot be expected that the simple system of Fig 11-5 will deliver a constant air-fuel ratio for the various loads and speeds of the engine. To determine the air fuel characteristic, consider that

11-4. The Elementary Carburetor.† That the flow of a liquid (gasoline) does not follow the same law as the flow of a gas (air) is apparent upon comparing Eqs. 11-1 and 11-3. Therefore, it cannot be expected that the simple system of Fig. 11-5 will deliver a constant air-fuel ratio for the various loads and speeds of the engine. To determine the air-fuel characteristic, consider that

$$\text{AF} = \text{air-to-fuel ratio} = \frac{\text{mass flow of air}}{\text{mass flow of fuel}} = \frac{\dot{m}_{\text{air}}}{\dot{m}_{\text{fuel}}}$$

and substitute Eqs. 11-1 and 11-3:

$$\text{AF} = \frac{1.62 C_a p_1 d^2 \sqrt{\left(\frac{p_2}{p_1}\right)^{1.43} - \left(\frac{p_2}{p_1}\right)^{1.71}}}{0.79 C_f d^2{}_f \sqrt{G\,\Delta p}\ \sqrt{T_1}} \qquad (11\text{-}4)$$

To make the appearance of Eq. 11-4 less formidable, let

$$\psi = \sqrt{\left(\frac{p_2}{p_1}\right)^{1.43} - \left(\frac{p_2}{p_1}\right)^{1.71}} \div \sqrt{\Delta p}$$

with values listed in Table 11-1. The following average conditions will be substituted for simplicity:

$$C_a = 0.8 \qquad p_1 = 14.7 \text{ psia} \qquad G = 0.74$$

$$C_f = 0.75 \qquad T_1 = 520°\text{R}$$

with the result (ignoring humidity which *decreases* the dry AF ratio)

$$\text{AF} = 1.64 \left(\frac{d}{d_f}\right)^2 \psi \qquad (11\text{-}5)$$

d = diameter of venturi
d_f = diameter of fuel orifice (jet)

Example 11-1. Determine, as a first approximation, the size of the orifice to give a 12-to-1 AF ratio, if the venturi is $1\frac{1}{4}$ in. in diameter and the vacuum in the venturi is 34 in. of water referred to atmospheric pressure.

Solution: For $\Delta p = 34$ in., it is found from Table 11-1 that $\psi = 0.0250$. By Eq. 11-5,

$$12 = 1.64 \times \left(\frac{1.25}{d_j}\right)^2 \times 0.0250$$

$$d_j^2 = 0.00534$$

$$d_j = 0.073 \text{ in.} = \text{diameter of orifice.}$$ *Ans.*

TABLE 11-1
AIR-FUEL RATIO CONSTANTS
(For $p_1 = 14.7$ psia $= 407$ in. H_2O)

(1)	(2)	(3)	(4)
Δp in. of water	$\sqrt{\Delta p}$	$\sqrt{\left(\frac{p_2}{p_1}\right) - \left(\frac{p_2}{p_1}\right)}$	$\psi = \frac{(3)}{(2)}$
5	2.236	0.05825	0.02605
10	3.162	0.08183	0.02588
15	3.873	0.09954	0.02570
20	4.472	0.11415	0.02552
25	5.000	0.12673	0.02534
30	5.477	0.13785	0.02517
35	5.916	0.14783	0.02499
40	6.325	0.15689	0.02481
45	6.708	0.16518	0.02462
50	7.071	0.17281	0.02444
60	7.746	0.18642	0.02407
70	8.367	0.19820	0.02369
80	8.944	0.20845	0.02330
90	9.487	0.21739	0.02292
100	10.000	0.22518	0.02252

Example 11-2. Calculate the changes in air-fuel ratio with air flow for the data of Example 11-1 if the maximum venturi depression is 60 in. H_2O.

Solution: Substituting $d = 1.25$ and $d_j = 0.073$ in Eq. 11-5,

$$AF = 480\psi$$

Substituting values of ψ from Table 11-1 and solving, the results follow:

Δp in. of water	5	10	20	30	34	40	50	60
AF Ratio	12.50	12.42	12.25	12.08	12.00	11.91	11.73	11.55
Change in AF Ratio	+0.50	+0.42	+0.25	+0.08	0.00	−0.09	−0.27	−0.45

Note that over the entire range, the air-fuel ratio decreases by 0.95. A simple carburetor (such as this is) would deliver a progressively richer mixture as the throttle is opened.

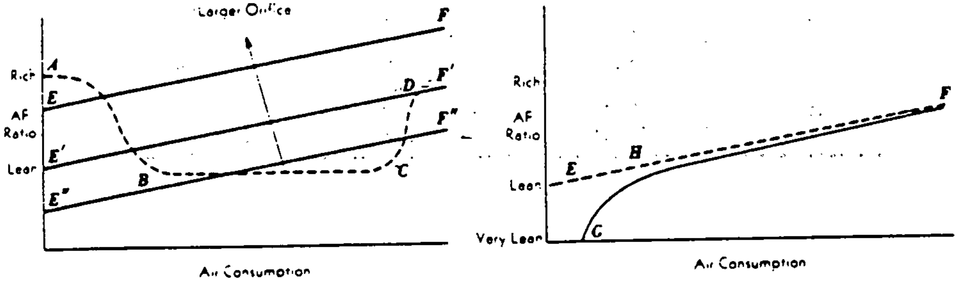
The results of Example 11-2, superimposed upon the engine requirements of Fig. 11-2, are illustrated in Fig. 11-6a for several sizes of the fuel-metering orifice:

1. The air-fuel characteristic curve can be raised or lowered by changing the area of the orifice.
   - (a) If adjusted for satisfactory idling, EF, the charge is too rich at WOT.
   - (b) If adjusted for satisfactory economy, E"F", (or max power, E'F'), the charge is too lean for idling.

These conclusions suggest that a variable-area orifice might serve the entire operating range (and such designs can be found). Most frequently, a tapered rod is inserted into the orifice and actuated either mechanically by the throttle (Fig. 11-8) or else by vacuum (Fig. 11-14). With this metering rod or economizer, the flow area is made small for the economy range, and larger, for the power range. Thus the problem of "jumping" from C to D in Fig 11-2 is easily solved. However, means must be found to

A. Hold constant the AF ratio from B to C and D to E, Fig. 11-2 (Sec. 11-5).

B. Enrichen† the charge at idling, B to A, Fig. 11-2 (Sec. 11-6).



(a) (b)

FIG. 11-6. (a) Effect of metering-orifice size on the delivery characteristic of an ideal plain jet. (b) Effects of viscosity, surface tension, and float height on the delivery characteristic of a plain jet.

The carburetor of the single-cylinder engine, when operating at wide-open throttle, can be adjusted to deliver the required mixture ratio. But when the throttle is not wide open, the pulsating flow is smoothed out over a greater time period by the throttling action, and therefore the mixture becomes leaner This tendency will be emphasized by the volume of the manifold. It is difficult to design the carburetor to operate equally well under all conditions of speed and load. Moreover, the speed of the engine, the volume of the manifold, and the presence of resonant pressure surges* further complicate the problem.

11-5. Main Jet Design.

In modern carburetors the metering orifice (called the main metering jet) is placed at the base of the nozzle (called the main discharge tube and also the main jet) where entry is made into the float chamber. With this location, the flow at low suctions is controlled by the size of the discharge tube and by the viscosity of the fluid (by Re). Before (and when) flow begins, the effect of surface tension of the liquid can be observed visually§: The liquid will cling to the nozzle—a drop will "grow" until it is torn away by either gravity or suction—and flow appears as a succession of large drops. Consider Fig. 11-6b. The initial flow of liquid G does not coincide with the initial flow of air because the liquid must be lifted to the top of the nozzle (the liquid level, controlled by the float, is below the tip of the nozzle to avoid spillage), and also, surface tension must be overcome. Viscous flow then occurs through the discharge tube until the velocity increases to a point where the effects of viscosity are minimal H; from here on the flow essentially follows the relationship of Eq. 11-4.

11-6. The Idling System.

When the throttle is near its closed position, a rich charge is demanded (AB in Fig. 11-2). But in this region, the main jet is ineffective (Fig. 11-6b) and therefore an auxiliary metering system is required. A modern idling system is illustrated in Fig. 11-7a and consists of

1. An idle tube F with metering orifice or entrace K (for the fuel).
2. A primary air bleed L (to emulsify the fuel, and to serve as an anti-syphon).
3. An idle-channel metering restriction M (for the emulsion).
4. A secondary air bleed N (to prevent too rich a charge at closed throttle [air pollution], and to act as an off-idle port).
5. Off-idle ports O (to increase the flow from the idling system when the throttle is slightly open).
6. An idle-mixture control needle P and discharge port Q.
7. An idling speed adjusting screw (a throttle stop; not shown in Fig. 11-7).

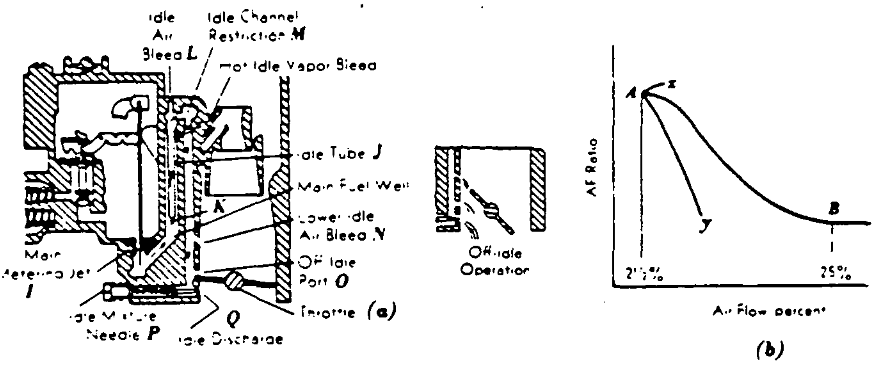


FIG. 11-7 (a) Idling system. Rochester Quadrajet Carburetor. (Courtesy of *General Motors Engineering Journal*.) (b) Idling AF characteristics

* * * * *

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11-12. Gasoline-Injection Systems.

The carburetor is a simple device with a minimum of moving or bearing surfaces, thus little maintenance is required; too, mass production dictates inexpensive* die-cast and stamped parts. Consequently, fuel injection is relatively rare,† being found on sports cars, where maximum performance is the objective, and on airplane engines, where carburetor icing is a danger.

Fuel injection systems can be classified as

A. Direct cylinder injection (following diesel practice, Fig. 12-1).
B. Port injection
   (a) Timed (b) Continuous
C. Manifold injection (pressure carburetion).

An SI engine with fuel injection, compared with a carbureted engine, should show (Prob. 11-36):

1. Increased power and torque, because of increase in volumetric efficiency from
   (a) large intake manifolds with small pressure losses,
   (b) elimination of carburetor pressure loss (Fig. 11-4),
   (c) elimination of manifold heating (Sec. 11-13).
2. Faster acceleration, since the fuel is injected into, or close to, the cylinder and need not flow through the manifold.
3. Elimination of throttle-plate icing, since fuel is not vaporized before the throttle.
4. Easier starting, since atomization of fuel does not depend on cranking speed. (Less pollution on federal tests, Table VIII, Appendix.)
5. Less knock, since heat need not be supplied to assist distribution (and therefore either lower-octane fuels or higher compression ratios or less TEL are feasible). (See Gasoline Standards, Table 10-6.)
6. Less tendency to backfire, since a combustible mixture is not in the manifold.
7. Less HC emissions. On deceleration, by cutting off fuel injection; on acceleration, by eliminating the accelerating pump (since manifold wetting is minimized, and fuel response is practically instantaneous with increase in air flow). No after-run, Sec. 10-10A(3).
8. Less need for volatile fuels, since distribution is independent of vaporization, and less evaporation controls, Sec. 10-10B.
9. Less FA variations arising from changes in position or motion, since float level is unimportant, or temperature, Sec. 10-10A(4).
10. Less height of engine (and hood), since position of injection unit is not critical.

This list, although impressive, must be carefully evaluated. An excellent carburetor and manifold system is more desirable than a poorly designed injection system (and vice versa Fig. 11-16b and a). Consider Fig. 11-16a which shows the comparative performance of well-adjusted injection and carburetion systems at constant speed—there is little difference. Although excess power is on the side of injection, it may be offset by other disadvantages. For example, a 1963 racing car (with methanol) was 8.1 mph faster (154.8 mph) with injection than with carburetion, but the fuel consumption was 2.22 mpg versus 6.41 mpg with carburetor†. (However, in the following year this gas-eating tendency was greatly improved.) Other advantages for injection, although real, may be minor, and not worth the added cost and maintenance.

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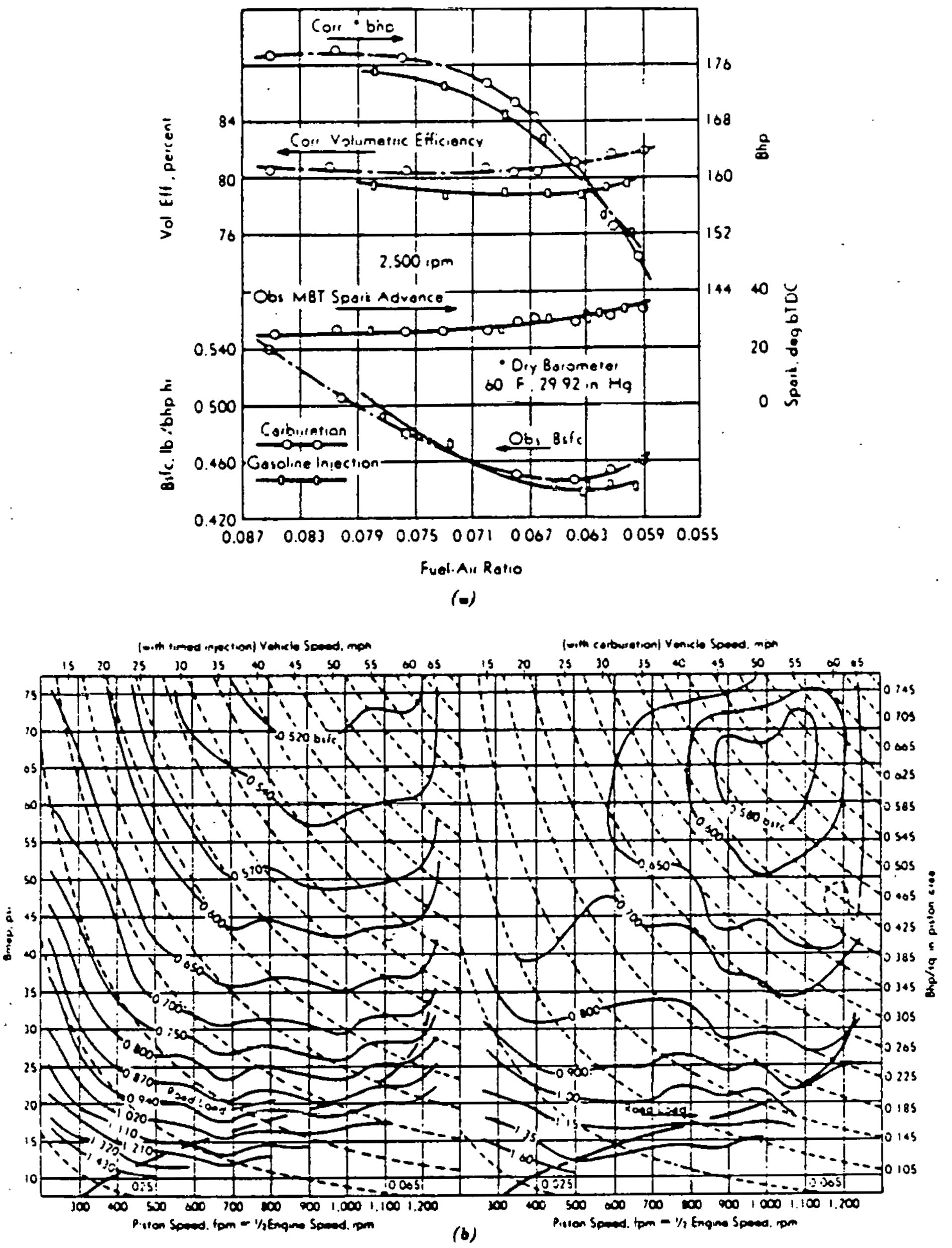

FIG. 11-16. (a) Comparison of performance with a timed gasoline injection system versus a well-designed carburetion system (6 cylinder in line, $4\frac{1}{4}$ by $4\frac{45}{64}$ in., 400 cu in., CR = 8). (b) Performance maps with gasoline injection and with indifferent carburetion (V-8, $3\frac{7}{8}$ by 3 in., 283 cu in., CR = 9.25, 2-barrel carburetor, 3.08 rear-axle ratio, manual transmission.) (Freeman, Ref. 13.)

* * * * *

The objectives of the injection system (or of the carburetor and manifold) are to atomize and distribute the fuel throughout the air in the cylinder while maintaining prescribed fuel-air ratios (Fig. 11-2). To accomplish these tasks, a number of functional elements might be required within the system:

A. Pumping elements to move the fuel from fuel tank to cylinder (plus piping, passageways, etc.)

B. Metering elements* to measure and supply the fuel at the rate demanded by the speed and load.

C. Metering controls to adjust the rate of the metering elements for changes in load and speed of the engine.

D. Mixture controls to adjust the ratio of fuel rate to air rate as demanded by the load and speed.

E. Distributing elements to divide the metered fuel equally among the cylinders.

F. Timing controls to fix the start and the stop of the fuel-air mixing process.

G. Ambient controls to compensate for changes in temperature and pressure of either air or fuel or engine that affect the elements of the system.

H. Mixing elements to atomize the fuel and mix with air to form a homogeneous mixture.

Several injection systems will be illustrated to show various solutions to the design problem. For example, the carburetor is a remarkable device since it combines several functional elements into one design element: It needs no mechanical pump (other than an inexpensive transfer pump to fill the float chamber) since it adapts atmospheric pressure (and venturi depression) to "pump" the fuel into the air stream with some degree of atomization. Also, the venturi is the meter for the air, and also (indirectly) for the fuel, thus pumping, metering, speed-metering control, mixture control, ambient control, and mixing are combined in one design element with a minimum of moving (or bearing-rubbing) parts.

Direct Cylinder Injection. Injection of gasoline directly into the cylinder is rarely† encountered because of (1) the difficulty of finding space in the head for an injection nozzle, (2) the added cooling and casting complications, (3) the added cost, and (4) the small* advantage that is gained over port injection.

The primary design elements are illustrated in Fig. 11-17a and consist of a transfer pump T, a filter F, a metering, distributing, and time pump P with speed-metering control (since it is geared to the engine), a load-metering control R, a mixture control M (a throttle in the air stream), and the nozzles or atomizing elements N.

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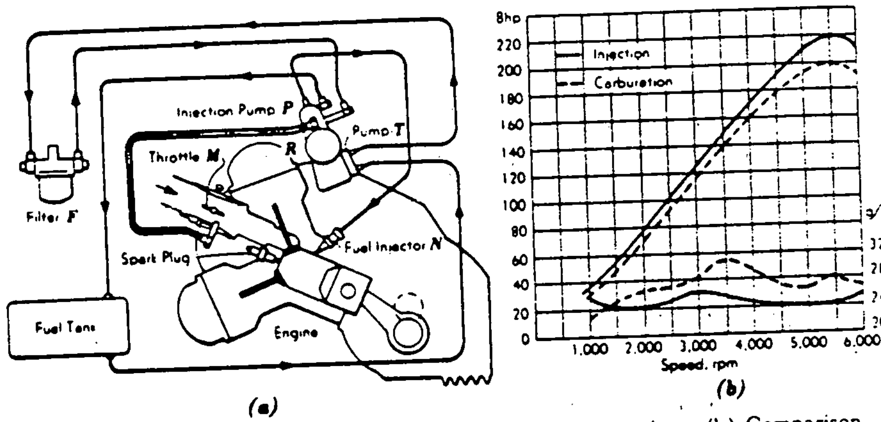


Fig. 11-17. (a) Fuel injection system on 2.5-liter racing engine. (b) Comparison of performance with carburetor and fuel injection on 300 SL engine.

It should also be remarked that the system described is an adaption of the expensive diesel pump to gasoline injection. For that matter, any of the systems in Fig. 12-1 could have been so adapted (and all have been advocated at one time or another). The primary advantages are precise, timed, high-pressure injection; the primary disadvantages are cost, and the problem of exact metering at light loads from cylinder to cylinder because of the individual plungers.

Port Injection—Continuous. The GM (General Motors Corp.) fuel-injection system†, illustrated in Fig. 11-18, supplies fuel continuously to eight nozzles B, each located in an inlet port C and aimed at an inlet valve. In operation, a conventional throttle D controls the flow of air entering through a large radial-entry, annular venturi E. A very small vacuum is created at the throat of the venturi M and increases with increase in air flow*. This air-metering signal is sent to the fuel meter and the fuel pressure is increased with increase in air flow, to maintain essentially a constant fuel-air ratio.

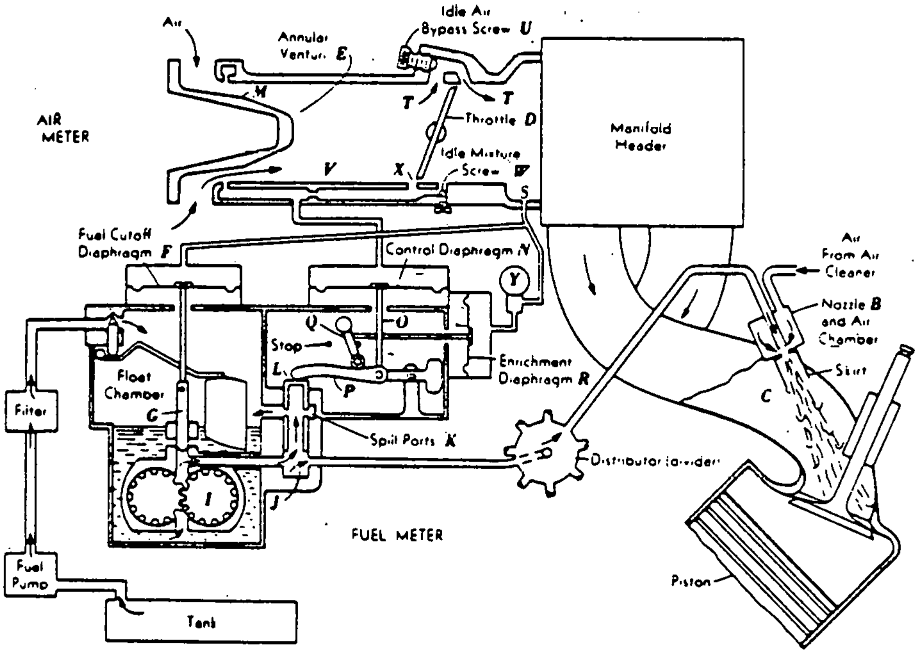


Fig. 11-18. Schematic of the General Motors Gasoline Injection System.

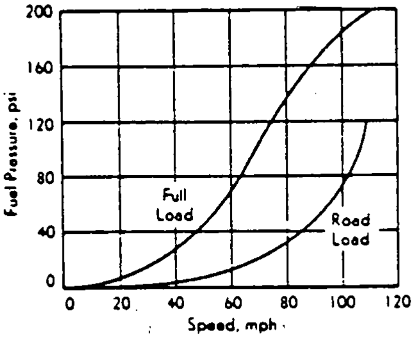


Fig. 11-19. Gasoline injection pressures at road and full load. (Courtesy of General Motors

* * * * *

Port Injection—Timed. The design elements of the Lucas[†] injection system, illustrated in Fig. 11-20, are a high-pressure (100 psi) gear pump A, a metering and timing distributor B (geared to the engine), a load control C, a mixture control (air throttle), and atomizing nozzles E (50 psi).

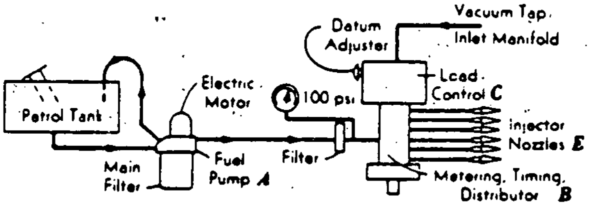


FIG. 11-20. Schematic diagram of the Lucas fuel-injection system.

* * * * *

A means for injecting fuel into the cylinder at the proper time in the cycle is a necessary component for operation of a CI engine since the injection system is called upon to start and to control the combustion process.

12-1. Objectives.

The injection system of the CI engine should fulfil the following objectives consistently and precisely:

1. Meter the quantity of fuel demanded by the speed of, and the load on, the engine.
2. Distribute the metered fuel equally among the cylinders.
3. Inject the fuel at the correct time in the cycle.
4. Inject the fuel at the correct rate.
5. Inject the fuel with the spray pattern and atomization demanded by the design of the combustion chamber.
6. Begin and end the injection sharply without dribbling or after-injections.

To accomplish these objectives, a number of functional elements† are required:

A. Pumping elements to move the fuel from fuel tank to cylinder (plus piping, etc.).
B. Metering elements to measure and supply the fuel at the rate demanded by the speed and load.
C. Metering controls to adjust the rate of the metering elements for changes in load and speed of the engine.
D. Distributing elements to divide the metered fuel equally among the cylinders.
E. Timing controls to adjust the start and the stop of injection.
F. Mixing elements to atomize and distribute the fuel within the combustion chamber.

Several injection systems will be illustrated to show various solutions to the design problem.

1-12. Fuel-oil Injection.

Methods—There exist two basic methods—air injection and mechanical injection. The latter is known under different names, as solid, hydraulic, or airless injection.

Mechanical-injection engines can be subdivided again into two groups—engines with an open combustion space and engines with a precombustion chamber.

All larger mechanical-injection oil engines are built with an open combustion space and use one of the two injection systems—the constant-pressure system or individual pumps.

It is obvious that in addition to the four enumerated main types there exist a great number of intermediate types having some characteristic of one and some of another system.

Air injection was first successfully developed by Rudolf Diesel. It requires a compression of about 500 to 525 lb/sq in. and injection air of about 1,000 lb/sq in. Its advantages are very good atomization and distribution of the fuel resulting in high mean effective pressures; its disadvantages are complication of the engine by a multistage air compressor which often is a source of trouble and in any event requires expert attention and at the same time lowers the mechanical efficiency of the engine. The latest achievements in mechanical-injection engines seem to spell doom for the air-injection engines and the number of manufacturers of this type decreases with every year.

Constant-pressure injection, also called Vickers, or monorail, or accumulator system, was developed by the Vickers Company and was the first satisfactory mechanical-injection system. It consists of a system of pipes which connect the high-pressure oil pump or pumps with the fuel or spray nozzle in each cylinder. A sufficient accumulator action maintaining a more or less constant pressure in the system is obtained by the compressibility of the fuel and elasticity of the pipes and other parts such as strainer and pressurerelief-valve body. The fuel is admitted into the cylinders by lifting the fuel valve, called also fuel needle on account of its shape, by a cam mechanism driven from the engine crankshaft.

The compression pressure of the air charge is lower than in air-injection Diesel engines, usually between 370 and 420 lb/sq in. The ignition pressure goes up to 550 to 600 lb/sq in., partially because it is difficult to obtain real constant-pressure combustion with mechanical injection of the fuel, partially because the increase of maximum pressure gives an increase of thermal efficiency. In the early Vickers engines the fuel pressure was about 10,000 lb/ sq in. Improvements in fuel spray tips and in the shape of the combustion space have permitted the lowering of the fuel pressure to about 4,500 and even 3,000 lb/sq in. without affecting the fuel economy.

A peculiarity of mechanical injection is the time lag of ignition, already discussed in Chap. 6, Fig. 8-6. Regardless of the shape and construction of the spray nozzle and of the fuel pressure, mechanical injection generally gives a coarser atomization than air injection and requires a considerably earlier injection timing—from 12° to 20° before dead center, depending upon the fuel characteristics.

The main advantage of constant-pressure injection is simplicity; its drawbacks are difficulty of obtaining uniform fuel distribution among the cylinders, which is noticeable at low loads and particularly at higher speeds and in smaller cylinder sizes. It gives good results in sizes from 20 hp per cylinder and up and with speeds up to 700 rpm.

Individual-pump injection differs from the constant-pressure injection chiefly in design. With each cylinder having a separate pump the fuel injector becomes a spring-loaded and hydraulically operated automatic valve and the cam mechanism is not required.

This system lends itself particularly well for large cylinders requiring several nozzles for each combustion space.

Precombustion Chamber—The compression space is subdivided into two parts, one formed by the space between the piston top and the cylinder head and the other formed by a special recess in the cylinder head and connected with the main chamber by a more or less restricted passage. The fuel is injected into the precombustion chamber sometimes during the compression stroke, the earlier the smaller the passage to the precombustion chamber. Thus the fuel is given time to evaporate before it ignites in the precombustion chamber. On account of the insufficient amount of air, only partial combustion occurs but sufficient to raise the pressure and to throw out the rest of the fuel into the main chamber where combustion is completed.

The oil-injection pressure may be considerably lower, 1,000 to 1,500 lb/ sq. in.

Solid Injection Engines.

Development of the solid injection engine in recent years has been directed toward increasing reliability in operation; securing greater economy in both initial cost and during operation, and augmenting the variety of duties to which it can be applied. Attainment of these objectives presented a three-fold problem in design, metallurgy, and improvement of the working cycle.

Design improvements have determined the shape, dimensions, and arrangement of parts which are best able to resist without failure, the mechanical stresses and temperatures to which the parts are subjected, and by which high mechanical efficiency is obtained.

Metallurgical research has evolved materials of greater strength, lighter weight and better heat-resisting properties. Improvements of the working cycle have been made in such a way that high mean effective pressures are obtained with low peak pressure and temperature, and with high thermal efficiency.

These desiderata regarding the working cycle are largely conflicting, and in order to arrive at the best all-around results, a certain compromise is unavoidable. The approach to these ideal characteristics is chiefly by suitably controlling the combustion, which in turn depends on the proper regulation of the state of the air and fuel.

This includes density, temperature, turbulence of the air, and the properties of the oil spray. Three factors are involved, as follows:

1. Introduction of the fuel at such a rate that too high peak pressures are avoided.
2. Distribution of the fuel uniformity in the combustion chamber, in order that complete combustion may be attained with the least waste of fuel and air.
3. Thorough atomization of the fuel in order that complete and rapid combustion of the charge be attained with as little time lag as possible.

Nomenclature of Fuel Injection.

In view of the paramount importance of the characteristics of the fuel spray for securing proper power output and high efficiency of the solid injection oil engine, these have formed the subject of thorough-going investigations by numerous individuals and research bodies.

Although an extensive literature deals with this subject, it appears that the terms defining the properties of the oil spray are not always consistently used, and are in need of sharper definition, according to K.J. DeJuhasz, Assistant Professor of Engineering Research, Pennsylvania State College.

For this reason, Mr. DeJuhasz presented a list of oil spray properties in an A.S.M.E. paper that are important from the combustion point of view together with their accurate definition. Some of these properties have an analogy with quantities used in electricity and also photometry, and in formulating some of these terms and defintions, use has been made of the well developed terminology of these branches of science. Mr. DeJuhasz offers the following terms and definitions:

<u>Time Rate of Discharge</u> is the weight of the fuel issuing from the orifice in unit time.

<u>Angle Rate of Discharge</u> is the weight issuing from the orifice during one degree of crankshaft travel. It can be expressed by the fraction $60q/360^{\circ}$ equals $q/6n$, where n equals rpm of crankshaft.

<u>Discharge</u> is the weight of liquid injected from the beginning to the end of one complete injection period.

Velocity of the Spray is measured with reference to the orifice. Symbol V, unit. Different kinds of velocity have to be distinguished, such as: Issue Velocity, which is the velocity measured at the orifice; Tip Velocity, which is the velocity of the foremost particle of the spray.

Mean Velocity of the Discharge: This is the ratio of the momentum of the spray to the discharge. It can be expressed by V_m equals M/Q.

Momentum of the Spray: This is the sum of the momentum components in the direction of the spray axes of the individual particles constituting the oil spray.

Intensity of the Spray in a given direction is the weight of fuel issuing in unit time through a cone enclosing a unit size of spherical surface at unit distance from the orifice, the cone having its axes in a given direction.

Fuel Distribution is the air/fuel mixture ratio in the combustion space.

Atomization: Though this word seems to be not particularly well chosen, it is, for lack of a better term, used to denote the size of the drops into which the fuel is broken up.

Penetration is the distance from the orifice which an oil drop attains at a given phase of the injection period.

Total Penetration is the distance from the orifice at which an oil particle comes to rest; that is, at which distance its velocity becomes zero. For a portion of the spray which issues in an infinitesimal time element the penetration can be represented by a curved surface.

There are, therefore, certain factors of fuel injection (Fig. 19) and the fuel spray which must be studied if a correct knowledge of the operation of this type of engine is to be obtained. These may be enumerated as follows:.

1. Physical properties such as viscosity, specific gravity, elasticity and surface tension of the fuel oil.
2. Nozzle length, shape and orifice area.
3. Oil injection pressure.
4. Pressure of the air into which the oil is injected.
5. Effect of pipe-line cross-sectional area and length.
6. Duration of the spray.

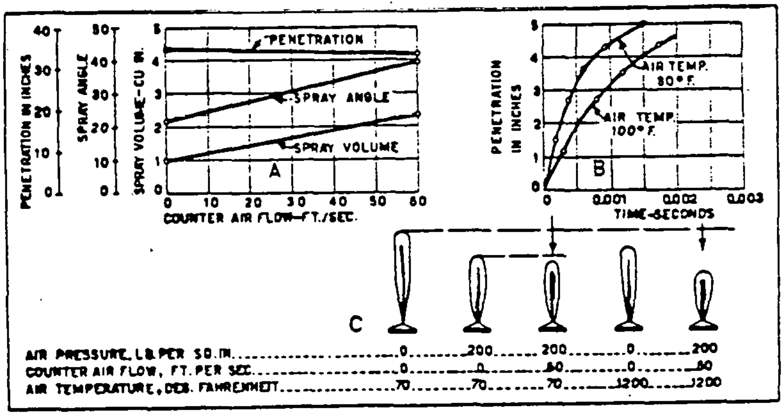


Fig. 19.—Effects of Air Pressure, Counter Air Flow and Air Temperature on Fuel Sprays (N.A.C.A.). A—Effects of Counter Air Flow. B—Effects of Air Temperature on Penetration. C—Relative Spray Penetrations.

12-2. CI Injection Systems.

Dr. Diesel introduced air injection as the means for atomizing and distributing the fuel throughout the combustion chamber. Here fuel was metered and pumped to the nozzle, (a mechanically actuated valve) which was also connected to a source of high-pressure air. When the nozzle was opened, the air would sweep the fuel into the engine and deliver a well-atomized spray even though heavy, viscous fuels were being injected. The size and cost of the air compressor, along with the power required for operation, has made air-injection obsolete.

Modern systems, with solid or mechanical injection of the fuel, are called

1. Individual pump systems, Fig. 12-1a (a separate metering and compression pump for each cylinder).
2. Distributor systems, Fig. 12-1b (a single pump for compressing the fuel [which may also meter], plus a dividing device for distributing the fuel to the cylinders [which may also meter]).
3. Common rail systems, Fig. 12-1c (a single pump for compressing the fuel, plus a metering elements for each cylinder).

All systems will be illustrated in following sections.

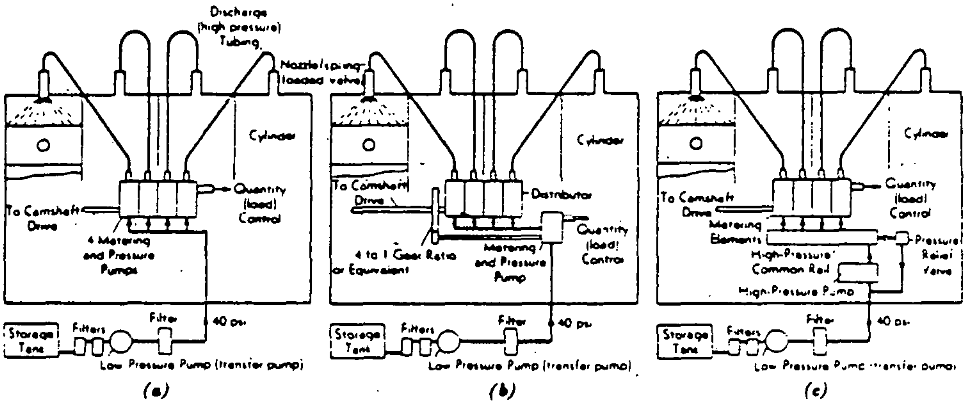


FIG. 12-1. Basic solid-injection systems. Four-cylinder, four-stroke, engines. (a) Individual-pump system; (b) distributor system; (c) common-rail system.

At least one low-pressure (40 psi) transfer pump (gear or vane type) is needed to lift the fuel from the tank, to overcome the pressure drop in the filters, and to charge the metering or pressurizing unit. Since the injection system invariably has close-fitting parts, several filters are necessary. Most fuel oils contain slight amounts of water, and a large amount of fine abrasive particles held in suspension. Bosch (Ref. 8) recommends three filters: (1) a primary stage (a metal-edge filter to remove coarse particles, larger than 0.001 in.); (2) a secondary stage (a replaceable cloth, paper, or felt element to remove fine particles, from about 4 microns to 0.001 in.); and (3) final stage (a sealed-nonreplaceable element to remove fine particles that escaped the secondary stage). The primary and secondary filters are placed between the storage tank and the transfer pump, with the final stage guarding the high-pressure or metering unit. (Most filters have water drains which should be opened frequently, while the supply tanks should be kept filled to avoid humidity condensation.)

CHAPTER IV

ENGINE CONVERSION FOR ALCOHOL FUELS

Introduction

Any gasoline engine can be modified to run on neat alcohol by eliminating plastic parts, changing the carburetor, and supplying a lot of heat to the carburetion and intake system, but to benefit fully from the advantages of alcohol as a motor fuel the engine must be specifically designed for that purpose.

The alcohol engine gives equal fuel consumption of that with a gasoline engine with a substantial bonus of greater power from the same size of engine. Advantages are available by using a smaller engine. This has particular application in aircrafts as well as giving fuel economy to automobiles.

Neat alcohol burns very cool. Since nitrogen oxides emitted by internal combustion engines originate from air being heated in the combustion chambers, a lower temperature of combustion will result in much lower levels of pollution without the necessity of any special devices. Alcohol engines are good for our environment.

The cool burning property of alcohol eliminates the possibility of burning valves, and opens up the possibility of designing large two stroke cycle engines.

Alcohol burns well with as much as 20 percent water added. The water adds bulk and cooling to operate gas turbine type engines very efficiently.

The cooling properties of alcohol also make it attractive to use for supercharging piston type engines. Alcohol does not evaporate as easily as gasoline. This becomes an advantage in tropical countries to avoid vapour lock of the fuel system. Unlike gasoline, alcohol is a pure chemical and does not degrade in storage.

Small alcohol fires can be extinguished using water, and alcohol fires don't start as easily as gasoline fires. Alcohol combustion is slower than gasoline and less noisy. Combustion of alcohol is more likely to be complete due to a wider range of fuel-air ratios which result in an explosion; the exhaust is practically odorless consisting mostly of water vapour and carbon dioxide.

The burning of alcohol forms no soot or carbon. Carbon build-up in an engine is eliminated. Pure alcohol burned in a lean mixture causes no undue corrosion in the interior of the engine.

The cool exhaust temperature of an alcohol engine results in less tendency to burn lubricating oil. Less cooling water and a smaller cooling system are needed to operate the alcohol engine.

There is no black smoke produced from an alcohol engine operating under heavy loads.

It seems reasonable to expect that the price of denatured alcohol will eventually become as low or lower than the price of gasoline.

A CHANGEOVER FROM GASOLINE SI ENGINES TO ALCOHOL OPERATION

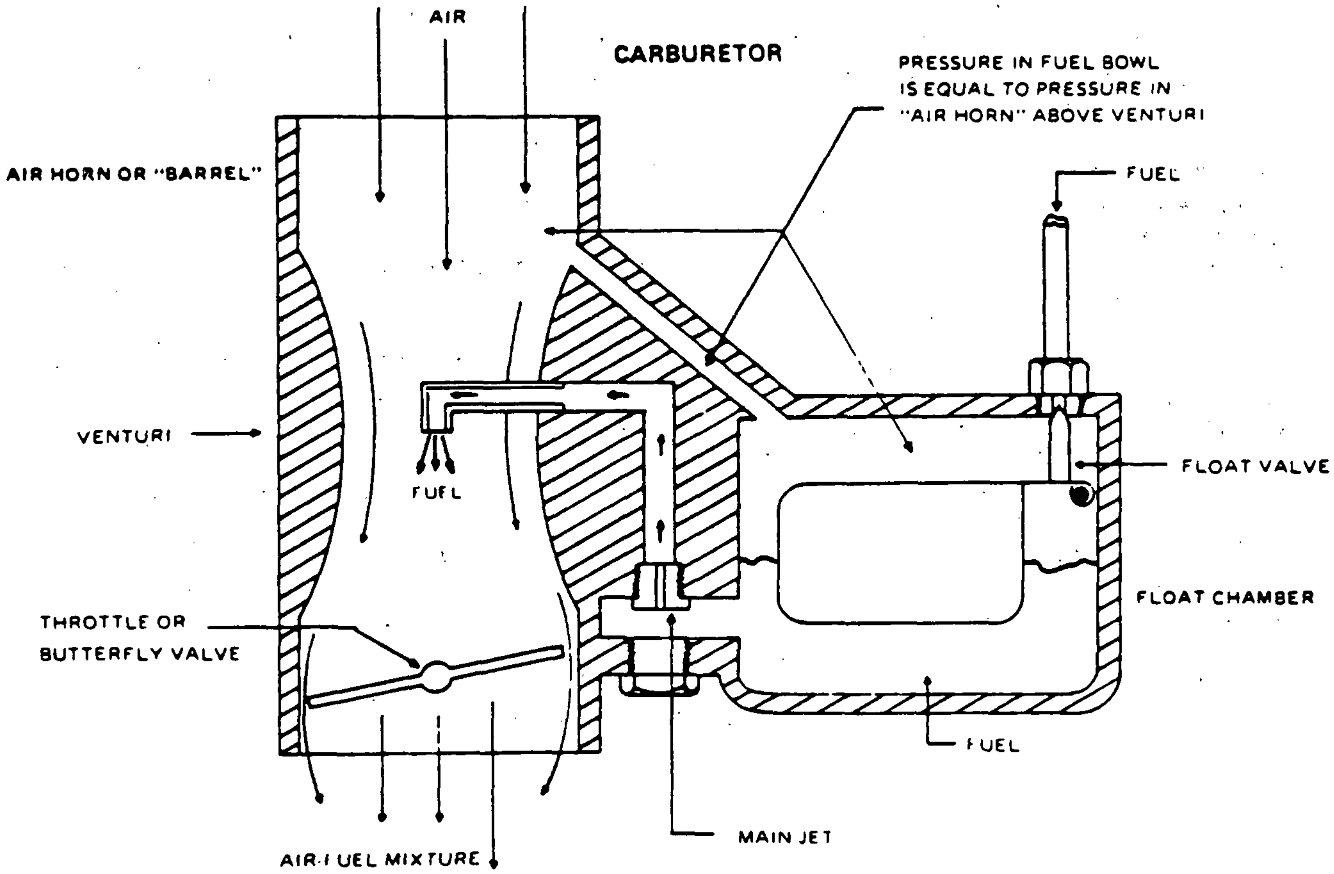
Vehicles which are to be operated with alcohols or mixed fuels containing alcohol must in every case by equipped with alcohol-resistant materials. The results so far available at Volkswagen suggest that it is sufficient for the use of M15 to select other materials for a number of plastic parts. Suitable materials are available. Their use in new vehicles does not involve any additional design expenditure and is possible with only a slight additional cost. On the other hand, in the case of the use of pure methanol and pure ethanol, especially with increased water content, corrosive attacks have also been observed on zinc injection molding and light metal materials as well as material connections. Parts of which are available today made of these materials must, in certain circumstances, be protected by an additional surface treatment. Additional costs will occur for this conversion which are in addition to the corresponding costs for conversion to M15. Further costs result owing to the increase in size of the vehicle tank which is required owing to the low alcohol calorific value as well as in certain circumstances owing to an adaptation of the chasis to the larger tank mass. A coarse cost estimate resulted for the additional costs which the purchaser of a pure alcohol vehicle would have to make as opposed to the purchaser of a gasoline vehicle which amounted to 200 dollars. A part of this amount would be required for the installation of a cold starting device when the vehicle would be operated exclusively with pure alcohol and without the assistance of a starting fuel. In the meantime, tests also revealed that, in the case of admixing lesser quantities (10 Vol. %), additives to alcohol (petroleum ether, dimethyl ether, isopentane) represent an exceedingly effective means for overcoming difficulties with cold starting and warm running. It is presently being investigated to find out whether, through this admixture, other operations-oriented problems (for example, with the hot start) would arise. If it should become possible to successfully formulate a "methyl or ethyl fuel" which satisfies all requirements, it is then possible to do without a cold start installation.

THE MANAGEMENT OF FUEL APPROACH

Excerpt from "Brown's Alcohol Motor Fuel Cookbook"

The first modification required to run an engine on alcohol consists of changing a tiny piece of brass called a jet. All carburetors designed to use liquid fuel have a jet, in the case of carburetors designed to work on V-8 engines there will normally be jets in multiples of even numbers. For example, a "two-barrel" carburetor will normally have two jets and two venturi tubes, a "four-barrel" carburetor will normally have four jets and four venturi tubes, and so on.

The venturi tube is a restricted passage in the body of the carburetor which causes the air to speed up, lose some of its pressure, and creates a partial vacuum. Since gasoline must be vaporized before it can be ignited and liquid cannot exist in a vacuum the partial vacuum created in the venturi tube helps vaporize the gasoline. It is possible to build a carburetor without a venturi tube. In the early 1900's some manufacturers did.



If all you want to do is be able to get from point A to point B on alcohol all that is required is a 40% enlargement over stock size of the main jet. That is, just make a 40% larger hole in it. The hole in the main jet that the gasoline flows through is normally in the .050 to .060 range. Just multiply the size of the main jet by 40% and add the product of the multiplication to the size of the main jet. Then find a drill bit to correspond to that dimension.

At this point the purist will be setting up his drill press but a handheld drill will work almost as well.

You can usually get the exact size jet your carburetor requires from the specification charts in most automotive repair manuals. Otherwise you had better take your jet (or jets) to a machinist and have him measure it (or them) for you.

There are several different schools of though as to why the jet(s) must be bored out to accomodate an alcohol-powered engine.

The first is that alcohol requeires a fuel/air or air/fuel ratio of 9 to 1 to ignite in the engine. That is, nine pounds of air for every one pound of alcohol. Gasoline requires a 15 to 1 ratio of air to fuel. The difference between alcohol and gasoline is roughly 40$. The alcohol carries oxygen in the fluid where gasoline does not, which may explain why alcohol requires less air to detonate or ignite. After the new jet is installed or the enlarged hole is done, the No. 44 would cause the engine to consume more fuel, through.

It is time for you, me, or us to reassemble the carburetor, stick it back on the vehicle, and run our first road test..

Be prepared for a couple of disappointments.

The first is that our car won't idle.

We didn't set the screws on the bottom of the carburetor which control what mechanics call the idel circuit, for alcohol. they have to be opened up. At this point, if we can feather the accelerator pedal and keep it running; let's just do that. We'll cover needle valves and such a little further on.

The next thing we notice is that our car doesn't seem to have any oomph at low speed (or rpm's). Most race car drivers never notice this since almost all their driving is done with their right foot all the way to the floor. Alcohol burns slower than gasoline and this is where we find out about it. It is especially noticeable on low-compression engines. On my old 1948 74 Harley-Davidson with 6.6 to 1 compression ratio it was all I could do to get it going more than 20 mph up a steep hill in the neighborhood. In most cases an old Harley-Davidson will literally walk up the side of a building. I could modify the machine to run on alcohol where it would out-climb and out-run any other comparable Harley in Kentucky if I was willing to forfeit gasoline complete as a motor fuel.

On the plus side, the "steam engine" effect of alcohol in a gas engine makes for an incredibly smooth ride down the road. The slower burning alcohol appears to lessen engine vibration considerably.

The last thing we notice as we refill the fuel tank for another road test is that we used a lot more fuel than we did with gasoline. If we got 18 mpg with gasoline all we got with alcohol was 10 mpg. This is, of course, if all we did was drill out the main jet or jets.

Fuel economy and power have been measured by a number of research departments using what are known as "bench tests." A stationary engine is hooked up to a dynamometer, emission control equipment, and so on. I did the same thing at Berea College. Such tests leave much to be desired since you can't climb a hill with an engine bolted to a shop floor and the air flow into the carburetor air horn simply isn't the same. There are too many variables. Not to mention most bench tests are almost always conducted at full load throttle.

If you drill your jets too large or too small a number of undesirable consequences occur.

If your drill is too large the resulting hole causes enormous fuel consumption. Alcohol will keep burning in an engine long after the same percentage (proportionately) of gasoline would have simply flooded and stalled the engine. In one case I heard of a race-car driver who had his main jets removed by his mechanic without his knowledge and drove off anyway: shooting 30 foot flames out of his tailpipes. Since alcohol has a generous supply of oxygen in the compound its propensity to keep running might be explained.

If your jet size is too small you are subject to burn your valves. A gasoline-fueled engine when the jets are too small will sputter and misfire. An alcohol-fueled engine with slightly undersized jets will simply burn a lot hotter, which in turn burns valves. Most American cars are designed to use unburned fuel and tetraethyl lead to lubricate the exhaust valves. This might not be a problem with engines designed to use unleaded gas since they come from the factory with hardened valve seats. Of course, fuel use or consumption goes down with small jets.

Valve burning can be prevented several ways. One is to simply chuck a half-cup of vegetable oil into the fuel tank with the alcohol. Diesel fuel (a half-cup) could be used in a pinch but is not recommended since alcohol and petroleum products will not mix if there is any water in the alcohol (there usually is).

If the engine runs cool enough, water in the alcohol will sometimes act as a valve lubricant. Sometimes.

The best procedure to follow if you are really serious is to install stellite or stainless steel racing valves with hardened seats. A lot of propane-powered vehicles are modified in this fashion since the propane burns completely dry in an engine.

If all you intend to do is go out and buy a spare carburetor for the day the gas pumps shut down there are a few pieces of information you might want to digest first.

You can normally put a Ford carburetor on a Chevrolet and vice versa with the aid of adaptor plates, you might want to consider it if push comes to shove since some carburetors are a whole lot easier to work on than others. A two-barrel Rochester has to be completely taken apart to get at the jets. You don't have to take the guts out of it but you do have to disconnect all the linkage and separate the top and bottom halves. A Holley has the jets behind the float and all that is required is for the float cover to be unbolted and the jets screwed in or out. Holleys have horizontal jets. That is, the holes in them are parellel to the horizon when the carburetor is mounted on the vehicle. Amost all others have vertical jets.

If you are willing to go to the extra trouble and expense you don't have to get out the toolbox very time you want to switch from gasoline to alcohol. Or back. There is only one thing required.

It's called a needle valve and at one time almost all carburetors came equipped with them. A tapered shaft was inserted into the main jet by means of a screw thread adjustment. The screw thread adjustment allowed the tapered shaft to be moved in and out of the hole in the jet. The further the shaft was inserted into the hole the smaller the opening (the hole) became. As it was unscrewed or withdrawn the opening became larger, which meant that if the hole area was .059 all it take is a flick of the wrist to bring it up to .082.

Since such precise measurements are almost impossible with the wrist, either the setting had to be done by ear or an rpm gauge had to be used; or a vacuum gauge. Ecology fans sometimes use emission control gauges (like on a Sun Tester) to set the opening, which is not a bad idea since less unburned hydrocarbons means that more fuel is being utilized by the engine which in turn means better mileage.

Most American car builders went to the fixed-jet principle with the advent of the down-draft carburetor. Most of the old updrafts (the air was sucked from the bottom up instead of the top down) had adjustable needle valves. Main jet adjustments come in quite handy for altitude adjustments as anyone who had ever driven from L.A. to Denver will tell you.

If you don't want to mess with all the rpm and vacuum gauges, you don't really have to. It's not mandatory. All that is required is a good "ear" to listen to the engine with. Start unscrewing the needle valve outward when you are going from gasoline to alcohol. On too lean a mixture of alcohol the engine will hestitate and sputter. Simply listen for the engine "smoothing out" and that's the setting you run it on. It might take a little practice. If you have ever used a power lawnmower that had a carburetor adjustment then you have already had the practice.

There are a few engines and a carburetor or two still on the market that come factory equipped with a main jet adjustment. Faucet carburetor corporation markets a number of carburetors with main jet adjustments for stationary power plants. Their primary drawback for automotive use is that such carburetors have no accelerator pump, meaning you might be able to get from point A to point B if you don't mind creeping through every intersection, never passing another car, and having your car die on you every time you push the gas pedal down a little too far.

Many small air-cooled engines have main jet adjustments. Normally labeled as needle valves in the parts manuals. I have 3 hp Briggs & Stratton with a Flo-jet carburetor that has one that I use for demonstrations - just twist the needle valve adjustment out one and a half turns, pour in a pint of liquor store whiskey, and fire it up.

My ten year old son uses rubbing alcohol in two of his Tecumseh engined mini-bikes. Same adjustment. He doesn't have to impress anybody with or by breaking a government seal and the rubbing alcohol is a whole lot cheaper. Obviously rubbing alcohol is a lot more expensive than gasoline, but it still beats walking.

The only full-sized vehicle still equipped with a main jet adjustment when it comes from the factory is probably the Harley-Davidson. At least, that's what the catalogs and around at 40 mph with your foot all the way to the floor-board) you should be able to run either gasoline or alcohol depending on how far up or down the rods are in the jets.

I say should, because if you aren't an experienced mechanic or machinist don't even think about it.

Another method is to simply buy two Quadra-jets, cut off the back two barrels with the metering rods in them on both of them, set them aside or throw them away, turn one Quad around backwards and weld them together. Welding pot metal isn't easy but there are folks who can do it. Install a gasoline fuel line to either the front or back half of the carburetor. Enlarge the jets and install an alcohol fuel line to the other half of the carburetor. Run the alcohol and gasoline fuel lines to their respective fuel tanks with shut off valves. You now have a duel-fuel carburetor. Obviously, you are going to have to fabricate an adaptor plate for the intake manifold.

There is one other carburetor adjustment possible if what you are after is maximum economy. As anyone who has worked on carburetors knows, float adjustment can alter fuel economy. Rather than go through a lot of trial and error adjustments the easiest thing to do is simply weigh the float on a gram scale, figure out what 10% ofthe total weight of the float is, and braze (or glue if you can get any to hold) that amount of weight to the top middle of the float. Remember, alcohol as a fluid is 10% heavier than gasoline.

THE 100 MILES PER GALLON ALCOHOL CARBURETOR

You have probably heard all the stories of someone's uncle who bought a new car, drove it around for awhile, and found he was getting 50 miles to the gallon of gasoline. You may have pooh-poohed the stories.

Don't.

There have been numerous inventors who tried to build such carburetors and succeeded. Every single one of them was designed and built on easily verifiable physical laws. Starting with the first one in 1912, including several built by Charles Pogue of Winnipeg, Canada in the 1930's that consistently reappeared in a 100 mile per gallon device built by a mechanic named Tom Ogle from Texas.

The standard carburetor is a rather crude device compared to what it could be. Fuel injection isn't much better. What happens when the fuel is sucked into the engine explains why today's carburetors are so crude.

As the gasoline passes from the venturi tube of the carburetor into the intake manifold and then into the cylinder it is supposed to be turned into a vapor. Only a vapor will ignite under the spark plug, small liquid droplets either burn or are simply heated up enough to leave in the exhaust manifold in a vapor state (too late to get the job done). A standard carburetor and intake manifold vaporize part of the fuel and allow part of it in the form of small liquid droplets into the combustion chamber. If it gets too bad in the intake manifold it is known as "pudding" or flooding. The compression stroke raises the internal temperature of the cylinder high enough to vaporize more fuel but still leaves it far short of the complete vapor state which is how and why the 50 mile per gallon carburetors work. The gasoline is simply turned into a complete vapor before it is allowed to enter the combustion chamber or cylinder which is turn means a lot more energy is extracted from it. You can verify this in a high school chemistry book. The auto manuals tells us the correct mixture for a standard carburetor is 15 pounds of air to 1 pound of fuel. Yet a high school chemistry book tells us that the correct explosive mixture for a vapor - any vapor - is 50 pounds of air to 1 pound of explosive liquid. Apparently two-thirds of our fuel is being wasted and we are only counting the power in the carbon of an explosive hydro-carbon.

Another way you can verify this tremendous fuel loss (or inefficiency) in our modern engines is to simply hook a spark plug into your tailpipe and wire it up to your electrical system. Make sure you have a switch or other method of disconnecting it. Drive down the road at night and flip it on. The unburned fuel coming out of the tailpipe will cause 30 to 40 foot flames.

The high-mileage carburetors did have a number of problems. The first obstacle that had to be overcome was the complete vaporization temperature of gasoline: well over 400 degrees F. Some parts of the gasoline, ordinary gasoline if actually a series of compounds vaporize as low as 90 degrees F., but only some, and 400 degrees heat causes other problems. Like warning the incoming air so much that the engine losses considerable power.

The main obstacle to any type of production was the amount of plumbing or gadgetry required to make a vapor-phase carburetor work. The ones built by Charles Nelson Pogue was almost the size of the engine itself, and a lot more complicated.

It is the opinion of this writer that the Pogues, the Ogles, and all the others had the right idea, they just used the wrong fuel.

Had they used alcohol, the attempted (and sometimes successful) attainment of 400 plus degrees temperature would have been totally unnecessary. Alcohol is a single compound that vaporizes at a temperature of less than 180 degrees F. Over 30 degrees F. less than the boiling point of water. Plus all the parts for such a carburetor are already production items available almost everywhere in the United States.

Propane parts will do for alcohol what $100,000 worth of tooling and research has done for gasoline. The reasoning and arithmetic is astoundingly simple.

Propane and gasoline will give almost the same mileage in the same vehicle. In many cases a car getting 20 miles per gallon will deliver 18 miles per gallon on propane. Yet the energy available in a gallon of gas is EIGHT TIMES that available in a gallon of propane. Logically and proportionately the gasoline should move the vehicle eight times the distance of the propane. In the cases of Charles Nelson Pogue, it did.

Propane vaporizes at 30 degrees F. below zero. By the time it gets to the engine block it is a complete vapor. The way gasoline should be the low vaporizing point of propane is the reason for keeping it in pressurized tanks. In some cases propane is passed through a pressure regulator filled with hot water to vaporize the fuel. Such hot water, if above 180 degrees F. and the passage fuel goes through is long enough to raise it to the same temperature, will also completely vaporize alcohol. A propane carburetor must be used since a vapor will not work in a normal carburetor with jets and float bowl.

This gives us the following mileage figures: if gasoline has eight times the energy of propane and alcohol has roughly five and one-half times the energy of propane. If our vehicle run 18 miles per gallon on propane and we multiply that performance by five and one-half we arrive at a figure of 99 miles per gallon. If, of course, the cooling water on a condensor on an alcohol still is allowed to get too hot. The same principle applies to a motor vehicle engine.

At this point I realize there are a lot of skeptics. Don't knock it until you have tried it. Charles Kettering, inventor of the electric starter and one of the "big guns" of the automotive world, said, "If the compression ration of an engine of 6.5 to 1 were raised to 10 or 12 to 1, little gain in power and efficiency should be expected due to the internal friction which is brought about by their lack of ragidy. Roughness, increased friction and other mechanical problems tend to counteract any gains from high compression ratios." He said this in 1947, over thirty years after he had invented the electrical starter. Published in MORE EFFICIENT UTILIZATION OF FUELS for the

Society of Automotive Engineers summer meeting of June 1-6, 1947. Thirty years after his remarks, Detroit was spewing out engines with 10.5 to 1 compression ratios by the trainload and some engine builders, such as Chrysler, sell off-the shelf parts of enable a car owner to raise his compression ratio to 12 to 1. Just because someone says something, including an expert, does not make it so. If Charles Kettering can be so wrong so can the skeptic down the street.

COMPRESSION

How much the piston compresses the fuel in the combustion chamber determines to a large extent how much energy is extracted. Back in 1906 folks at the Department of Agriculture thought they had really done something when they ran alcohol-fueled engines on compression pressures of 180 lbs per square inch. Tetraethyl lead hadn't been discovered and gas at that pressure would simply blow the engine apart. Today most gasoline powered engines operate in that pressure range.

The compression ratio of most full-size auto engines manufactured in the last fifteen to twenty years is usually 8.5 to 1 or better. If you run alcohol in your engine you won't have anywhere near the power loss problems I had in my old Harley-Davidson. However, to extract maximum power and economy from alcohol, the compression ratio can be raised to 15 to 1 on most engines. If you intend to use gasoline also you will have to compromise since at 15 to 1 gasoline will simply blow the engine apart. 12.5 to 1 will work if you stick strictly to premium gasoline. There are a number of ways to modify the engine in this regard.

The most expensive ways appear to be the most well-known. Install high compression pistons. Pull the cylinder heads off, strap them to a milling machine, and remove some of the metal, called "milling the heads. "Take the main body of the engine and shave more metal from it, called "decking the block." Expensive, complicated, and time consuming.

The easiest way to raise a compression ratio on a large engine is to simply pull off the stock cylinder heads and replace them with ones from a smaller engine. For example, if you have a 350 engine just go to a junkyard and pick up a set of 255 heads. Be sure your junkman looks in his parts books and verifies that the 255 heads from that make and model have the same belt pattern as yours and will belt right on. Normally this will raise your compression ratio to the 11.5 to 1 range. If you have a large-block engine, you may have a problem.

It is not even necessary to clean the carbon off the heads if you are going to run alcohol first. Just bolt the nasty things on. The alcohol will clean them up as you drive. Before World War II many Europeans would run a tank of alcohol through their cars every now and then because of the natural biological solvent properties of alcohol. The alcohol would pick up all the gum and varnish out of the fuel tank, fuel lines, and carburetor (sometimes plugging up the jets), and clean all the carbon off the cylinder heads. If you have carbon deposits on your present cylinder heads its easy to tell. Your car will keep running after the ignition has been shut off since the carbon deposits become hot enough to ignite the fuel on their own, called "dieseling."

How fast the alcohol cleans the carbon off is amazing and has to be seen to be believed. The head chemist of the Alcohol Fuels Corporation of Gering, Nebraska and I were running alcohol through a variable-compression engine one day to see how high a compression ratio and the engine would start knocking. In a few seconds a layer of carbon would be cleaned off and he would raise the compression again. The engine would start knocking again, the next layer of carbon would be cleaned off, he would raise the compression again, and so on.

IGNITION

Alcohol is a cooler and lower burning fuel than gasoline. The slower burning requires an advanced ignition timing. That is, the spark plug must fire a point or time before what it would require for gasoline. Timing for alcohol is not a mandatory procedure but it does help to give better fuel economy and power.

Timing for gasoline is usually set by a timing mark on a flywheel pulley in front of the engine and a strobe light. The timing mark is put on at the factory and it is not always accurate. If it is, then for alcohol you must set the timing somewhere ahead of it. The accepted procedure is to simply time it on gasoline, start it up on alcohol, and then turn the distributor until the engine starts knocking, a few degrees in front of the position it begins to knock is your setting. If you want to be really scientific about it use astethoscope to pick up all the engine noises and knocks.

Blank

The absolute best way to go back and forth from gasoline to alcohol is to install a spark advance on the columnn like the old model A Fords had. Once installed you can change timing in an instant.

If you are going to run alcohol only in your engine, you may want to run hotter spark plugs in your engine. You will have to experiment.

COLD WEATHER STARTING

After several weeks of running bench tests at Berea College with my alcohol-fueled Briggs & Stratton, I thought I had the energy crunch solved. Alcohol Polluted less. It gave more power at high rpm. It could be produced from renewable starch and sugar crops. It started on the first crank every morning, better than gasoline.

Or so I thought.

On a cold morning in November I walked into the shop, set the choke on the carburetor as its usual setting, and yanked on the recoil starter. It should have started.

But it didn't.

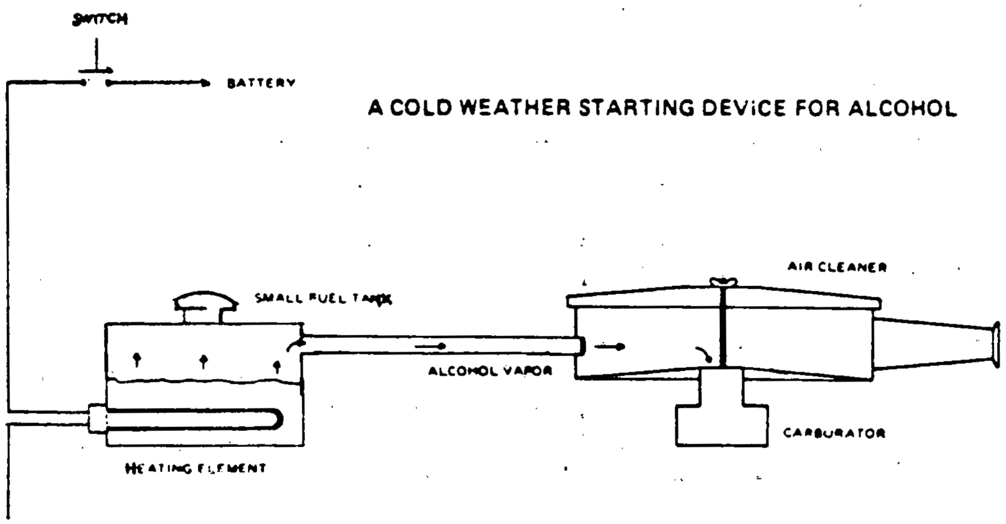
Half an hour later I was still yanking on the starter cord and nothing was happening. It finally dawned on me that something was wrong. Either something with the engine or the fuel. Since the fuel was the easiest to check I drained the tank and refilled it with gasoline. It started right up. Therefore, it had to be the fuel, which led me to the conclusion that alcohol would not ignite readily in freezing weather.

I was only partially correct.

A few minutes after I got the cole engine running on gasoline I switched back to alcohol just to see what would happen. It worked perfectly. My next conclusion was obviously that in cold weather an engine had to be started on gasoline first. All I had to do was get the engine warm.

A two-way directional valve would solve running the different fuels into the same carburetor but then there would be the problem of different jet sizes. A duel-fuel Quadra-jet or a carburetor with an adjustable needle valve would work. The other alternatives simply consist of a spray mist of gasoline introduced into the engine via a nasal spray bottle (just hold it over the carburetor air horn and squeeze, hook up a windshield spray device but load it with gasoline, or use a diesel starter fluid tube. Don't use a bottle of ether unless you know exactly what you are doing. The stuff has a tendency to blow head gaskets.

Chrysler solved the problem in 1936 in cars exported to New Zealand that were set up to run alcohol from the factory (New Zealand had no domestic oil supplies) by putting heat on theintake manifold under the float blow. Once an engine is started it will run on alcohol at 20 degrees F. below zero with no problem.



A COLD WEATHER STARTING DEVICE FOR ALCOHOL

A method used early in the 20th century was to simply add benzine (from petroleum) or benzene (from coat tar) to the alcohol to raise the vapor pressure. Messy.

The best method I have come across is to simply install a small sealed fuel tank off to one side of the engine with a heater element immersed in the fuel. A tube leads from the small fuel tank to the air cleaner. When the heater element is activiated the alcohol heats up past 180 degrees in a matter of a minute or two, the vapors rise into the air cleaner, and the vaporized fuel ignites instantly when the engine is cranked over and the fuel makes contact with the spark plug flame.

DEVELOPMENT OF METHANOL AND PETROL CARBURATION SYSTEMS IN THE NETHERLANDS

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Carburetion systems for methanol tend to become rather complex due to the fact that a higher amount of the fuel has to be carburated together with the fact, that the heat of evaporation is very high. The problems arise particularly with respect to the driveability and the cold start. Also the shortage of a methanol/petrol mixture aboard of the vehicle is difficult when the methanol content exceeds 15%. The research and development work in the Netherlands regarding hardware development to meet these problems will be presented.

1. Modification of a constant venturi carburetor.

The scope of this part of the work was to convert a constant venturi carburetor to enable the car to run on petrol or methanol by means of electrical switching from the dashboard. The data of the car and the carburetor are as follows:

BMW 2000, 1968. Solex carburetor 36-40PDSit.
In figure 1 the layout of this system is given.

It will be noticed that the system operates relatively simply. The main jet and the idle jet are drilled or set for pure alcohol fuels operation. By actuation of solenoids separate for the main jet and the idle jet, the cross area of the jets is reduced by about half. Thus the setting for petrol.

The test results of this system are expressed in general terms as follows:

Petrol carburetion: nearly the same as the original situation.
Methanol carburetion: air fuel ratio control reasonable
Homogeneity of the mixture: poor
Cold - start condition: not lower than + 50°C (without additive in the methanol)
Driveability: poor (due to the maldistribution and some richer setting to increase driveability)

A further disadvantage of the system is that for retrofitting of modern two or more barrel carburetors the amount of parts to be fitted is rather high, while often the accessibility to the jets is insufficient.

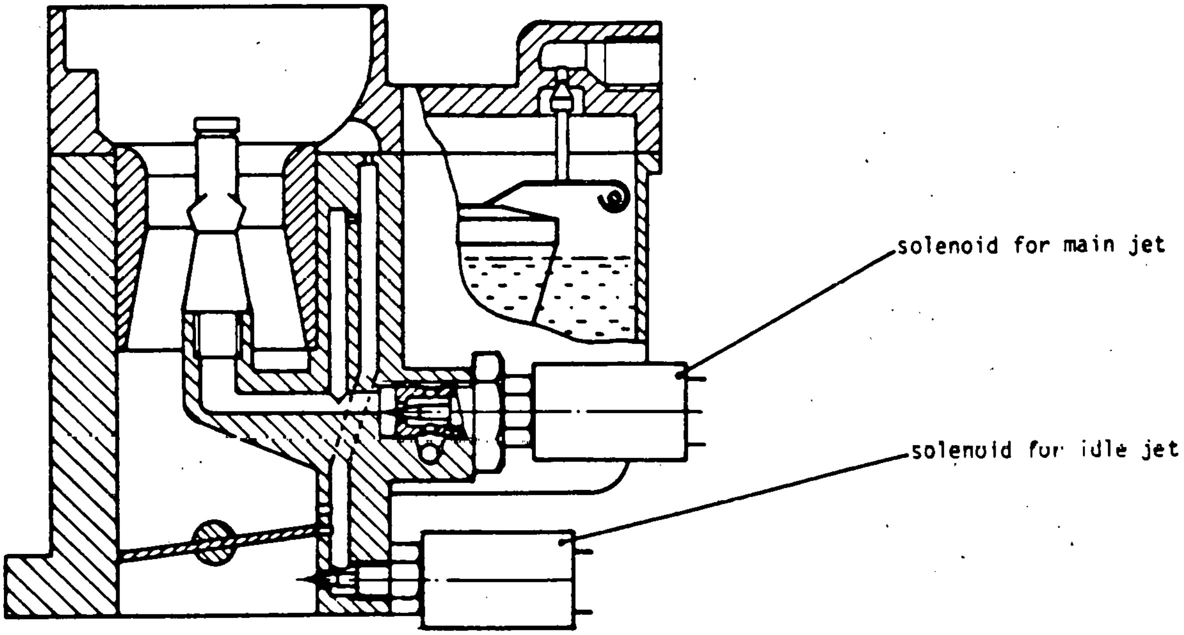


Figure 1. A constant venturi carburetor modified for petrol operation. In methanol operation, the solenoids clear the jets.

2. Modification of a constant vacuum carburetor.

The scope of this part of the work was to convert a constant vacuum carburetor to enable the car to run on petrol or methanol by means of electrical switching from the dashboard. The data of the car and the carburetor are as follows:

Mercedes 220, 1969, 4 cylinder, Stromberg carburetor 175CD.

In figure 2, the layout of this system is given.

It will be noticed that the system operates relatively simply.

The test results of this system are expressed in general terms as follows:

Petrol carburetion: nearly the same as the original situation.
Methanol carburetion: air fuel ratio control reasonable.
Homogeneity of the mixture: poor
Cold starting condition: not lower than + 50°C (without additive in the methanol)
Driveability: poor

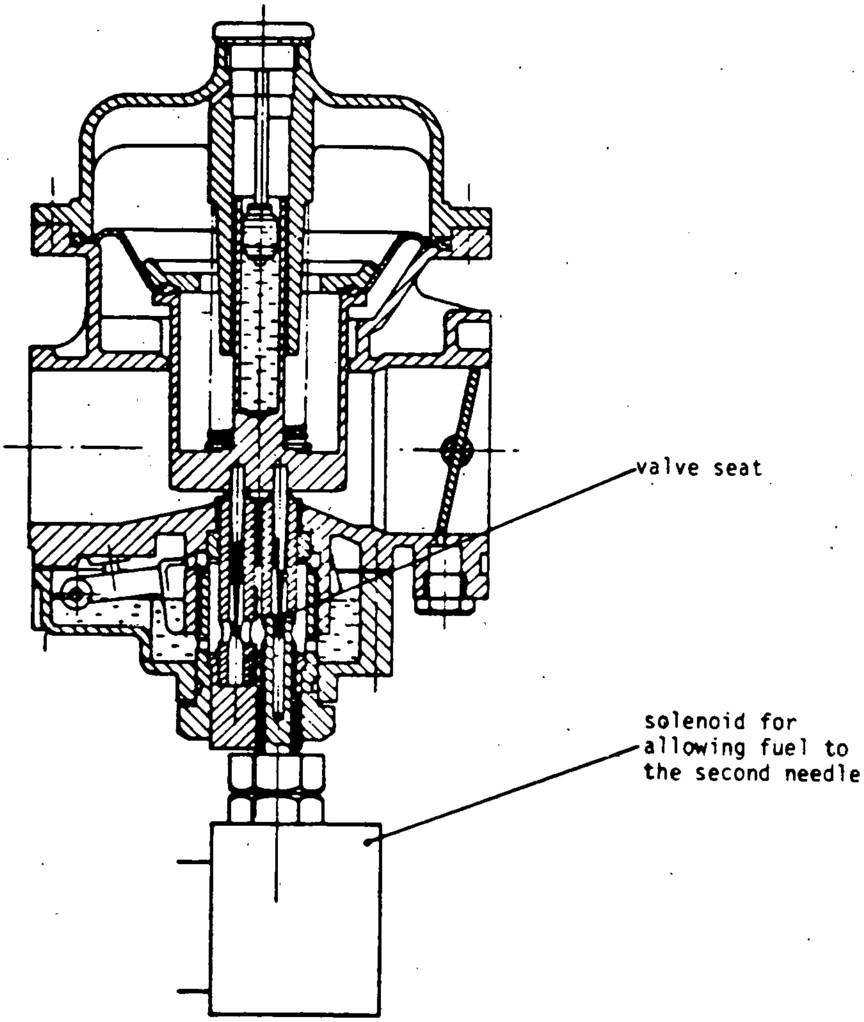


Figure 2. A constant vacuum carburator modified for petrol and methanol operation. In methanol operation the solenoid allows fuel to the second needle.

Normally this type of Stromberg carburetor has one needle, which controls the amount of fuel in an orifice. In this case the construction has been made so that two needles operate in two orifices but the admittance of fuel to one orifice can be shut off or opened electro-mechanically. Thus with petrol carburetion one needle is controlling the amount of fuel similar as in the original conditions, while at methanol carburation the second orifice is also opened, hereby doubling the amount of fuel.

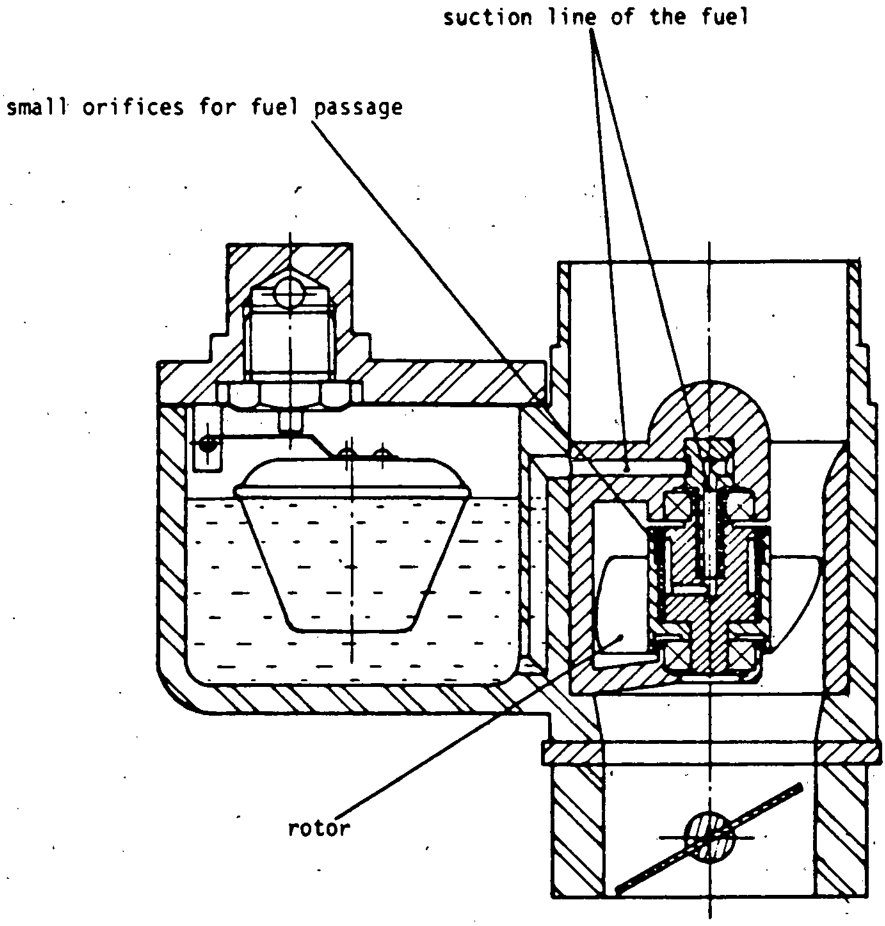
An important advantage of this system is that for retrofit the number of parts is low and the fitment work to be done is rather simple.

3. Rotorcarburator.

The company Autoelektronik AG Chur at Zurich, Switzerland is developing already during some years a new type of petrol carburetor which works on the following principle. In the air-duct above the butterfly a rotor is fitted which is forced to high speed rotation by the passing air. The fuel is sucked centrally and is enforced centrifugally through small orifices with a relative high pressure of many atmospheres. When the air speed increases the speed of the rotor increases linear with it. Pressure on the fuel is square, while the fuel speed through an orifice increase by square root. Thus principally a constant air fuel ratio is obtained over the whole range.

Within the scope of this part of the work only a methanol carburetor with this system was created, thus not suitable for petrol.

In cooperation with the mentioned company such a carburetor was adapted for methanol operation. Because part of the fuel is thrown against the walls of the duct, an external heating of this duct was created by copper piping. In figure 3 the layout of the system is given. On photo 3 a prototype is shown. For test purposes this carburetor was fitted in a Peugeot Van J 7, 1971. In general terms the results can be described as follows:



Petrol carburetion: has not been tested with this vehicle, but from other experiments it is known that the system can work properly and create expecially a good mixture homogeneity, so a good distribution.

Methanol carburetion: air fuel ratio control poor, especially at engine full load.

Homogeneity of the mixture: reasonable.

Cold starting condition: + 10°C (methanol without additives). This can be improved by creating a better cold starting device.

Driveability: poor

Exhaust emission: poor, due to incomplete air fuel ratio control.

It should be noted that theoretically the carburetor can be enlarged with a device which enables it to run on a petrol as well. Then internally a variable restriction has to be fitted while the rotating orifices have to be enlarged. But it can be expected that the characteristics will be influenced by that.

4. Fuel injection system.

Within the scope of this part of the work a fuel injection system for methanol which can be retrofitted was developed. This is mainly done because of the poor performance of the system earlier described. This system enables the car to run on petrol on its original carburetor and to run on methanol on an additional injection system. With methanol operation the fuel supply to the carburetor is shut off. A layout of this system is given in figure 4. An important goal of this system is to enable different makes and types of cars to run on methanol and petrol with standard components and with minimal special adaptions for the different cars. The principle of operation of the system is as follows. In the air inlet a rotor (rather similar to the one described under chapter 4) is fitted, with a photo electronic sensing of the speed. Thus the amount of air is sensed electronically. Through a double gasket of the intake manifold small injectors are fitted which inject the fuel to the intake valve. The injectors themselves are very small, while the opening and closing is performed by modified Bosch injectors.

By the electronic system the air speed is, in relation to the engine speed, converted to the opening time of the injectors.

The fuel is kept under a constant pressure of 1.5 bar. The timing of injection is directed by a signal from the distributor.

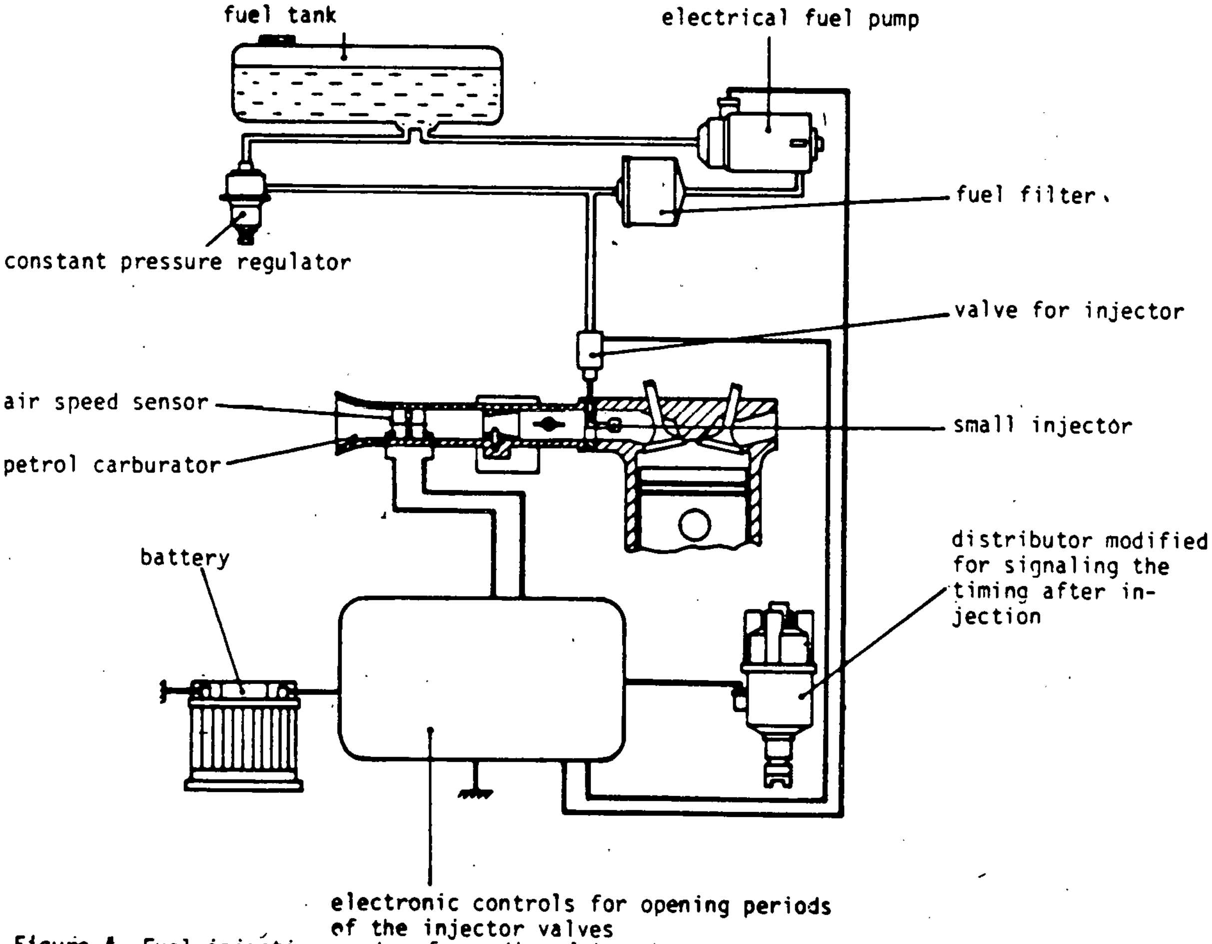


Figure 4. Fuel injection system for methanol based on variable opening times of injectors.

Photo 4 shows the mounting of the injectors in a double gasket of the inlet manifold.

Photo 5 shows a complete injector with solenoid valve.

The test results of this system are expressed in general terms as follows:

Petrol carburetion: remains original. The small injectors in the intake manifold do not create an influence
Methanol carburetion: air fuel ratio control good
Homogeneity of the mixture: good
Cold starting condition: 0°C
Driveability: good, when engine is warm, poor when engine is not warmed up yet
Exhaust emission: fair

So far this system gives the best results. A point of concern however is the cost of such a modification kit. This of course depends also on the future fuel price and tax policy of governments. Said otherwise, when the fuel is cheap enough, relatively high costs of a conversion unit are no problem.

The costs of such a modification kit in large scale production are not yet calculated.

5. Transducer for the detection of methanol/petrol ratio.

In this part the work is described of the research and development of a transducer which could enable cars to run on all mixtures varying from 100% methanol to 100% petrol even when such a mixture is homogeneous, or even with a nearly complete separation of the two fuels in one tank. It is clearly mentioned that this work is not yet completed, also it is questionable if it ends positively. Of course it would be highly attractive to have a system which can be retrofitted and which can handle both fuels out of the same tank. This would highly overcome the problems of a slow growing infrastructure for methanol fueling stations as mentioned in the introduction. Then also the problem for car manufacturers to start production of the vehicles capable of running on methanol would be overcome.

Due to the strong chemical and physical differences in electrical characteristics could be measured in a relatively simple way and be used in the system described in chapter 5.

Also the system described in the chapters 2, 3 and 4 could in principle be adapted with such a transducer but than the yes-no controls which are described there have to be replaced by proportional controls like e.g., analogue electrical-mechanical valves. A transducer was built existing of two concentrical isolated tubes. A cross-section of this transducer is given in figure 5. Photo 7 shows a prototype transducer.

This transducer can be mounted in the feedline of the fuel injectors or just before the carburetor for metering. The difference in electrical conductivity of the mixture.

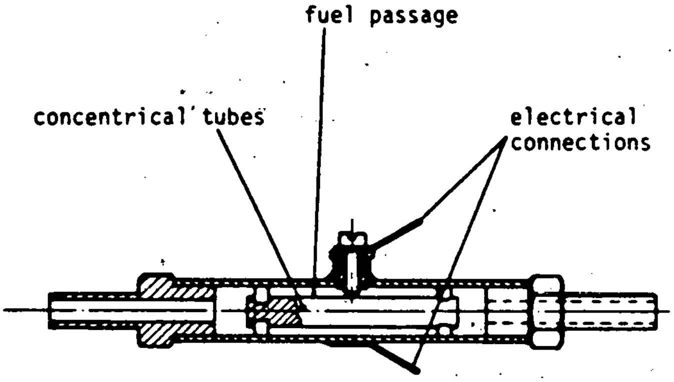


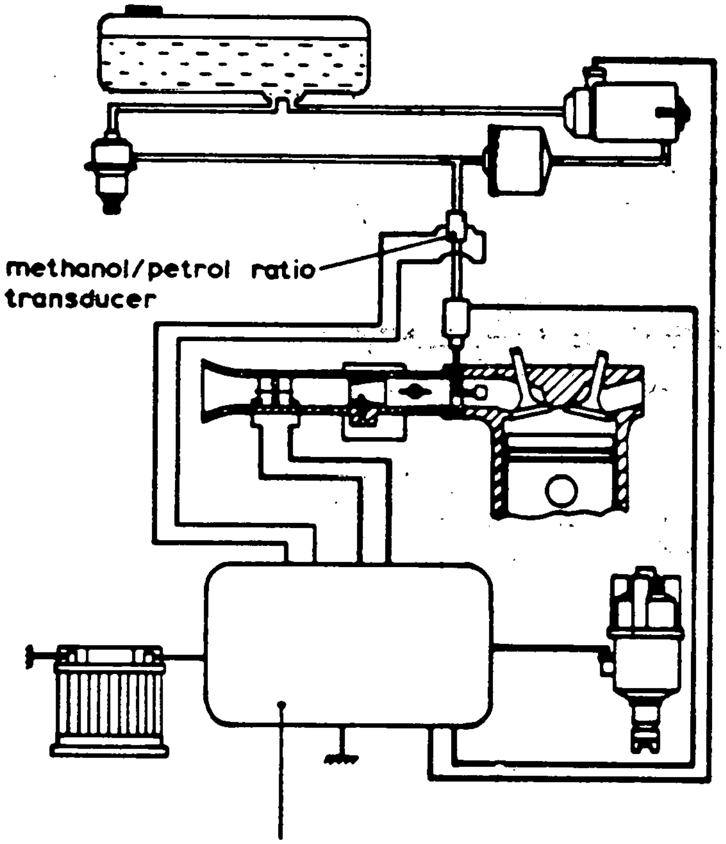
Figure 5. Transducer for detection of the petrol/methanol ratio based on measurement of conductivity, capacity or tangens-ϕ measurement.

6. Fuel injection system with methanol/petrol

This system which we have in mind is not yet in operation due to the fact that the work on the methanol/petrol ratio is not yet completed as described in chapter 6.

Probably at the meeting in November some more information concerning this system will be available. In fact this system is completely similar to the system described in chapter 5 but with the sensor.

When the sensor can work properly with limited amounts of electronics behind, the period of injection will depend on the ratio of petrol/methanol. Thus as 100% methanol the period of injection will be about double compared to petrol, while for the ratios between the period of injection is adapted linear to that ratio.

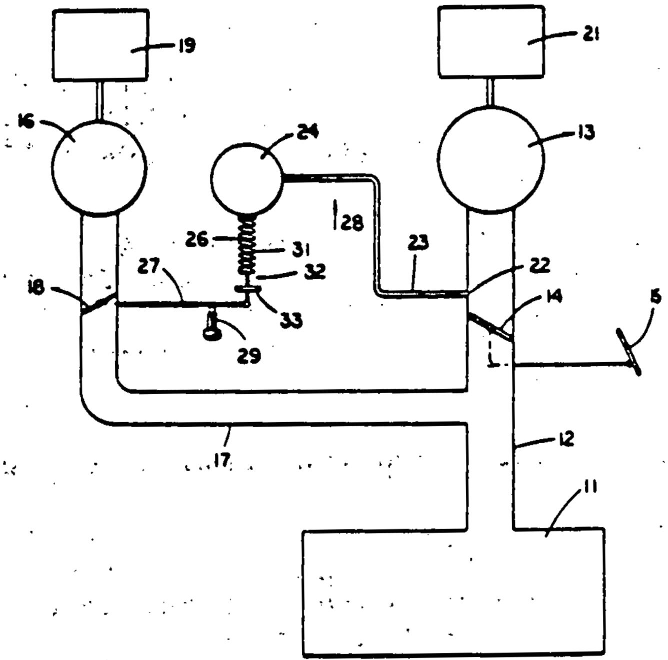


electronic controls for opening periods of the injector valves, also influencing the opening periods independence of the methanol / petrol ratio

Figure. 8. Fuel injection system for methanol based on variable opening times of injectors (similar to fig. 4) with methanol/petrol ratio transducer

THE DUAL FUEL APPROACH

The Overton Corporation



DESCRIPTION OF THE INVENTION

The Overton dual fuel system is a two carburetor set-up with two different fuels feeding two carburetors from separate fuel tanks. Gasoline is one fuel. Methanol is the other. The fuels are blended as a vapor in varying amounts at the moment of entry into the engine itself.

The invention allows for differing amounts of each fuel to be fed into the engine under different circumstances. A single vacuum system isused for both carburetors and the pressure at each fuel entry point dictates how much fuel of each kind is admitted. Gasoline explodes at a lower temperature than methanol and therefore creates quicker power. When power is needed for starting or passing, strong throttle pressure permits more gasoline than methanol to enger the engine, giving the needed quick power. When the engine is at idle or at the lower r.p.m.'s used in maintaining a speed, the engine receives greater amounts of methanol than gasoline.

The invention requires two fuel tanks on the vehicle and two fuel pumps to feed the two carburetors. However, with this minor modification, the invention uses Detroit's internal combustion engines exactly as they are presently manufactured. There is no need to develop a whole new concept in internal combustion engines.

An automobile equipped with this sytem is able to run on gasoline if methanol is not available as the carburetor continues to feed the gasoline vapor into the engine in the absence of methanol.

For those technically able, Appendix A to this Pamphlet contains the full patent as granted by the United States Patent Office for this invention. The concepts are simple and clean, easily understood by those acquainted with internal combustion engine carburetion.

INVENTION USE RESULTS

Tests results by the inventor have led to the granting of a United States patent, and application for patents in several countries. However, extensive and independent tests must be made before the Overton Corporation could ethically advocate nationwide and perhaps worldwide adoption of the system. The inventor's own test results, using the best equipment affordable by him, indicate that methanol usage is nearly equivalent to the gasoline used. In the inventor's tests, where ten (10 gallons of gasoline would otherwise be used, the Overton dual fuel system used only six (6) gallons of gasoline, plus six (6) gallons of methanol. The Overton Corporation believes that independent testing will bear out these figures and that with further development more decrease in gasoline consumption likely.

Of equal significance is the decreased pollution. Methanol burns cleaner and more completely and contains few harmful emissions. Accurate testing of emission levels has been impossible to date without expensive equipment. The Overton Corporation, however, believes a decrease in pollutants can be expected which is comparable to the decreased amount of gasoline used, i.e., forth per cost (40%) or more. These estimates are born out by the inventor's test results, but the Overton Corporation believes further testing is necessary to pass muster with the scientific community. However, all methanol-fueled (in whole or part) engines previously tested have shown marked decreases in pollutants emitted.

Volkswagen Approach

Figure 7 shows a VW prototype engine, water-cooled, stroke volume 1.6 l and which produces 65 kW (88 hp) in pure methanol operation. It is fitted with a mixed preheating system which allows a very intensive heating up by means of hot exhaust gas ("early fuel evaporation", EFE, or "hot spot"). A thermal valve controls a butterfly valve in the exhaust gas system using exhaust pipe underpressure and a control member (cf. also Figure 8).

Figure 7. VW alcohol engine (prototype).

1 = Thermal valve
2 = Hot spot (illeg)
3 = Exhaust gas throttle valve
4 = Exhaust gas system

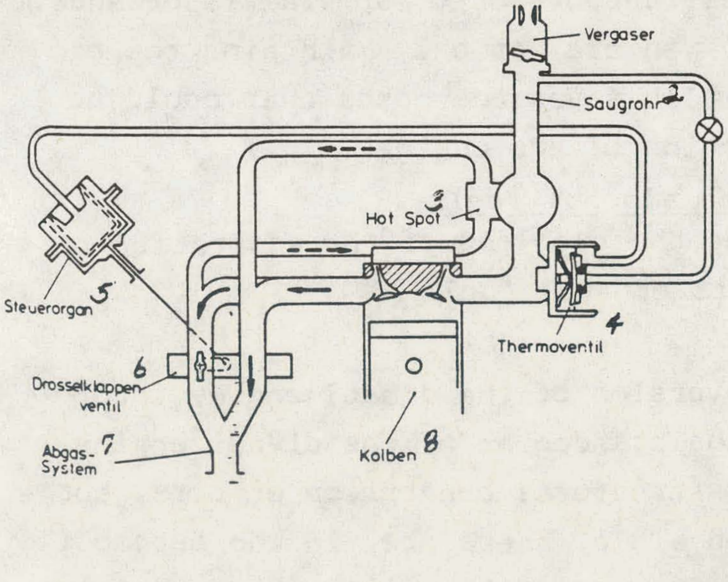


Figure 8. "Hot spot" exhaust pipe preheating.

1 = Carburetor
2 = Exhust pipe
3 = Hot spot
4 = Thermal valve
5 = Control member
6 = Butterfly valve
7 = Exhuast gas system
8 = Piston

Conversion of Diesel Engines to Alcohol Operation

INTRODUCTION Two methods are possible to make ethanol, which is by its nature unfriendly to diesel engines, applicable to such engines either, one determines that only ethanol in its usual form will be considered as a substitute fuel and makes the necessary changes on the diesel engine in order to make its operation with ethanol possible, or one establishes that the diesel engine is to remain essentially unchanged and reforms the fuel ethanol in such a manner as to enable normal diesel operation.

The one way means an adaptation of the engine to the fuel, the other an adaptation of the fuel to the engine.

The way of adapting the engine to the fuel, would be conceivable, if it were desirable to have a single fuel, country-wide, and if a potential increase of freight and person mass transport rates would be acceptable. For the production of ethanol quantities sufficient for the purpose, only the planting of appropriate areas with sugar cane or other suitable plants and the erection of corresponding distilleries would be required. The more difficult task would be left to the manufacturer of the diesel engines, in this case, the conversion of the engines to exclusive ethanol consumption. The costs that are, directly and indirectly, connected with this would have an additional effect on transport tariffs.

The approach of adapting the fuel to the engine, on the other hand, appears to be sensible in the case, where continued economy of freight- and person- masstransport of of special importance. The operator of the utility vehicle not only maintains the economical diesel process, he also saves the costs that could be encountered with the conversion of the engines.

Adaptation of the engines to alcohol fuels

We will, first, examine the problems of the adaptation of the original diesel engine to ethanol fuel.

Otto-type Engine.

The most obvious is the conversion of the diesel engine into an Otto-type engine. From the standpoint of the diesel engine, this is connected with some structural conversion efforts, but it is, otherwise entirely possible. There are, in the automobile industry numerous examples of successful engine-series that contain both diesel- and Otto-versions with a large number of uniform structural parts.

It would disrupt the framework of this presentation, to now discuss the details of the required different parts, such as cylinder head, pistons, intake- and exhaust systems, fuel supply and ignition system. It is only to be pointed out that additional measures have to be taken, when a usual gasoline-powered Otto-engine or an engine that has been converted from diesel to Otto-type, is to be converted to ethanol.

- caused by the low heating value resp. the smaller air requirement of ethanol, a changed carburetor adjustment is required.
- caused by the high vaporization heat, the low vapor pressure and the small ethanol-vapor take-up by the air, a stronger mixture preheating as well as a cold-start support have to be provided.
- the low vapor pressure of ethanol can require a change in the fuel pump in order to avoid steam bubble formation and hot-start difficulties.
- if one wishes to utilize the anti-knock properties of ethanol in comparison to gasoline, the combustion area must be changed in the direction of higher compression ratios, the gain in the degree of effectiveness should also not be forgotten in this connection (Figure 6).

But we shall not concern ourselves further with comparisons between gasoline and ethanol, but, instead, with those between ethanol and diesel.

If a high compression ration is used (e.g. =12) then, in the ethanol-Otto-operation, a higher degree of output can be expected than with diesel operation because of the better air-utilization. The degree of effectiveness is, however, smaller than that of the diesel engine, not only because of the lesser compression ration (= 12 as opposed to =17), but also because of the well-known disadvantages of air-choking in partial-load operation, something that should not be forgotten in the economic considerations.

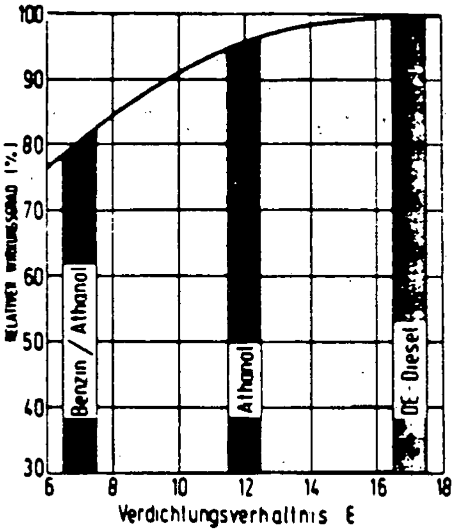


Figure 6: Relative degree of effective force in relation to compression ratio.
Where: Relativer Wirkungsgrad (%) = relative degree of effectiveness (%); Verdichtungsverhältnis = compression ratio; Benzin/Athanol = gasoline/ethanol; Athanol = ethanol; DE-Diesel = injected diesel fuel.

In addition, it should be pointed out, that it is not necessarily sensible to use the highest possible compression ratio. An engine designed with = 12, does result in a very advantageous degree of effectiveness, does not, however, permit knock-free operation with normal filling station gasoline. In the case of a temporary shortage of ethanol, e.g. caused by a poor sugar cane harvest, the usefulness of the vehicles would be endangered. The engine built on the basis of = 7, could, on the other hand, be readily re-converted to gasoline, this would require merely a change in the carburetor. But the degree of effectiveness would, in comparison to diesel engines, be very much poorer, however.

High Compression Diesel Engine

Still within the framework of the adaptation of the engine to the fuel, in other words, further under the assumption of an exclusive ethanol operation, another possibility of the conversion of the diesel engine is conceivable, which more closely approaches the original engine from the standpoint of economy: a direct-injection engine in which the self-ignition of ethanol is forced by means of extremely high compression and additional preheating of the intake-air (5).

The properties of the various fuels that have been shown at the beginning, make it clear that ethanol is, by its nature extremely unwilling to be ignited, something that does not, however, exclude that this high-octane fuel can be forced to self-ignition.

The principle of the highly compressed engines capable of using a variety of fuels from diesel to super gasoline, is generally known. Purely theoretically, a further increase of the compression would merely be required for ethanol.

There is no specific relationship between cetane number and required compression ratio, but from experience values a corresponding scatter-curve can be established (Figure 7).

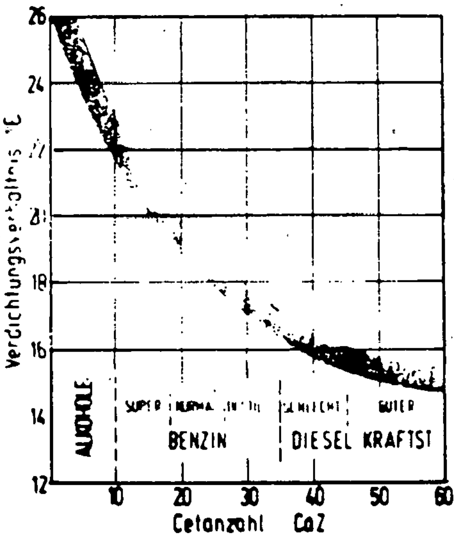


Figure 7: Required compression ratio with decreasing cetane number (Direct-injection diesel engine).

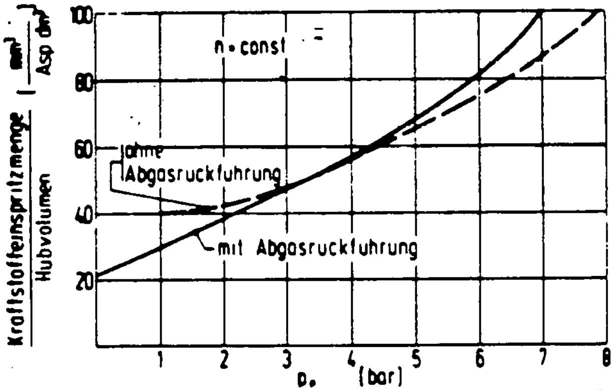
Where: Verdichtungsverhältnis = compression ratio; Cetanzahl = cetane number; schlecht. - guter Diesel kraftst. = poor - good diesel fuel; super - normal - distilled gasoline, alkohole=alcohols

Own experiments showed that self-ignition of ethanol is possible with a compression ratio = 25, not, however, in partial-load operation and even less on starting.

In order to facilitate a satisfactory engine operation at partial load and in idling, in addition to the high compression, the pre-heating of the intake air is required, e.g. by means of a heat exchanger or by exhaust recycling. The latter can be used without concern, since, caused by the soot-free ethanol combustion, no soiling of the pure-air paths need to be expected.

Experiments with exhaust recycling brought good results, but the problem of the control of such recycling has not been further examined. Conceivable would be a load-dependent control by way of the exhaust temperature or by way of the injection pump control rod.

The control of exhaust recycling must choke the recycling in the upper load range, in order to avoid a decrease of life and excessive heating of certain engine parts (Figure 8).



<u>Figure 8</u>: Willans line of an ethanol engine (=25) with and without exhaust recycling.

Where: Kraftstoffeinspritzmenge = amount of injected fuel; Hubvolumen = displacement volume; mit - ohne Abgasrückführung = with - without exhaust recycling.

Intake air preheating and extremely high compression will guarantee satisfatory engine operation, however, the peak pressure and pressure rise- values are far above those of the original diesel engine. Added to this is the fact that it is useful to add an exhaust turbo-loader, in order to compensate for the loss of the degree of filling effectiveness, that is caused by air preheating. Charging is unavoidable, if no output losses can be acceptable.

The starting process is not possible without starting aids. Aside of the known aids such as starter pilots and flame-start arrangements, the temporary switch-over to diesel fuel is conceivable as a starting aid, something that could also produce the following further advantages: On the one hand, by switching over to diesel prior to shutting down the engine, a preservation of the entire injection mechanism would result, on the other hand, diesel operation for some period beyond the starting process would guarantee an appropriate heating up period. Disadvantageous in this case, would be the additional container for diesel fuel. One can, therefore, see that the change-over expenditures is considerable in comparison to the original diesel engine (Figure 9).

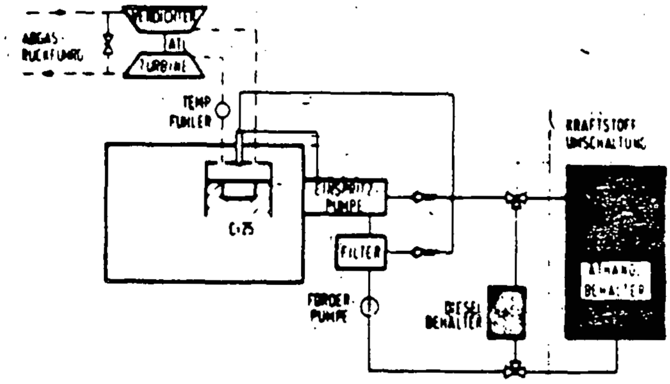


Figure 9: Characteristics of an ethanol-operated direct-injection engine (= 25) with exhaust recycling.

Where: Abgasrückführung = exhaust recycling; Verdichter Turbine (ATL) = compressor (charger) turbine (exhaust turbo-charger); Temp. Fühler = Temperature sensor; Einspritzpumpe = injection pump; Förderpumpe = fuel pump; Diesel,- Äthanol- Behälter = diesel-,ethanol- containers; Kraftstoff Umschaltung = fuel switch-over.

The specific fuel consumption of the high compression engine is, corresponding to the reduction of the degree of effectiveness, worse than that of a normal-compression direct-injection engine. A further worsening of consumption occurs when, for example, a displacement of the start of injection is arranged in the direction of "later" with the aim of obtaining a reduction of peak pressures.

In comparison to the ethanol-Otto-type engine that was developed from the diesel engine, the extremely highly-compressed engine has, in addition to the somewhat better consumption values, also the advantage that a re-conversion to diesel operation is possible at any time. Only the injected amount needs to be re-set and the exhaust recycling shut off.

In addition, the question of the lifetime is to be clarified. Delayed injection and air-preheating are not sufficient to obtain the peak-pressure- and pressure rise-values of the original engine. Unless the engine is not originally equipped with corresponding reserves, a constructionreenforcement is unavoidable.

Two-fuel mixed operation.

Still within the framework of the "adaptation of the diesel engine to ethanol as fuel", a third possibility should be mentioned, we shall call it "two-fuel mixed operation" (6,7).

However, in this case, only a partial substitution of diesel fuel by ethanol, is possible.

It concerns the following method: To the otherwise unchanged diesel engine, a certain amount of finely divided ethanol is added to the intake air as a spray, e.g. by means of low pressure injection. The engine takes in this thus produced lean, homogeneous air-ethanol mixture and compresses it. Combustion is initiated at the suitable time by the usual high-compression diesel injection. The essential part of energy supply takes place by diesel fuel.

The ethanol fuel that is homogeneously divided with the air sees to it that the combustion air is utilized appropriately because the air that is present outside of the combustion chamber in the pinch slots participates intensively in the combustion. The obtainable output is somewhat higher, the fuel consumption in the upper load-range is somewhat more advantageous and the exhaust turbidity, caused by the soot-free combustion of the ethanol, is less than in the diesel fuel operation alone (Figure 10).

The control of the ethanol supply must be carried out in such a way that the additional fuel is supplied only beginning with a specific engine-load and then still only up to a maximal amount which, in the present is represented as 25% at full load (Figure 11). Varying data are available concerning this maximally possible

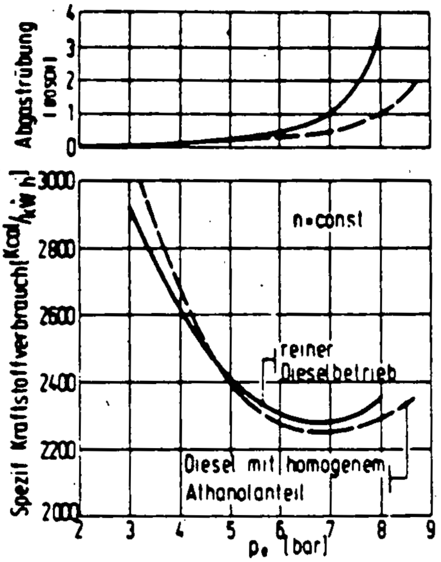


Figure 10: Influence of a homogeneous ethanol-addition to the intake air on consumption and exhaust turbidity.
Where: Abgastrübung = exhaust turbidity; Spezif. Kraftstoffverbrauch = specific fuel consumption; reiner Dieselbetrieb = pure diesel operation; Diesel mit homogenem Athanolanteil = diesel with homogeneous ethanol component.

ethanol admixture (5, 6, 7). It is, however clear that beyond certain limits no appropriate combustion is possible. In order that the energy supply be kept constant, the admixed amount of ethanol must be greater than that of the substituted diesel fuel. The ratio is inversely proportional to the corresponding heating values. The control must be arranged accordingly.

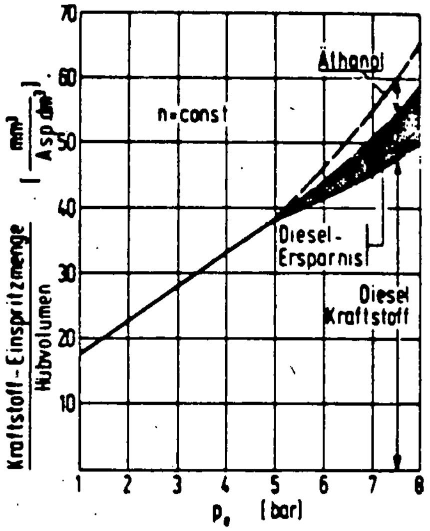


Figure 11: Control of ethanol supply in two-fuel mixed operation. Where: Kraftstoffeinspritzmenge=amount of injected fuel; Hubvolumen= piston displacement; Äthanol= ethanol; Ersparnis = savings.

The following are to be mentioned as disadvantages of this process: the fact that exclusive ethanol operation is impossible, the requirement of two separate fuel arrangements, the expensive regulation of the ethanol addition and the knock-destruction that is to be expected by an uncontrolled combustion of the ethanol-air-mixture with excessive proportion of ethanol.

The advantage in comparison to the earlier described possibilities is the somewhat less expensive conversion of the diesel engine. In principle, only the complete second fuel installation is required, but the costs for the control and the homogenization of the ethanol additive cannot be ignored. In connection with this, changes on important engine parts, such as e.g. on the cylinder head, can become necessary.

Adaptation of the substitute fuel to the diesel engine.

As has already been pointed out, the path of adapting the fuel, ethanol to the unchanged diesel engine is then sensible, when it is considered valuable that, on the one hand, no conversion of the engines need to take place and, on the other hand, a price-differential between diesel fuel substitute and the Otto-engine fuel must be continued. In this connection, it would also be possible, at any time, to make a reverse change to the original diesel fuel.

It has also been pointed out that a pure ethanol fuel, because of its unwillingness to ignite, is extremely unsuitable for operation in the diesel engine.

In order to make ethanol "diesel-capable", the willingness to ignite must be elevated considerably. One possibility that is known in principle for the elevation of cetane numbers is by the addition of so-called ignition enhancers. This is a matter of fuel additives which, by means of their more or less expressed explosivity cause an increase of the willingness to ignite on the part of poor diesel fuels.

It is, therefore, obvious to investigate the effect of such additives on ethanol as a motor fuel.

Among the known and tried ignition enhancers, amyl nitrate and cyclohexanol nitrate may be mentioned, the one represented more strongly in the U.S., the second, more so in Europe.

In principle, all alkyl nitrates are ignition enhancers. For the case examined here, it is useful to select a fuel additive that can be produced from plant-material alcohols. For this, especially ethyl nitrate would seem to offer itself, since it can be produced directly from ethanol. But, because of its high explosivity, ethyl nitrate in its pure condition is very hard to handle. One would have to mix it, immediately after its production, with the ethanol fuel in order to be able to guarantee its storage- and transport-capability.

The mentioned ignition enhancer amyl nitrate could also be of interest inasmuch as it is produced from amyl alcohols that are produced anyway as a side-product in alcoholic fermentation.

Own experiments were carried out with the ignition enhancer that is well-known in Europe, cyclohexanol nitrate, that is being sold commercially under the designation Kerobrisol MAR.

The determination of the required additive amounts to ethanol took place by way of ignition delay measurements (Figure 12). It was determined that the thus produced fuel with about 10% of Kerobrisol, acts exactly like a normal diesel fuel, nothing needed to be changed in the engine. In order to attain the same outputs, it was merely necessary to increase the fuel supply. The relatively high amount of ignition enhancer additive, however, requires a low price for the ignition enhancer in order to be able to guarantee competitiveness of the fuel mixture. The volumetric fuel consumption, corresponding to the lower heating value of ethanol, was higher, in comparison to diesel fuel. Relative to the energy provided, no mentionable difference could be noted (Figure 13).

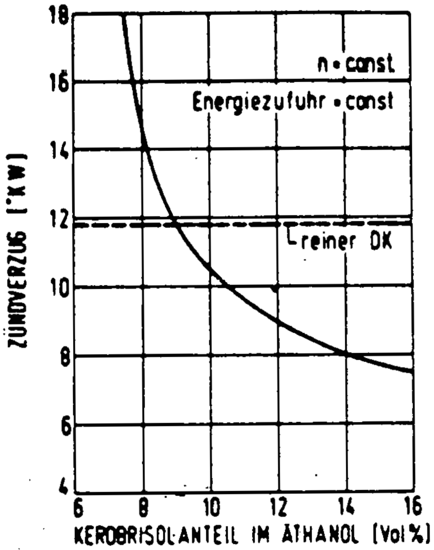


Figure 12: Ignition delay on addition of "Kerobrisol MAR" to ethanol.
Where: Zündverzug = ignition delay; Energiezufuhr= energy supply; Kerobrisol-Anteil im Äthanol = Kerobrisol component in ethanol. reiner DK = pure diesel fuel.

A further optimization of the course of combustion in ethanol-operation could take place by tuning the injection equipment for a higher amount of injected material.

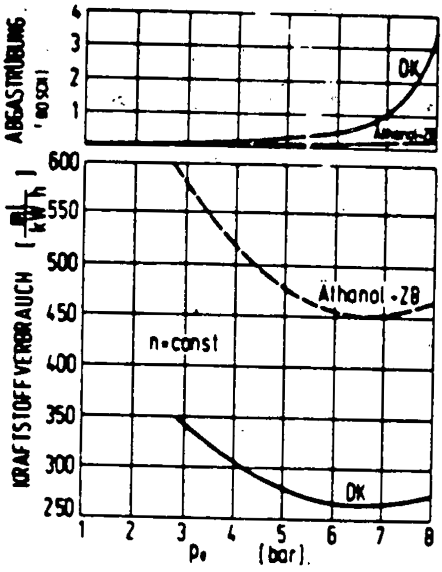


Figure 13: Engine values in operation with diesel fuel and with ethanol + ignition anhancer.

Where: Abgastrübung = exhaust turbidity; Kraftstoffverbrauch = fuel consumption; Äthanol + ZB = ethanol + ignition enhancer.

One must also not forget the fact that combustion is practically free of soot in ethanol operation.

As has been mentioned, no changes must, in principle, be made on the engine, Only the injection pump must be adapted to the new fuel: On the one hand in respect of increased injected amounts and on the other hand in respect of lubrication and sealing of the pump elements. In this case, the generally known multi-fuel pump with oils leak barriers is required.

Other fuels of plant origin

Before bringing the subject "Adaptation of the substitute fuel to the diesel engine", the following question should also be posed: Are there other fuels of plant origin, other than ethanol, that, according to their properties, are closer related to diesel fuel? Yes, there is something in that direction, the oils of plant origin!

We do not wish to become too involved in the problems of the application of plant-oils in diesel engines. The present subject concerns ethanol. We merely wish to point out that a country, such as Brazil, which we have selected as our example, need not necessarily concentrate itself only on ethanol in its search for fuels of plant-origin as substitutes for mineral fuels. Plant-origin oils must also be considered, especially when thinking in terms of diesel engines.

In Brazil, today, the economical production of soybean oil, Babassu nut oil, cotton seed oil and castor oil are being examined as potential fuels. Among the most important properties that differentiate these oils from usual diesel fuels, are the viscosity, the cloud point and the coke residues. The cetane number is of the same order of magnitude as diesel fuel. Seen from the stanpoint of the volumetric heating value plant-oils also correspond to diesel fuel, so that, on the assumption of an equal degree of effectiveness, the liter-price for plant-oils would have to be equated to the price of diesel fuel in order to guarantee equally economical operation.

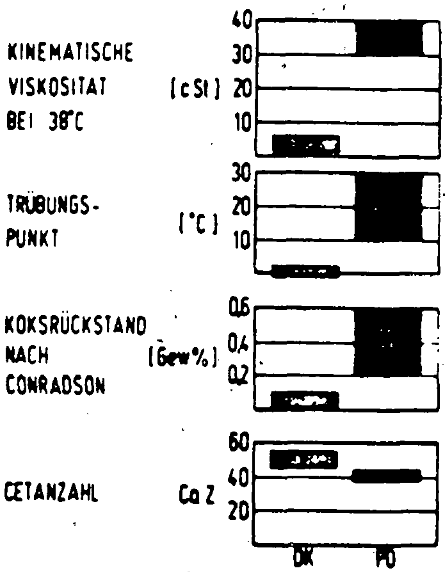


Figure 14: Properties of plant-oils in comparison to diesel fuel

Where: Kinematische Viskosität = kinematic viscosity; Trübungspunkt = loud point; Koksrückstand = coke residue according to Conradson; Cetanzahl = cetane number; DK = diesel fuel; PO = plant-oils

Because of the detrimental properties in exclusive use of plant-oils, such as excessive viscosity, excessive cloud point, and coke residue, an admixture of smaller amounts of plant-origin oils to diesel fuel could be of special interest.

Concluding observations

In conclusion we shall once more briefly summarize:

The ability of ethanol and oils of plant-origin to compete in respect of mineral fuels is only present when the per-liter price of the substitute fuel, under consideration of the volumetric heating value and the degree of use-effectiveness is considered in the corresponding combustion method (Figure 15). Here, the alternative "Ethanol-Otto-type method" is unsuitable inasmuch as,

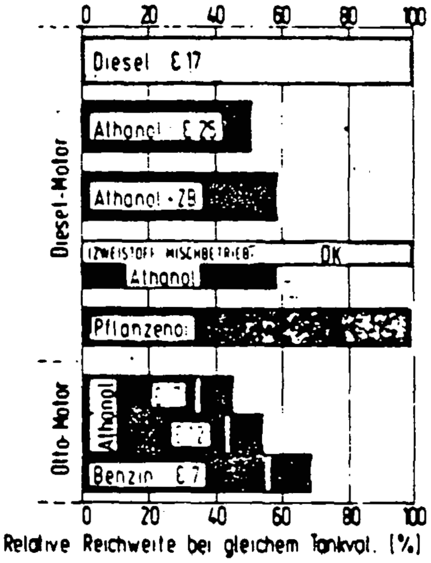
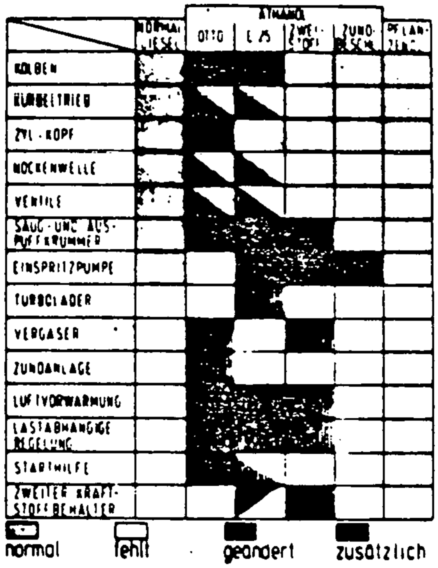


Figure 15: Relative ability to compete for substitute fuels in relation to diesel fuel.

Where: Diesel Motor = diesel engine; Otto-Motor= gasoline engine; Äthanol = ethanol; ...+ZB = + ignition enhancer; Zweistoff Mischbetrieb = two-fuel mixed operation; DK = diesel fuel; Pflanzenöl = oils of plant-origin; Benzin = gasoline; Relative reichweite bei gleichem Tankvolumen = relative distance reached with equal volume tank.

as, in addition to the low compression, the disadvantages of the partial-load losses must be considered. Within the framework of all the considerations, one may not forget that the differentiation of the fuel prices for utility vehicles and for automobiles is of importance to countries like Brazil, in which such a price-differentiation serves to maintain a hold on the transport tariffs.

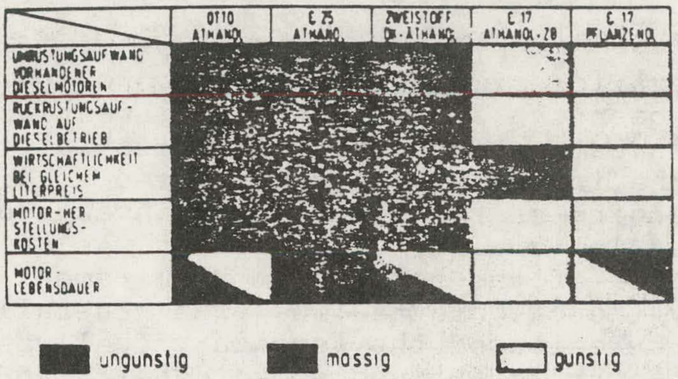
General economy-comparisons also must consider the expense of adaptation that will be required by the conversion to ethanol, starting with the original diesel engine. The variations "Otto-type engine" and "highly compressed diesel engines, are at a disadvantage in that respect (Figure 16).



<u>Figure 16:</u> Expense of changes for operation with substitute fuels in comparison to a normal diesel engine.

Where: Zweistoff = dual fuel; Zündbeschl. = Ignition enhancement; Pflanzenöl = Oil of plant origin; -- Kolben = piston; Kurbeltrieb = crank gear; Zyl.-Kopf = Cylinder head; Nockenwelle = camshaft; Ventile = valves; Saug- und Auspuffkrümmer = intake and exhaust manifold; Einspritzpumpe = injection pump; Turbolader = turbocharger; Vergaser = carburetor; Zündanlage = Ignition system; Luftvorwärmung = air preheating; Lastabhängige Regelung = load-dependent control; Starthilfe = starting aid; Zweiter Kraftstoffbehälter = second fuel tank; --- normal = normal; fehlt = lacking; geändert = changed; zusaetzlich = additional.

A final decision in respect of the most suitable alternative for ethanol application in originally diesel-driven vehicles, can only be made after precise weighing of all advantages and disadvantages (Figure 17). In connection with this, the judgement is encumbered by the fact that in some cases, there still are unanswered questions as well as incomplete edvelopment.



<u>Figure 17:</u> Evaluation of the substitute systems for usual diesel engines.

Where: Athanol = ethanol; Zweistoff DK + Athanol = two-fuel, diesel fuel + ethanol; Ethanol + ignition enhancer; Pflanzenöl = oil of plant origin;
Umrüstungsaufwand vorhandener Dieselmotoren = conversion expense on present diesel engines; Rückrüstungsaufwand auf Dieselbetrieb = re-conversion expense (back) to diesel operation; Wirtschaftlichkeit bei gleichem Literpreis = economy at equal price per liter; Motorherstellungskosten = production costs of engine; Motorlebensdauer = engine life;
ungünstig = disadvantageous; mässig = moderate; günstig = advantageous.

ETHANOL-DIESEL OIL DUAL-FUEL ENGINE

REVIEW OF PREVIOUS WORK

Dual-fuel operation of diesel engines covers a wide area and has been the subject of many investigations. In these investigations, the proportion of the heat supplied by the inducted fuel was limited to different levels depending on the aims of the investigators. When utilization of low quality diesel fuels was of importance, the proportion of the total heat requirement of the engine supplied by the carburetted fuel was generally less than 25. When carburetion of the secondary fuel was aimed at increasing the power at a given smoke density and proportion of the heatsupplied by the carburetted fuel was higher, in the range of about 25-50%.

When the aim is to reduce the consumption of diesel oil the carburetted fuel becomes the primary fuel and the proportion of the heat supplied by it is about 50%. Operation in this range with non-petroleum fuels as the inducted fuel has largely been limited to alcohols.

OBJECTIVES OF THE PRESENT WORK

The works referred to above were the pioneering efforts in dual-fuel operation with alcohol and were largely exploratory. The quantitative assessment of the performance of the engine was based on thermal efficiency, exhaust temperature and to some extent on the ignition delay. Qualitative assessment of combustion noise and engine wear was also made. But information on optimum proportions of diesel oil and alcohol, combustion characteristics viz., peak pressure, rate of pressure rise and ignition delay and also information about exhaust emissions were not available. Hence a research program on the use of alcohols in dual-fuel engines has been taken up at the I.I.T., Madras with the objective of determining the factors that would allow the maximum use of alcohol in these engines with the best possible efficiency and power output. The experimental investigations carried out in this regard are reported in the later sections.

TESTS WITH CONSTANT DIESEL FLOW

RATES: Our preliminary tests indicated that the combustion of alcohol-air mixture depends very much on the relative proportion between the alcohol inducted and the diesel oil. Hence this was investigated in constant diesel flow rate tests. Tests were conducted with the normal compression ratio of 16.5:1 and the recommended injection timing of 27° bTDC for pure diesel operation. The diesel flow rate was maintained constant at a chosen value but alcohol induction was varied. It can be seen from Fig. 3 that with 30% of the full load diesel flow rate only a small amount of alcohol could be burnt before the engine started missing and the maximum power developed was only about 1.3 HP. With higher percentages of diesel flow the increase in the delay period with alcohol induction is less marked. With 40, 50 and 75% of full load diesel flow rates, a maximum of about 1.8 litres/hr could be burnt as against 0.77 litres/hr of alcohol with 30% diesel flow rates. But with 40% diesel flow rate the delay period with this alcohol flow was excessive, about 43.5°CA which means the pressure rise started 16.5°CA after TDC. With 50% diesel flow the starting point of rapid pressure rise came down to 11° aTDC and to 6° aTDC with 75%. It can be seen from Fig. 3 that there is a certain critical proportion between the quantities of alcohol and diesel oil, lying between 30% and 40% diesel flow rates. From later graphs it will be seen that the value of this proportion depends on variables like the compression ratio, injection timing and ignition quality of alcohol.

The brake thermal efficiency (Fig. 4) with dual-fuel operation was less than that of pure diesel operation in the part-load range for all the diesel flow rates. It was lowest with 40% diesel flow rate and was only slightly better with 50%. In the overload range dual-fuel operation had a higher thermal efficiency than pure diesel operation. Exhaust temperatures were generally lower than pure diesel values.

Due to increasing delay periods both peak pressure and rate of pressure rise decreased continuously with 30 and 40% diesel flow rates (Figs. 5 and 6). Peak pressure with 75% diesel flow rate was of the same order as with pure diesel operation, but the rate of pressure rise was higher in the high output range.

HC emissions, which were of the order of 150 ppm in pure diesel operation, rose steeply with the start of alcohol induction and stabilized at a value dependent on the diesel flow rate. It was about 800 ppm for 40% diesel flow, 500 ppm for 50% and 300 for 75%. NO_x emissions varied between 100 ppm at no-load to 500 ppm at 7 HP in pure diesel operation. NO_x emissions were lower with dual-fuel operation for all diesel flow rates and the difference was of the order of 100-150 ppm.

The higher HC emissions are obviously due to incomplete combustion, also reflected by the general decrease in efficiency with alcohol induction. The lowering of compression temperature due to the high latent heat of alcohol causes decrease in NO_x formation.

A diesel flow of at least 50% of the full load flow rate seems to be necessary for a satisfactory performance with alcohol induction with the normal specifications of the engine: C.R. of 16.5 and injection timing of 27° bTDC. Even with 50% diesel flow rate the rise in delay period due to alcohol induction was large and also only a maximum of 60% of the total heat could be derived from alcohol.

TESTS WITH ADVANCED INJECTION

TIMINGS: Lower temperatures during compression due to vaporization of alcohol increases delay before heat is released from the injected diesel spray. With the recommended injection timing of 27° bTDC, pressure rise starts near about TDC in pure diesel operation and with alcohol induction it shifts to several degree after TDC due to the cooling effect of alcohol. Hence advancing the injection timing, to some extent, should bring the start of pressure rise nearer to TEC. Heat release nearer to TDC means higher temperatures and higher pressures and consequently more quantity of alcohol should be burnt even with 30% diesel flow rate. This reasoning was tested by engine operation with advanced injection timings of 29,31 and 33° bTDC.

The most remarkable outcome of tests with advanced injection was that the engine could be operated over the entire load spectrum with only 30% of the full load diesel flow rate with 31 and 33° bTDC injection timings (Fig. 7). It was possible to develop as much as 8.32 HP with 31° bTDC injection timing while with 33° a maximum of 7.65 HP could be developed. At these maximum power outputs the heat supplied by alcohol was over 80% of the total heat input. The maximum amount of alcohol that could be burnt and the maximum power developed remained practically the same with higher diesel flow rates. Fig. 8 shows the variation of delay period with alcohol flow for different injection timings for 30% of full load diesel flow rate. It can be observed that with 27 and 29° bTDC injection timings, the delay period increased continuously and the engine reached the missing point with relatively low alcohol flow rates and hence low power outputs. There was not much difference in delay periods with different injection timings for alcohol flow rates less than 1. litre/hr. In the high alcohol flow region (above litre/hr), there were significant differences. Bearing in mind that the position of PDC is different in the figure for different injection timings, it can be observed that in the high alcohol flow region the start of pressure rise occurred within about 6.5° after TDC for 31 and was written 2.25° after TDC for 33°. But operation with advanced injection timings was not an unmixed blessing , for beyond 6 HP the rate of pressure rise was quite high with 31° and 33°, increasing from 2.5 kgf/cm^2/°CA to about 10 Rgf/cm^2/°CA at the maximum power which led to high peak pressures.

The results indicate that advancing the injection timing adequately allows a fairly good degree of substitution of diesel oil by alcohol. The increase in delay period in dual-fuel operation is still large for low diesel flow, indicating that a single injection timing is not likely to be satisfactory for the entire load range. The thermal efficiency of the engine is marginally improved by advancing the injection. Combustion at part-loads with low diesel flow rates is still poorer than pure diesel combustion. These observations indicate that advancing the injection timing is only a partial solution and hence other factors were also investigated.

TESTS WITH HIGHER COMPRESSION RATIO:

Performance with a higher compression ratio was studied to bring down the increase in delay period due to alcohol induction. A compression ratio of 20:1 was tried out. Tests were conducted with constant diesel flow rates of 20,30,40 and 50% of full load flow rate. Injection timing was kept at 27° bTDC. The increase of delay period (Fig. 9) with alcohol induction reduced considerably with the compression ratio of 20:1 in comparison with compression ratio of 16.5:1. Even with 20% diesel flow rate the increase was only 3.5°CA and for the most part it varied by 1°CA. Range of variation as well as absolute value of delay period decreased with higher percentage of diesel flow. Range of variation was only 1.5°CA with 50% diesel flow rate.

The percentage of heat supplied by alcohol (%H.Al.) versus BHP is shown in Fig. 10. It can be seen that with 20% diesel flow rate it was possible to supply as much as

80% of the total heat from alcohol at the engine rated output. Heat supplied by alcohol varied from 55% at no load to 83% at 6 HP. It was above 70% for most of the load range. At no load, fuel consumption was about 30% of the full load diesel flow rate in pure diesel operation and hence to operate with 20% some amount of alcohol induction was necessary even for idling. With 30% diesel flow rate also, substitution by alcohol was good reaching 70% at rated load.

Even with the compression ratio of 20:1 part load operation with alcohol was less efficient than pure diesel operation but was marginally better than for compression ratio of 16.5:1 for corresponding diesel flow rates. The peak pressures varied between 55 and 80 Kgf/cm^2 while the rates of pressure rise varied between 2 and 4.5 Kgf/cm^2/$^{\circ}$CA. In dual-fuel operation knocking sets in at about 6 HP for all the diesel flow rates tried. This is less than the maximum power developed in pure diesel operation with this compression ratio. HC emissions were lower than those with compression ratio of 16.5:1 for corresponding diesel flow rates, but NO$_x$ emissions were of the same order.

From these results it can be seen that the increase of delay periods with alcohol induction was smaller with compression ratio of 20:1 and was comparable to the values in pure diesel operation. Hence a fixed injection timing will be satisfactory for the entire load range. Knocking sets in rather early and some remedial measures are necessary to increase the maximum power output.

TESTS WITH ADDITIVES TO ALCOHOL:

As one of the means of reducing the delay period, addition of ignition accelerators to fuels was studied. It has been reported (5) that addition of even 10% by volume of amyl nitrate to the injected diesel oil was not very effective in an alcohol-diesel oil dual-fuel engine. Amyl nitrate is a tested cetane number improver and 10% by volume is very high as an additive. Some of our own preliminary tests also confirmed that additives to the injected diesel oil have little effect. After considering the above findings it was felt that the increase in delay period was primarily due to sluggish ignition of the alcohol-air mixture. Hence improving the ignition quality of the alcohol by additives was tried out.

Nitromethane and aniline were chosen as additives to the alcohol. Nitro-methane is an explosive and belongs to the class of additives which reduce ignition delay continuously with increasihg concentrations, although not linearly. Aniline belongs to another class of additives which reduce the ignition delay at small concentrations and increase the ignition delay at large concentrations. It has been reported (6) that the critical concentration at which aniline changes its behaviour is about 0.8% by volume from engine tests. Hence it was decided to try concentrations of 0.5% and 1% by volume of both the additives.

The tests were conducted with a compression ratio of 16.5. and injection timing of 27° before TDC. Under these conditions the additives were not effective enough to enable operation in the entire load spectrum with 30% diesel flow rate. Effects of additives were more pronounced with 40% diesel flow rate. Delay periods decreased with all the additves by various amounts as indicated in Fig. 11. Aniline 0.5% by volume was the most effective and brought about a maximum reduction of about 11°CA in delay period in comparison with pure alcohol operation. The range of variation of delay period which was about 16°CA with with pure alcohol was only 6°CA with aniline 0.5°. Aniline 1% was not as effective as Aniline o.5%. The reduction in delay periods with Notromethane 0.5% and 1% and Aniline 1% were of the same order.

Thermal efficiency (Fig. 12) increased with all the additives and the relative effects were largely in conformity with the trend observed in delay periods. Thermal efficiency increased by about 3% at full load with Aniline 0.5%. Higher power outputs were obtained with all the additives except Nitromethane 0.5%. Due to more rapid combustion, the peak pressures and rates of pressure rise were generally higher with additives.

The additives were very effective in reducing HC emissions (Fig. 13). A maximum reduction of about 600 ppm in HC emissions was observed with Aniline 1% in comparison with pure alcohol emissions whereas only about 300 ppm reduction was observed with Aniline 0.5%. HC emissions decreased with addition of Nitromethane also but not as much as with Aniline. NO_x emissions (Fig. 14) increased with the addition of additives and generally conformed to the trend that would be expected due to better combustion and higher temperatures due to reduced delay periods.

CONCLUSIONS

The combustion in alcohol-diesel oil dual-fuel engine is a complex one, involving the ignition of a homogeneous alcohol air mixture by a spray of diesel oil. The combustion delay is afunction of several factors like the alcohol-diesel oil ratio, compression ratio, injection timing, ignition quality of the fuels, etc. A long delay period results in late combustion and loss of thermal efficiency.

A second factor of importance in this combustion is the rate of burning of the alcohol-diesel oil air mixture once the delay period is over. The present work shows that as the alcohol air mixture becomes richer the combustion rate increases very rapidly, some times to unacceptably high values.

For a perfectly satisfactory operation, these twin problems have to be overcome for this type of engine.

In this work, it has been shown that an optimised timing of injection reduces the delay period and makes it possible to run the engine with a higher proportion of alcohol. An optimised compression ratio also allows a high proportion of alcohol to be used. Certain ignition accelerating additives to alcohol in the right concentration have the effect of improving the thermal efficiency. Further, tests are now under way to determine optimum settings of these factors when they are all simultaneously varied.

Alcohol-diesel oil dual fuel engines have some remarkable advantages. They permit the use of alcohol (a renewable fuel) as the main fuel. Due to better air utilization they achieve substantially higher peak outputs than comparable diesel engines. Their thermal efficiency is even better than that of diesel engine in the higher output range. Further work is however necessary to find ways of controlling the burning rates at high outputs.

The present work indicates some methods of improving the part load efficiency, one of the chief defects of his engine. It also contributes to a better understanding of the combustion process in the dual-fuel mode of operation.

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TECHNICAL APPROACH

Previous attempts to operate direct injection diesel engines on methanol using the normal compression ignition cycle, notably by Mühlberg in Reference 1 showed the need to modify the fuel injection system, and the engine operating conditions including the use of modulated exhaust gas recirculation in order to inject and ignite the highly volalite, low ignition quality methanol. The desire, therefore, for a bolt-on conversion package led, naturally, to consideration of dual fuel operation in which the normal diesel Injection system would provide the pilot ignition charge and the methanol could be introduced with the inlet air This technique is commonly used in larger industrial engines to be operated alternatively on diesel fuel or natural gas. Methanol, being a liquid, lends itself to being carburetted using an unthrottled gasoline carburettor fitted with a variable main jet only.

Since the purpose of this investigation was to promote the use of methanol as an alternative to normal diesel fuel in large commercial vehicles, the test programme was designed to establish means of operating with minimum pilot charge and therefore the maximum replacement of gas oil with methanol.

It was expected that in common with other systems involving aspiration of gaseous or liquid fuels, often referred to as fumigation, there would be an increase in smoke limited performance. This would be an additional advantage of operating on methanol using the dual fuel principle.

TEST ENGINE AND INSTRUMENTATION

A single cylinder direct injection engine of 1.6 litres swept volume was selected, having a bore of 121 mm and stroke of 140 mm. The unit was representative of a typical large truck engine having a compression ratio of 15.3:1 and a combustion bowl in the piston with a diameter depth ratio of 2.5:1. Air swirl was generated by a masked inlet valve. The fuel injection system was also typical using a 4 hole injector nozzle and normal jerk type injection pump. The pump drive incorporated a manual advance device.

To the inlet system was connected a Zenith down draught carburettor fitted with a variable main jet. The throttle was locked in the open position and all additional components such as the automatic choke and accelerator pump were removed.

A duplicate fuel system with flowmeter for the methanol was installed as shown in Figure 1 together with a viscous flow air-meter to monitor air consumption. Subsequently, as explained later, a mixture heater was added to assist with evaporation of the methanol.

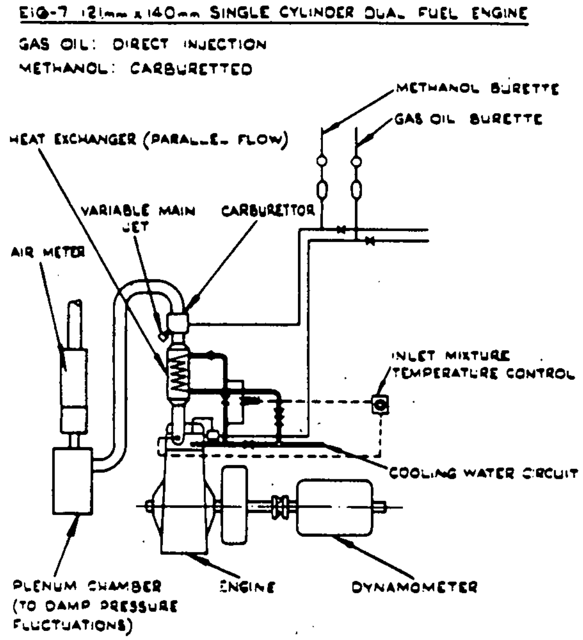


FIG. 1 TEST ENGINE SHOWING DUAL FUEL SYSTEM WITH INLET MIXTURE HEATER

DESCRIPTION OF TESTS AND OBSERVATIONS

Phase 1 - Simple Aspiration of Methanol

Having established the base line performance of the engine as a pure diesel, tests were carried out by aspirating the methanol/air mixture with various levels of pilot diesel fuel to establish the required pilot quantity at the various loads and speeds. It was, of course, hoped to be able to use a fixed quantity of pilot fuel so that engine control could be as simple as possible by modulating only the methanol flow.

At small pilot levels it was soon discovered that, although it was relatively easy to operate at light loads with small quantities of methanol, progressive increases in methanol resulted in an abrupt failure of ignition. This was subsequently referred to as "quenching" as it was assumed that evaporation of the methanol was depressing the charge temperature to a level too low to permit compression ignition of the pilot diesel fuel. This phenomenon placed a limit on the quantity of methanol which could be burned at any one speed, the effect being more severe as the speed was increased due to lengthening of ignition delay relative to crank angle.

Figure 2 shows load range curves obtained under dual fuel conditions compared with the normal diesel performance at 16.7 and 36.7 rev/s. The numbers at the ends of the curves indicate the percentage diesel fuel replaced. It will be seen that the higher replacement rates at each speed were limited in maximum power due to quench. The substitution rate at high speed was substantially less than at low speed.

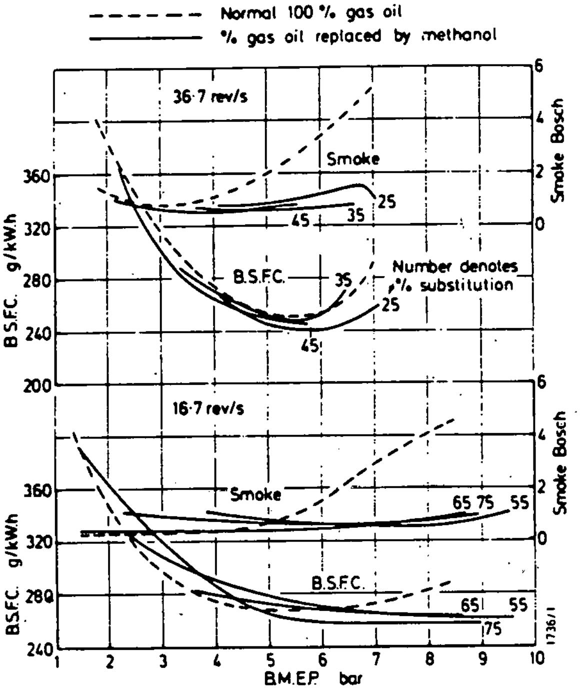


FIG. 2 LOAD RANGE CURVES AT TWO SPEEDS SHOWING % GAS OIL SUBSTITUTION LIMITED BY QUENCH

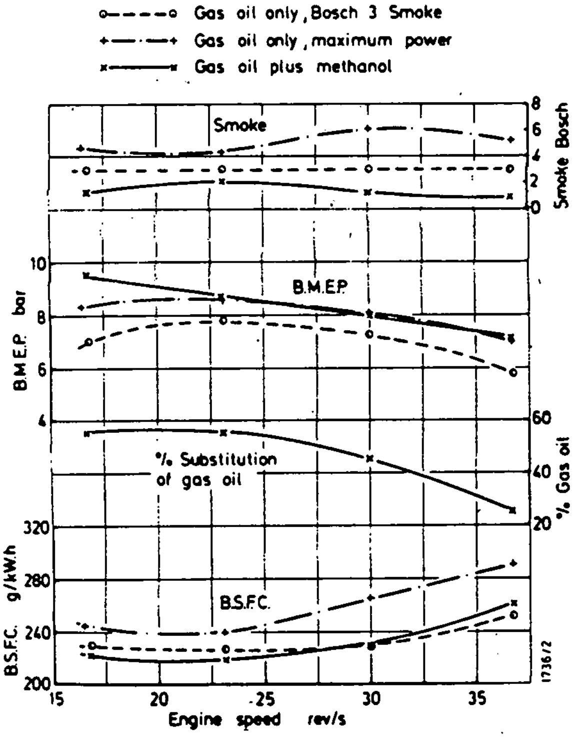


FIG. 3 FULL LOAD PERFORMANCE COMPARED WITH NORMAL GAS OIL OPERATION

Having established the maximum replacement rate to achieve power equal to normal diesel operation a torque curve was obtained for comparison with pure diesel curves at both maximum power and when the smoke is limited to Bosch 3. Figure 3 shows the anticipated improvement in smoke level when operating on methanol typical of the better air utilisation obtainable using aspirated fuel.

This improvement in air utilisation results from some of the aspirated fuel being carried into remote parts of the combustion space not normally reached by the diesel fuel. These spaces are generally outside the main combustion bowl and the mixture in these areas will behave much as the end gases in a spark ignited engine. However, the multi-point diesel ignition will increase the chance of complete combustion.

This better air utilisation also results in a specific fuel consumption on an equivalent diesel fuel basis at full power equal to that of the pure diesel at the Bosch 3 smoke rating. The methanol smoke is around Bosch 2 at this rating.

Also shown is the diesel oil replacement rate over the speed range dictated by quench. This clearly leaves room for further development towards maximum replacement rate to make engine conversion economically worthwhile.

Using the above data, estimates of the approximate methanol replacement rates were made for large commercial vehicles in various duties. It is, of course assumed that a suitable system can be developed to modulate the methanol/diesel proportions with speed. The replacement rate below is given as a percentage of normal diesel consumed.

Fully laden 35T truck	
On motorway	52%
On trunk road	50%
On city ring road	44%

City bus	
On city ring road	46%

For a part laden truck the replacement rate was significantly less, being:-

On motorway	47%
On trunk road	41%
On city ring road	20%

Since the limitation was mainly that of quench at higher methanol levels it was decided to provide extra heat to the mixture to assist with evaporation and thus maintain higher compression temperatures.

Phase 2 - Heating of Inlet Mixture

The latent heat of vaporisation of methanol at 15°C is 1100 KJ/Kg and it was clear that heating the intake air alone upstream of the carburettor would not appreciably improve the conditions at the start of compression. A heat exchanger was therefore fitted between the carburettor and the engine to apply heat from the engine coolant to the methanol/air mixture. By this means it was possible to exceed the normal diesel intake temperature conditions. Analysis of cylinder pressure diagrams showed that the air/methanol mixture has a compression index close to that of pure air and therefore the ignition delay of the diesel fuel should be restored to that in a normal diesel engine once normal intake conditions are established.

Since the main problem area was identified as the high speed condition work continued at 36.6 rev/s only to investigate the effect of mixture heating on ignition delay. Selecting an arbitrary level of pilot of 40% the effect of charge heating was investigated at a constant load of 3.0 bar. As is seen in Figure 4, for the same intake temperature, the presence of methanol in the charge resulted, still, in a longer ignition delay than when running on diesel fuel alone. The measured temperature drop when operating with air heating alone confirmed that evaporation of the methanol was completed, thus it is assumed that with the more effective heating of the mixture and higher intake temperatures the methanol was completely evaporated when comparing these ignition delay values.

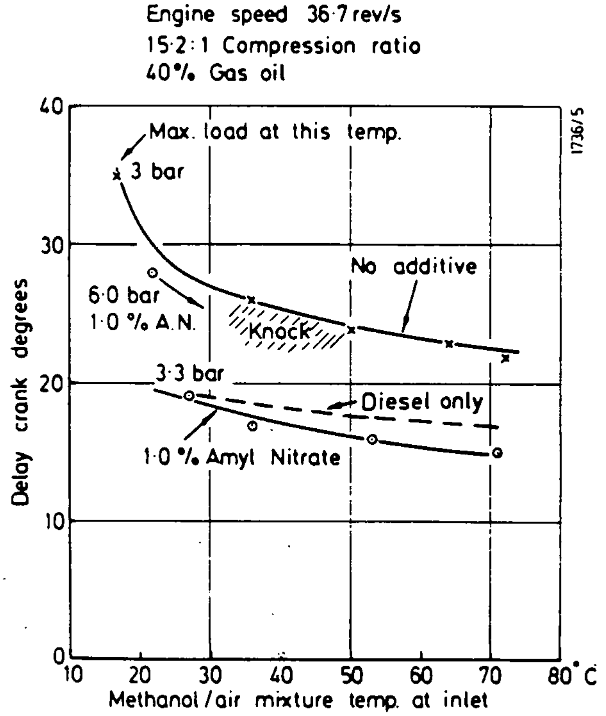


FIG. 4 VARIATION OF DELAY PERIOD WITH INLET TEMP. AT CONSTANT LOAD

With mixture heating it was possible to achieve 55% gas oil substitution at about 6.0 bar bmep as compared with 35% with no heating. This was achieved with a mixture temperature of 75°C and the maximum load limit was no longer quench but knock of the end gases.

Tests at 16.7 rev/s with mixture heating showed that with 20°C inlet temperature and 20% pilot or 80% gas oil substitution a load range equivalent to normal diesel operation could be achieved. At higher temperatures and greater substitution rates the load range was limited by knock. Consequently it became clear that knock is as restrictive in limiting the methanol utilisation at high loads and low speeds as quenching was at high speed. In fact it became clear that the operating conditions are going to be markedly different between low and high speed if similar methanol utilisation is to be achieved without running into knock at low speeds and quench at high speeds.

A further solution was considered, that of using a higher ignition quality pilot charge to reduce the incidence of quench without promoting knock of the end gases. This was achieved by addition of amyl nitrate to the gas oil.

Phase 3 - Ignition Improving Additives

The longer ignition delay when burning methanol under normal start of compression conditions was assumed to be the result of blending of the methanol with the evaporating diesel fuel round each droplet. Methanol has an octane number (motor method) of 105.

Assuming the relationship:-

$$CN = \frac{104-ON}{2.75} \quad \text{(Ref. 2)}$$

to establish the cetane number of methanol it is seen that the result of blending methanol with gas oil of 50 cetane number will be severe depression of the latter.

The addition of amyl nitrate is an accepted method of improving the ignition quality of gas oil and tests were carried out to investigate the effect of both 1 and 2% additive levels on ignition delay.

The results of the amyl nitrate tests are also summarised in Figure 4, where it is seen that 1% amyl nitrate has effectively restored the ignition delay of the 40% pilot change to the normal diesel level at the load of 3.0 bar and removed the quench limitation. However, with this quench barrier removed it was found that, at the same speed the engine ran into knock above 6.0 bar if the mixture inlet temperature rose above 30°C.

Exhaust Emissions

Comparative gaseous exhaust emission tests were carried out under the conditions of the Phase 1 testing. Results are not included due to lack of space but generally NOx levels decreased and HC levels increased with increase in methanol. The effect on NOx is assumed to be due to the charge cooling effect of the methanol whilst this and the increase in remote unburned mixture were responsible for the increase in HC. Mid load emission of CO was also higher than for the normal diesel. It is assumed that with subsequent measures to reduce delay the NOx levels would increase but hydrocarbon problems from the end gases would remain.

Other Problems

Some consideration was given to other problems likely to arise in the use of methanol.

Firstly methanol can be absorbed into the human body with disastrous results, the main one being permanent damage to the nervous system. Thus care is necessary in the dispensing of methanol and would be difficult to ensure on the garage forecourt, hence the preference for use by fleet operators.

Some problems were experienced in the electrolytic corrosion of the Mazak zinc based alloy used in the construction of the carburettor used for these tests. This is electrolytic attack when the methanol contains some water and is not an insuperable problem but care would be needed in the selection of fuel system materials.

Methanol is also an effective solvent for paint and other materials and if spilt on vehicle body work would cause damage. Likewise rubber and other sealing materials may have to be replaced.

Owing to the low calorific value of methanol the tankage for carrying the methanol on the vehicle would be large and in addition to the diesel tank. A capacity approaching twice that of the diesel tank would be required to match the mileage between refils.

SUMMARY OF RESULTS AND DISCUSSION

With regard to the main objective of this exercise i.e. the maximum possible substitution of diesel fuel by methanol employing the dual fuel process, Figure 7 summarises the results to date.

Firstly it will be seen that the level of substitution relative to the measures taken is very different between high and low speed. 80% is only reached at 36.7 rev/s by inlet mixture heating to 30°C and 2% amyl nitrate whereas, at 16.7 rev/s, 75% was achieved without heating whilst at 80% the engine was knock limited to a lower load. Consequently to achieve these maximum levels of substitution over the speed range, both mixture heating and ignition promoting additives would have to be modulated. The latter is clearly not possible.

At part load the substitution is less, if the pilot charge is held constant. The pilot charge could be modulated with the methanol with some extra complication.

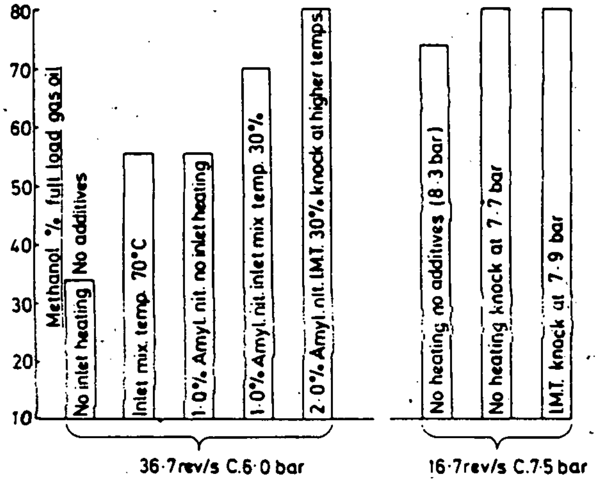


FIG. 7 PERCENTAGE SUBSTITUTION WITH METHANOL TO GIVE NORMAL DIESEL PERFORMANCE AT FULL LOAD (BOSCH 3 SMOKE)

Ignoring the use of amyl nitrate it would appear that a turbocharged engine would have a more suitable characteristic for operation on methanol, the natural characteristic of the turbocharger being to deliver air at increasing temperature with load and speed. Some preliminary tests showed that incomplete evaporation of the methanol when introduced immediately downstream of the turbocharger compressor resulted in poor distribution and quench in some cylinders. This was followed by explosions in the exhaust system as the fuel was ignited by the exhausts of the cylinders still firing. It would thus be necessary to provide accurate metering of the methanol to the individual inlet ports.

Throughout this programme a major problem was the extended ignition delay associated with the introduction of the methanol into the air charge. On the basis of comparing methanol's octane rating, ignition temperature and limits of flammability with fuels such as methane and propane, it would seem reasonable to expect satisfactory performance of methanol in dual-fuel mode. An undesirable temperature quench effect is encountered if liquid methanol is used due to methanols high latent heat of vaporisation in relation to its calorific value (5.5% of the calorific value).

Chapter V - Developing an engine for Multifuel Capability

The approaches

1. For more than 40 years of expending billions of dollars, the government concern has supported several alternatives for allowing multi fuel capability to the internal combustion engines - namely

   a) The stratified charge engines

      Texaco Combustion Process Advance to Disc
      (direct injection stratified charge)

      ProcoFord
      (programmed combustion Ford)

      Stratified Charge Rotary Engine

      NOTE: the only successful operative engine of this type is the Japanese Honda, a version of a 1924 invention of Mr. Jobes from Anne Arbor, Michigan, USA.

   b) Substitute Power Plants

      Turbine
      Stirling Engines
      Steam Engines

NAHBE III - RETROFITTING PROGRAM

DUAL FUEL _ GASOLINE/ALCOHOL

SCOPE - OPTIMIZATION OF GEOMETRY FOR THE USE OF HARVEST FUELS - GRAIN OR WOOD ALCOHOL

OBJECTIVE: FARM EQUIPMENT ADAPTATION

SELECTED EQUIPMENT - U S MIL DESIGN

GENERATOR SET A.C.

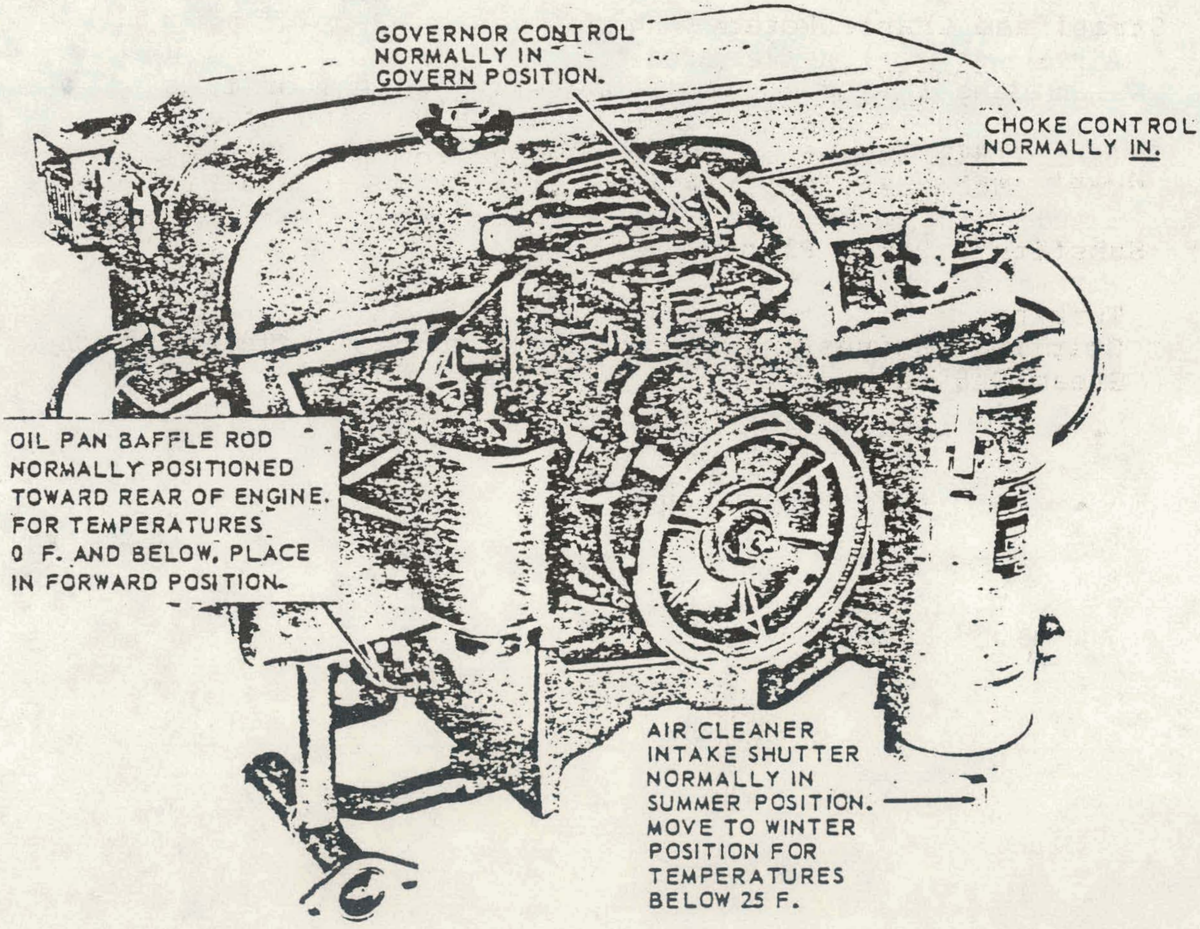
FSN 6115 074 8830

FSN 2805-952-3927

FSN 2805-872-5971

ENGINE, GASOLINE, 10 HP.

(MODEL 2A042-2 AND MODEL 2A042-3)



Tabulated Data

a. General. This paragraph contains all tabulated data pertinent to direct support and general support maintenance personnel.

b. Nut and Bolt Torque Data.

c. Engine Data.

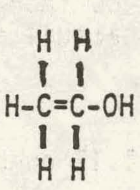
Bore	3.00
Stroke	3.00
Compression	6.9 to 1
Brake horsepower	16.7 at 3,600 rpm
Cylinder compression (minimum)	110 psi
Spark plug gap	.028 -- .033
Magneto contact gap	.013 -- .017
Maximum runout on flywheel	.006
Carburetor float level	25/64 to 27/64 from casting opposite hinge
Fuel pump outlet pressure	3 to 4.5 psi
Air blower impeller clearance to housing	.016 -- .051

NAHBE CONVERSION

Standard Engine Parameters

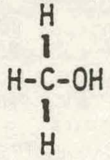
Parametric Analysis

In comparison with gascline, the energy conversion process of ethyl alcohol (C_2H_5OH)



$$H-\overset{H}{\underset{H}{C}}=\overset{H}{\underset{H}{C}}-OH$$

and methyl alcohol (CH_3OH)



$$H-\overset{H}{\underset{H}{C}}-OH$$

requires higher pressures and temperatures at the beginning of the molecular dissociation process. The number and quality of intermediate species of molecules generated by the breaking of molecular bonds have a lower probability of combining successfully and sustaining the rate of the dissociation process for converting chemical energy into heat during the available time.

The NAHBE configuration for this type of fuel will require (1) an increase in the compression ratio--r=8.5 to 1 and (2) a larger than gasoline balancing ratio-- =.5 to .8.

BASIC CONFIGURATION

BORE	3.000 inch	AREA	7.068 Sq inch
STROKE	3.000 inch	DISP.	21.205 Cu inch
COMPRESSION RATIO	r=8.5 to 1	CHAMBERS	2.827 Cu inch
BALANCING RATIO	$\beta = .5$		

$V=21.205$ cu in $V_c=2.827$ cu in

COMBUSTION CHAMBER $VA=\frac{1}{1+\beta}$ $V_c=1.885$

BALANCING CHAMBER $VB=\frac{\beta}{1+\beta}$ $V_c=.942$

$\beta = \frac{VB}{VA} = .5$

THEORETICAL MAXIMUM PRESSURE P=1500 psia
OTTO MAXIMUM TEMPERATURE $T=8650^{O}R$

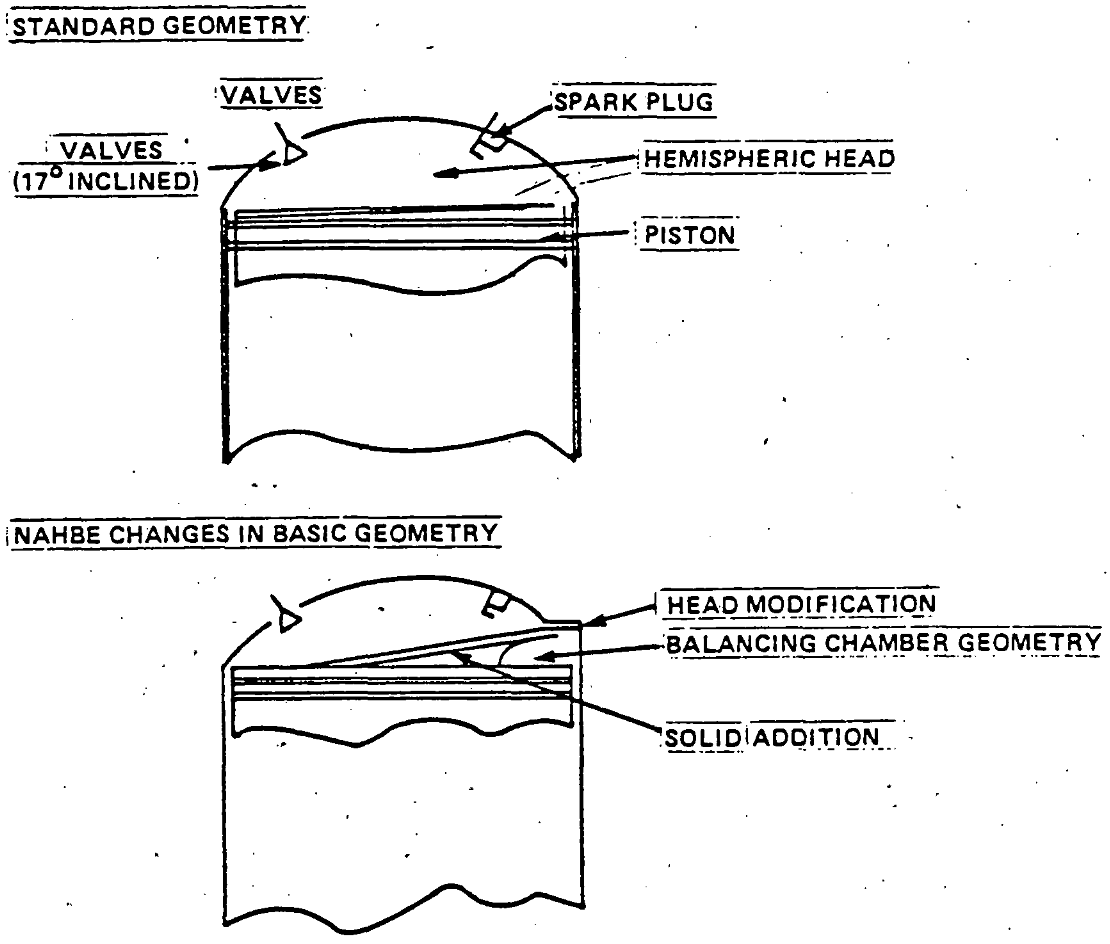
r=6.9:1

THEORETICAL
NAHBE MAXIMUM TEMPERATURE PM=1300 psia
r=8.5:1 B=.5 MAXIMUM TEMPERATURE $TM=8100^{O}R$
VC OTTO — VC NAHBE = .767 cu inch
.767 cu in of solids must be added to the actual combustion chamber to achieve r_n=8.5:1

DENSITY OF ALUMINUM .095 #/cu in.
WEIGHT OF SOLIDS 73 gm proportional 1.17 ounces

Chamber Geometry Approach

The NAHBE conversion involves certain changes in the standard geometry of the basic engine (See Figure 2.). The engine combustion chamber is modified as shown to increase the availability of oxygen and to sustain the rate of energy conversion. This also provides for better control of the poisoning of the balancing chamber which enhances the achievement of the NAHBE mode of operation. The term "poisoning" refers to a condition of flooding or excessive fuel being present in the balancing chamber.

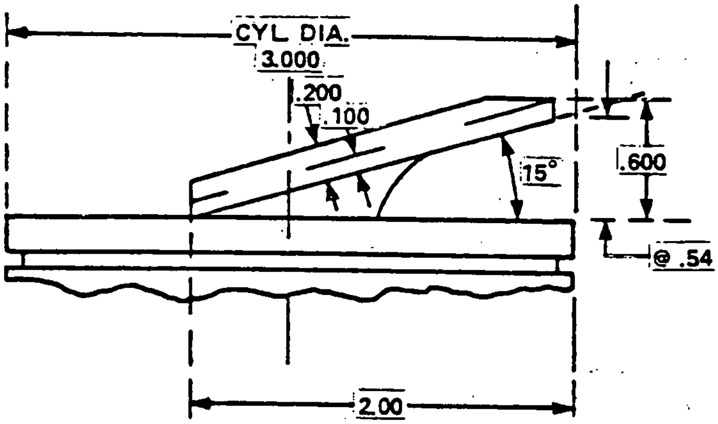


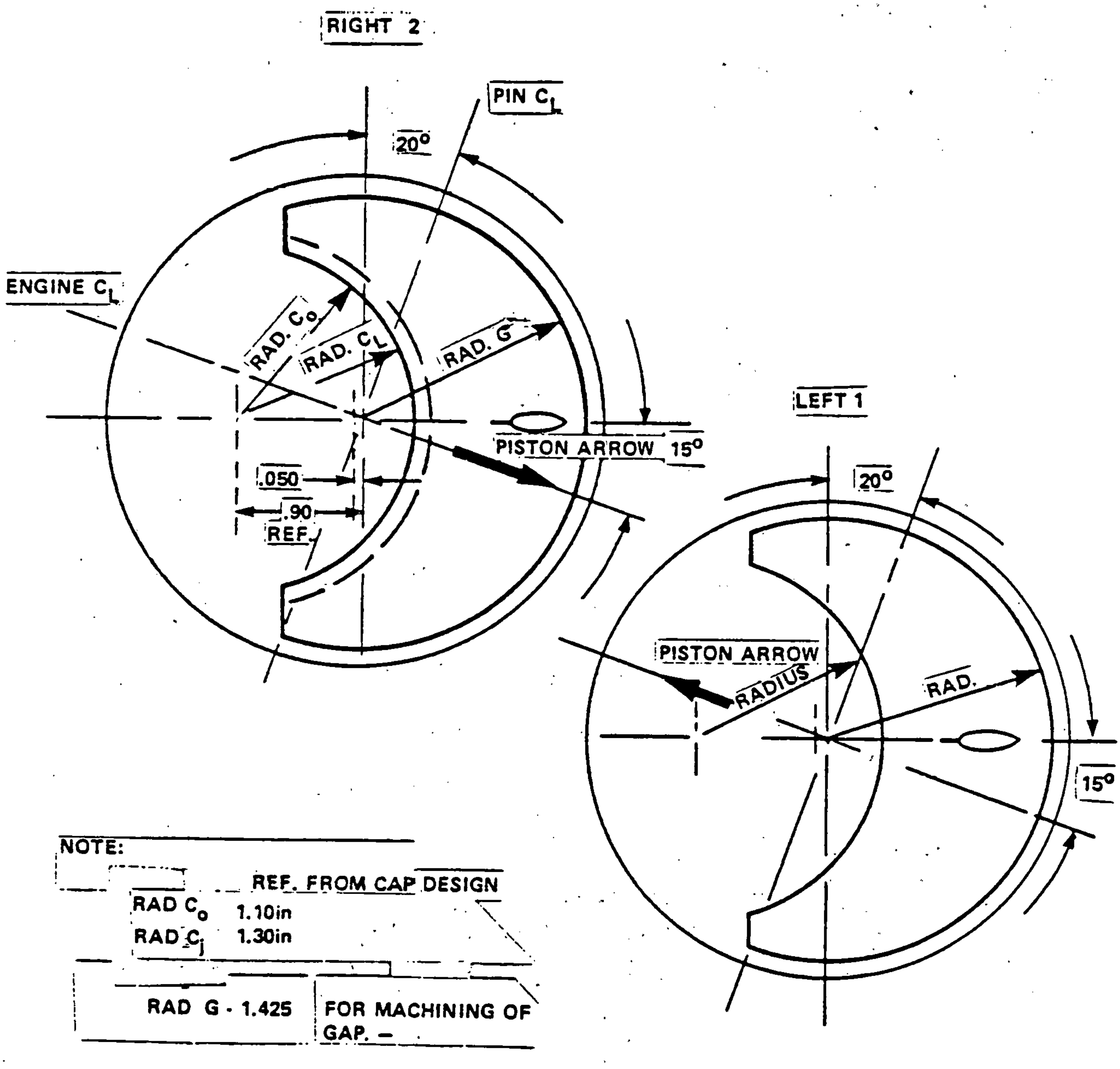
NOTE DUE TO THE INCREASE IN COMPRESSION RATIO SOLID SHOULD BE ADDED

$Vc_{OTTO} > Vc_{NAHBE}$

Figure 2. Chamber geometry.

DIMENSIONING





NOTE:

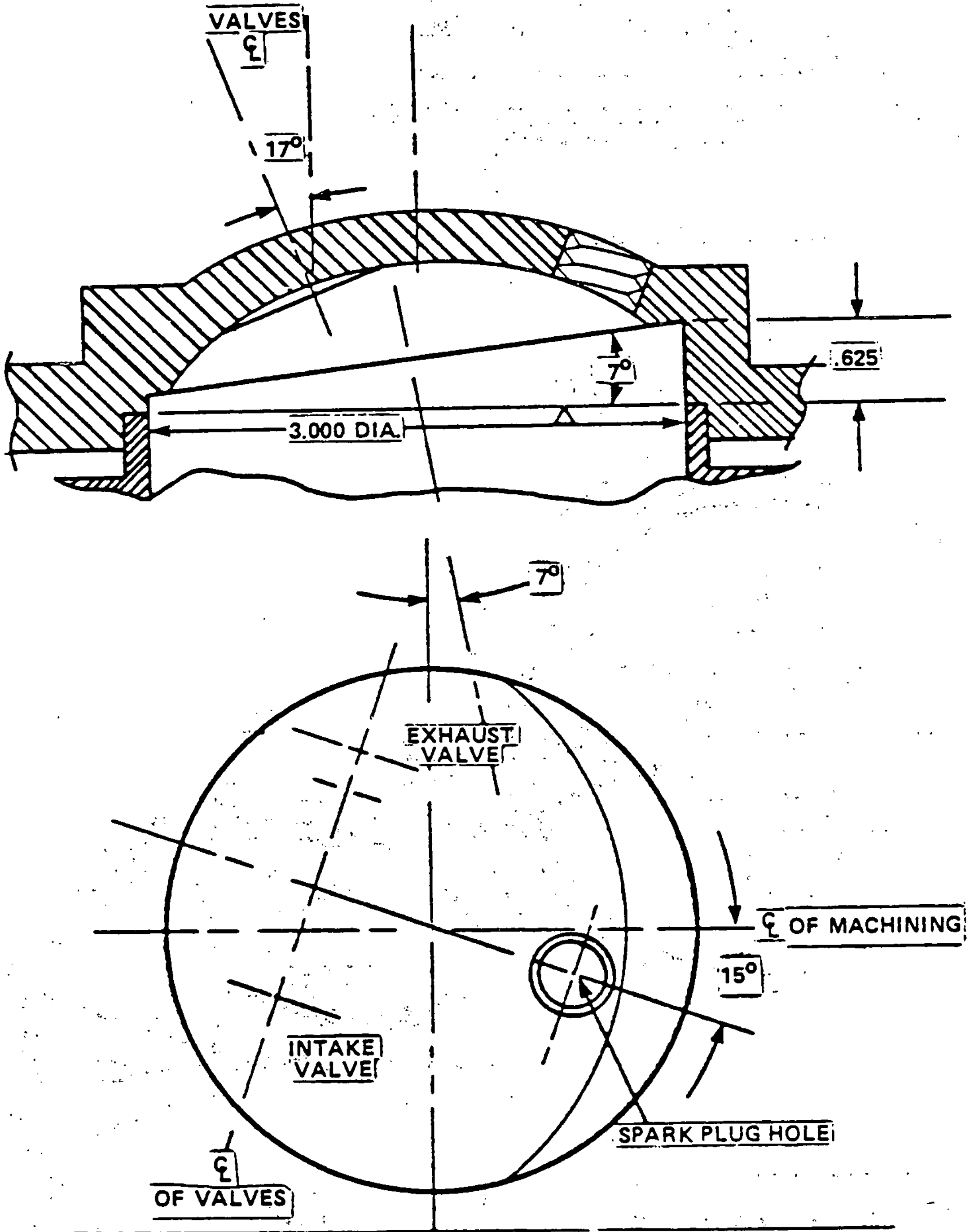
REF. FROM CAP DESIGN

RAD C_o 1.10in

RAD C_j 1.30in

RAD G - 1.425 FOR MACHINING OF GAP. –

CYLINDER HEAD MODIFICATION



NOTE – 1) MACHINING 20° OFFSET OF HEAD REFEARNCE CENTER LINE FROM SPARK TO EXHAUST VALVE

2) ORIGINAL DATA FOR MACHINING AT 12° ANGLE INTERS. OF 3.000 DIA
- BORE AXE AND HEAD AND CYLINDER INTERFACE PLANE

NAHBE FUEL SUPPLY SYSTEM

The manual operating requirements for standard engines are: (1) a constant running speed of 3600 RPM, (2) a variable load of .0 to 17 HP, and (3) a continuous operation at 5 KW. For the fueler fixed calibrated holes are provided for air bleeding in order to optimize the alcohol fuel combustion at continuous load. Air is supplied through a hole in the carburetor located between the choke and the venturi. This allows for full choking when starting the engine.

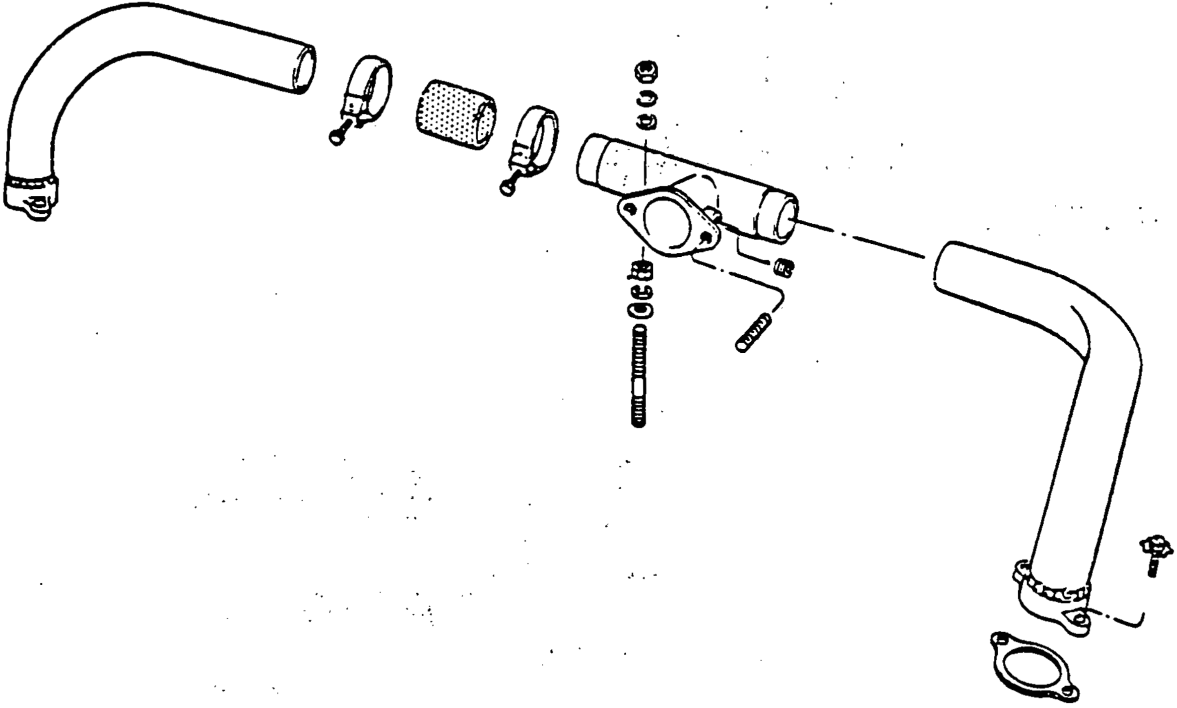
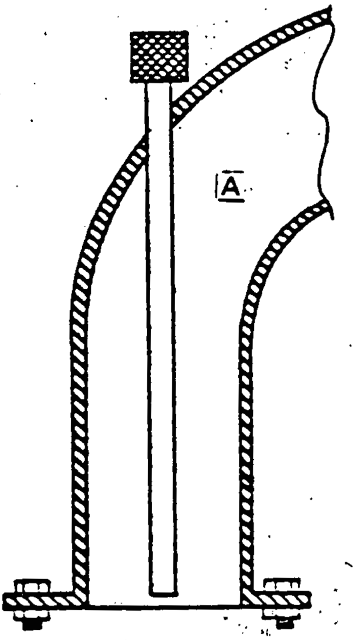


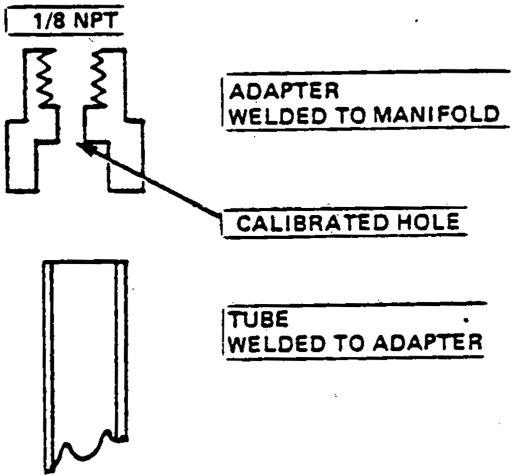
Figure 5. Intake Manifold Standard Components

AIR BLEEDER FUELER

A – MANIFOLD
B – AIRBLEEDER



BASIC BLEEDER



TUBES AND FITTING TO CONNECT TO THE CARBUREUTOR
1) 1/8 NPT ELBOW MALE TO MALE – QTY 1
2) F ─┬─ F 2 FLARE FITTING 1/4 TUBE MALE – 1/8 NPT
NPT FAMALE – QTY 1
3) ELBOW 1/8 NPT MALE 1/4 FLARE MALE – QTY 2
4) 1/4" TUBING NUTS FOR FLARE FITTING QTY 4
5) 1/4" TUBE QTY 3 FT.

DUAL FUEL ENGINE PROJECT

PERFORMANCE AND OPERATION (GASOLINE/ALCOHOL MODE)

The objective was to determine the characteristics of operation for both fuels. The operative variables considered were (1) output, (2) peak pressures, (3) exhaust temperatures, (4) specific consumption, (5) pollutants (CO and UHC) and (6) reliability and maintainability. An evaluation was made to compare the standard engine and NAHBE III on the factors of consumption, pollution, and operation.

One standard 2A042-3 engine and the NAHBE III dual-fuel prototype were each tested individually. The data compiled from these tests is presented in Appendix A. After the testing NAHBE III was operated continuously for two periods of eight hours each at a rated power of 5 KW. The reliability and maintainability of both engines were evaluated.

TESTING PROCEDURE AND EQUIPMENT

EQUIPMENT

1. BECKMAN HC-CO TESTER MODEL 590
2. TEKTRONIX TYPE 502 DUAL-BEAM OSCILLOSCOPE
3. GOULD BRUSH 220 CHART RECORDER
4. DIGITEC - THERMOCOUPLE THERMOMETER
   MODEL 590KF TYPE K - RANGE - 310 TO 2500F°
5. KISTLER DUAL MODE AMPLIFIER
6. KISTLER PRESSURE TRANSDUCER
7. 200cc GLASS BULB FUEL METERING DEVICE
8. STOP WATCH.

TESTING PROCEDURE

1. WARM TESTING EQUIPMENT UP FOR APPROX. 20 MIN.
2. START ENGINE.
3. SET 3-WAY VALVE TO AUXILIARY INLET W/MEASURING BALL.
4. ALLOW TIME FOR FUEL TO ARRIVE TO THE CARBURETOR.
5. REFILL MEASURED BALL AND SET DESIRED LOAD RANGE AND START STOP WATCH.
6. TAKE READING OF: CO, HYDROCARBONS, EXHAUST TEMP, VOLTS, % LOAD, OIL PRESS, AND LOAD SETTING AND RPM.
7. STOP THE CLOCK WHEN 200cc RUN OUT, TAKE TIME READING, REPEAT PROCEDURE FOR OTHER LOAD SETTINGS.
8. BEFORE POWER DOWN, CHANGE TO GAS FOR 5 MINUTES.

RESULTS

The results of the conversion to NAHBE geometry are as follows:

1. When the compression ratio was increased from 6.9 to 9.0, no noticeable changes in peak pressure, exhaust temperatures, knock tendency or vibration were observed in either the gasoline or alcohol mode.

2. The maximum output and operative characteristics were not altered in either the gasoline or alcohol mode.

3. There was an increase in the efficiency of combustion of up to 25 percent at the rated output for both fuels.

4. Pollution was substantially reduced. Carbon monoxide (CO) was reduced from the 6 to 9 percent range to a 0.2 to 0.7 percent range. There was also a reduction in the quantity of unturned hydrocarbons from 150-200ppm to 50-100ppm at rate output. This represents an improvement of 96 to 98 percent for CO and 50 percent for UHC.

5. After a 20-hour endurance test, the NAHBE III experienced no mechanical or thermal problems. There were no heavy carbon deposits on the piston or engine head such as those which frequently appear in a standard engine. All combustion chamber surfaces of the NAHBE III remained exceptionally clean.

NAHBE III - OPERATION INSTRUCTION

I. STARTING PROCEDURE

A. Always check oil before cranking engine.
B. Check water level in battery on a weekly basis
* C. Check toggle switches (starting from top left switch on control panel); local, normal; started switch is spring loaded.
Selector switches on right from top to bottom - V2=3, middle selector set at 120V - 60 cycles approximately, last selector switch to be set at 13.
D. Set 3-way valve for gas or alcohol and governor control to full open position.
E. Start engine R_1 holding the start-stop switch in the start position until engine speeds up. Note - If engine does not start, help by pulling choke rest of the way out by hand.
F. Before loading engine, let warm up for a few minutes.

* Connect load cell wired to L2 and L3 on load terminal board.

10 HP DUAL FUEL AIR COOLED ENGINE
MODEL NAHBE 2A042-2 and 2A042-3

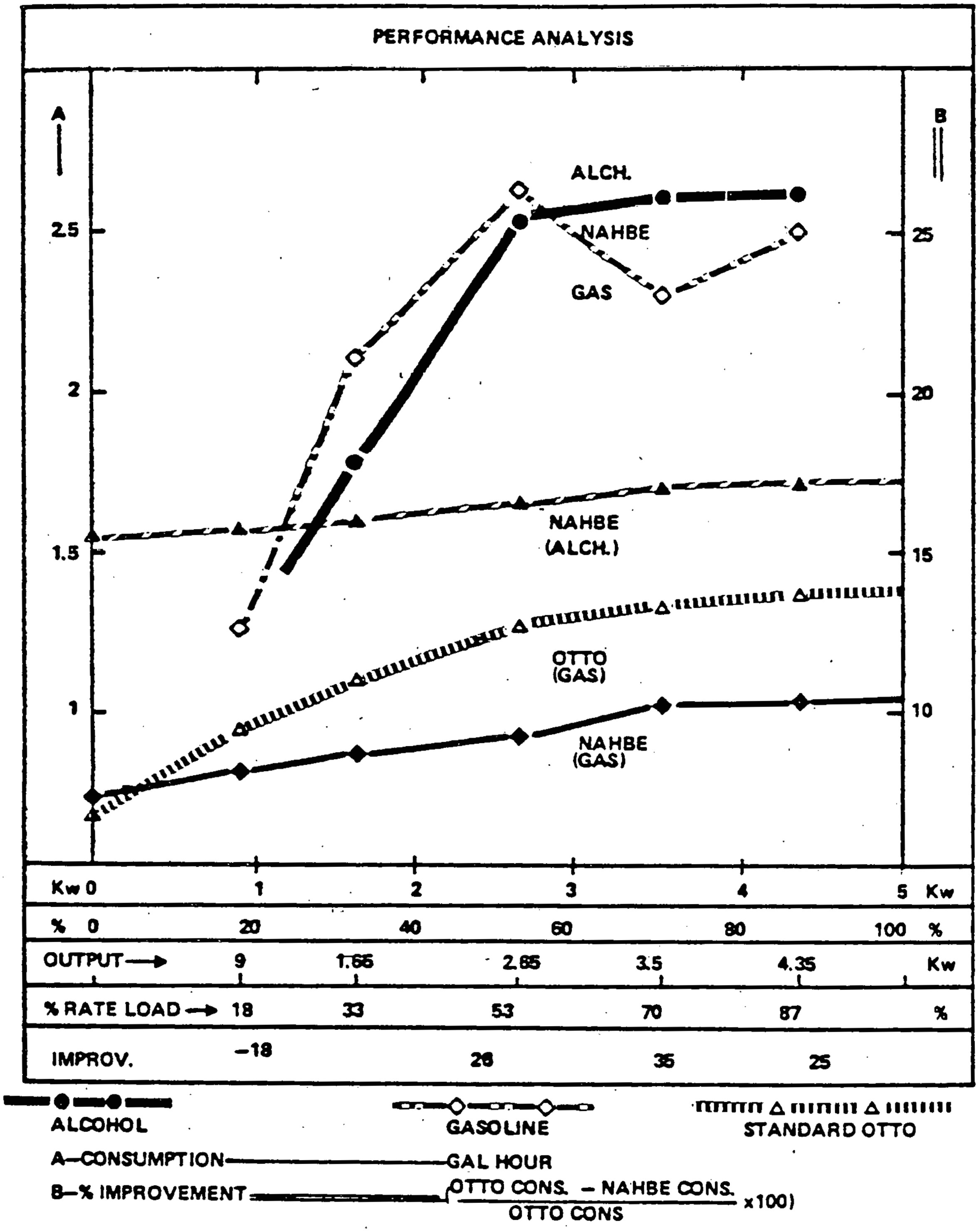


Figure 7. Variable load comparison:
Specific fuel consumption and improvement

10 HP DUAL FUEL AIR COLLED ENGINE
MODEL NAHBE 2A042-2 and 2A042-3

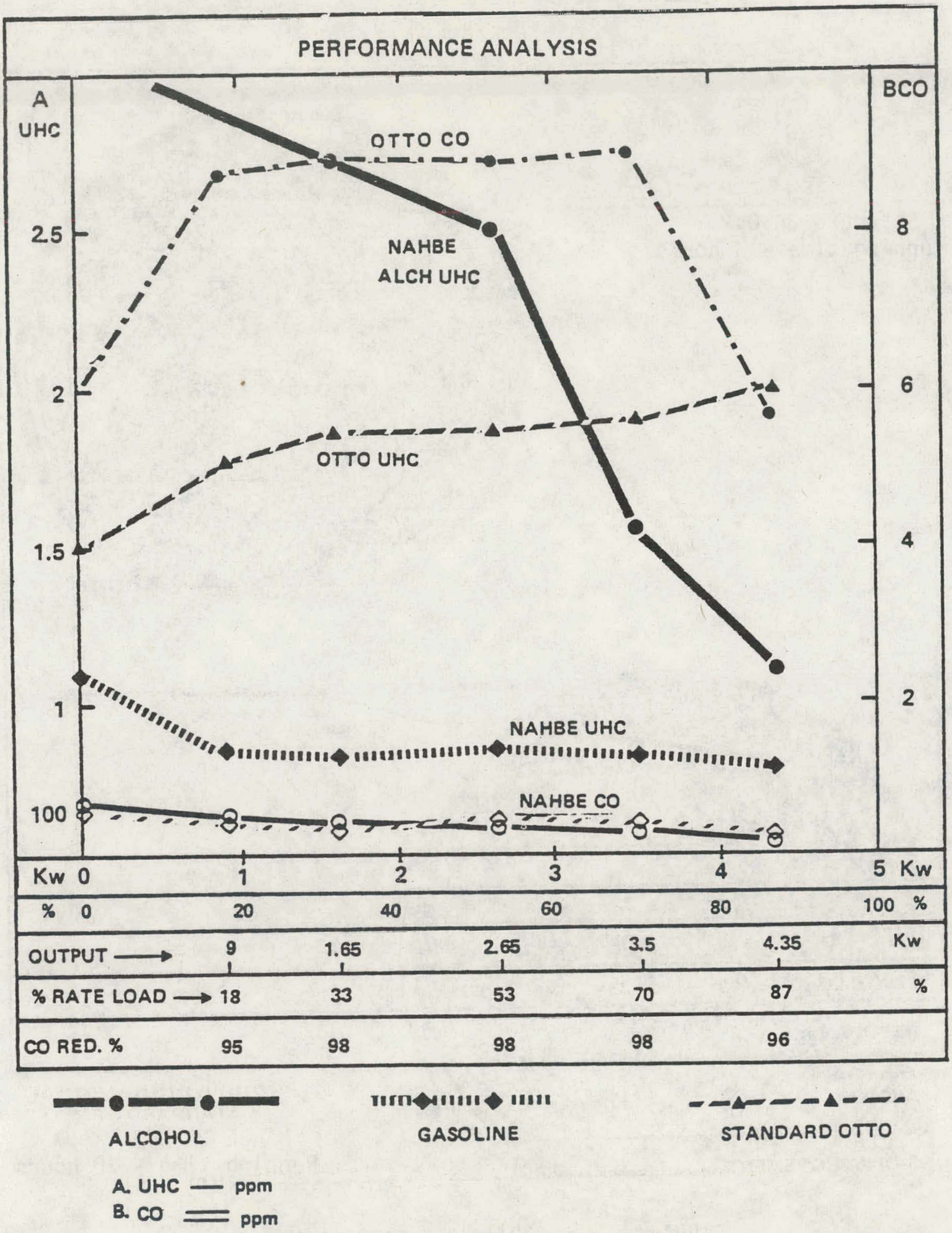
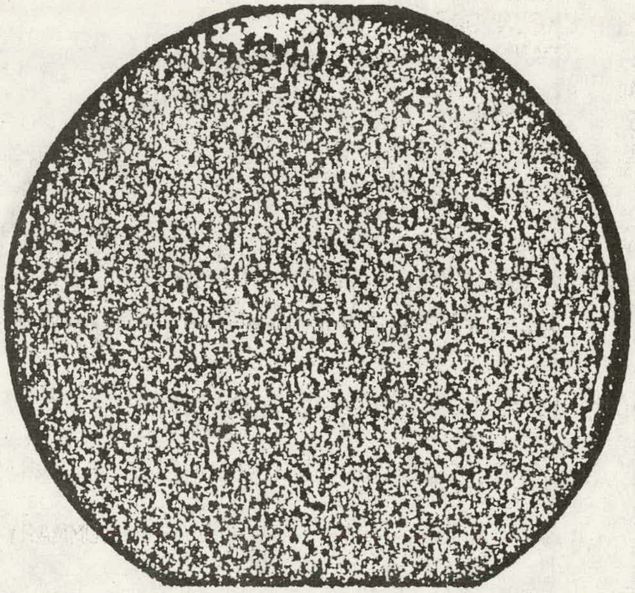
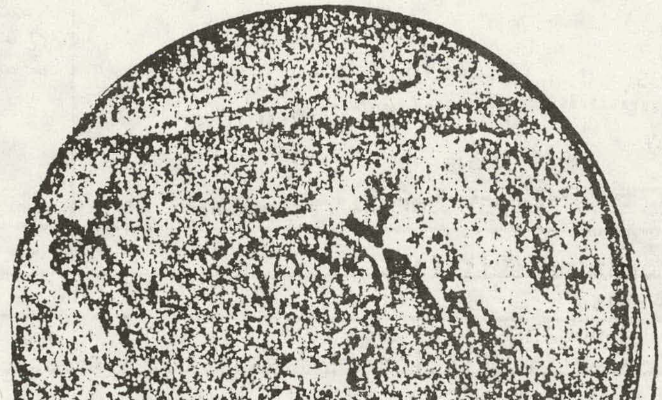


Figure 8. Variable load comparison:
Exhaust gas analysis.

ENDURANCE TEST
CARBON BUILDUP

Standard 2A-042
Running time - 3 hours





NAHBE 2A-042
Running time - 20 hours

OPERATION

1. CHECK OIL
2. CHECK GAS IN TANK
3. START ENGINE AT NO LOAD
4. ALLOW ENGINE TO WARM UP
5. SWITCH TO ALCOHOL
6. PROCEED TO LOAD
7. CHANGE TO GASOLINE
8. WAIT 2 OR 3 MINUTES
9. STOP ENGINE BY OVERRIDING GOVERNOR
10. WHEN ENGINE STOPS, DEPRESS STOP SWITCH
11. TURN 3-WAY VALVE TO OFF POSITION

* ALWAYS STOP ENGINE WITH GAS.

ALCOHOL SITTING IN CARBURETOR OVERNIGHT WILL DAMAGE IT.

SUMMARY

The NAHBE design offers a variety of advantages for optimizing the performance of the standard internal combustion engine. Among these are:

- multi-fuel capabilities
- mechanical simplicity
- increased fuel economy
- ease of modification
- reduced peak pressures and temperatures
- more efficient combustion
- reduction of carbon monoxide emissions.
- reduction of hydrocarbons
- less carbon build-up in engine
- elimination of need for anti-pollution devices.

The NAHBE design is compatible with the goals of the Alternative Fuels Utilization Program (AFUP) of ERDA which is developing new substitute fuels to replace or reduce dependence on petroleum fuels. This program has been exploring the possibilities of engine modification such as compression ratio, valve timing, combustion chamber shape and other parameters.

The NAHBE concept could eventually offer great advantages to the agricultural community particularly because of its multi-fuel capabilities. As alcohol becomes more widely used as an alternative fuel it is entirely possible that it could be produced locally from excess grain or organic waste products. This development would increase the efficiency of farming by reducing fuel costs and providing a feasible means for disposal of residues.

As more research is done on alcohol fuels, it is expected that the results will show considerable gains in fuel usage efficiency. Current research has focused primarily on relatively minor engine modifications such as carburetor and ignition distributor calibrations.

Methanol is also being explored as an alternative fuel because it reduces pollution and supplements energy supplies. It is especially advantageous in view of the fact that it can be produced from agricultural and municipal wastes as well as methacoal, a coloidal suspension of coal (30 percent) in methanol.

Investigations have indicated that methanol is superior to gasoline in thermal efficiency, operational range of equivalence ratio, and emission levels.

The research data on the Heat Balanced Cycle also shows that significant increases in fuel economy and significant reductions in pollutant emissions can be achieved. In addition present engines can be modified either during production or with a retrofit package at relative low cost.

Eventually the incorporation of the Heat Balanced Cycle offers the prospect of designing and manufacturing a less costly, lighter weight engine with a higher power-to-weight-ratio than present conventional engines. The NAHBE engine can meet emission standards without adding costly and inefficient devices such as catalizer systems and/or afterburners.

BETA ENGINE TECHNOLOGY

DISCLOSURE

REQUEST FOR EVALUATION

of an

ENERGY RELATED INVENTION

TITLE

ENERGY CONVERSION CYCLE FOR THE INTERNAL COMBUSTION ENGINES (ICE) AND APPARATUS FOR CARRYING OUT THE CYCLE.

THE BETA CYCLE describing its events in the MICRO DOMAIN of the enrgy fluxs by using the micro coordinates of momentum and position is updating the scientific foundations of the ICE technology.

THE BETA ENGINE,basic implementation of the theory,is overlapping the state of the art of the ICE and is the starting real opportunity for the betterment of those unreplaceable Internal Combustion Engines,by

*IMPROBING THEIR COMBUSTION PROCESS

*INCREASING THEIR EFFICIENCY

*CONTROLLING THEIR POLLUTANTS

*ACHIEVING THEIR MULTIFUEL CAPABILITIES

Presented to: OFFICE OF ENERGY RELATED INVENTIONS

National Bureau of Standard
U.S.Department of Comerce

RICHARD F. BLASER
June 1980

ABSTRACT

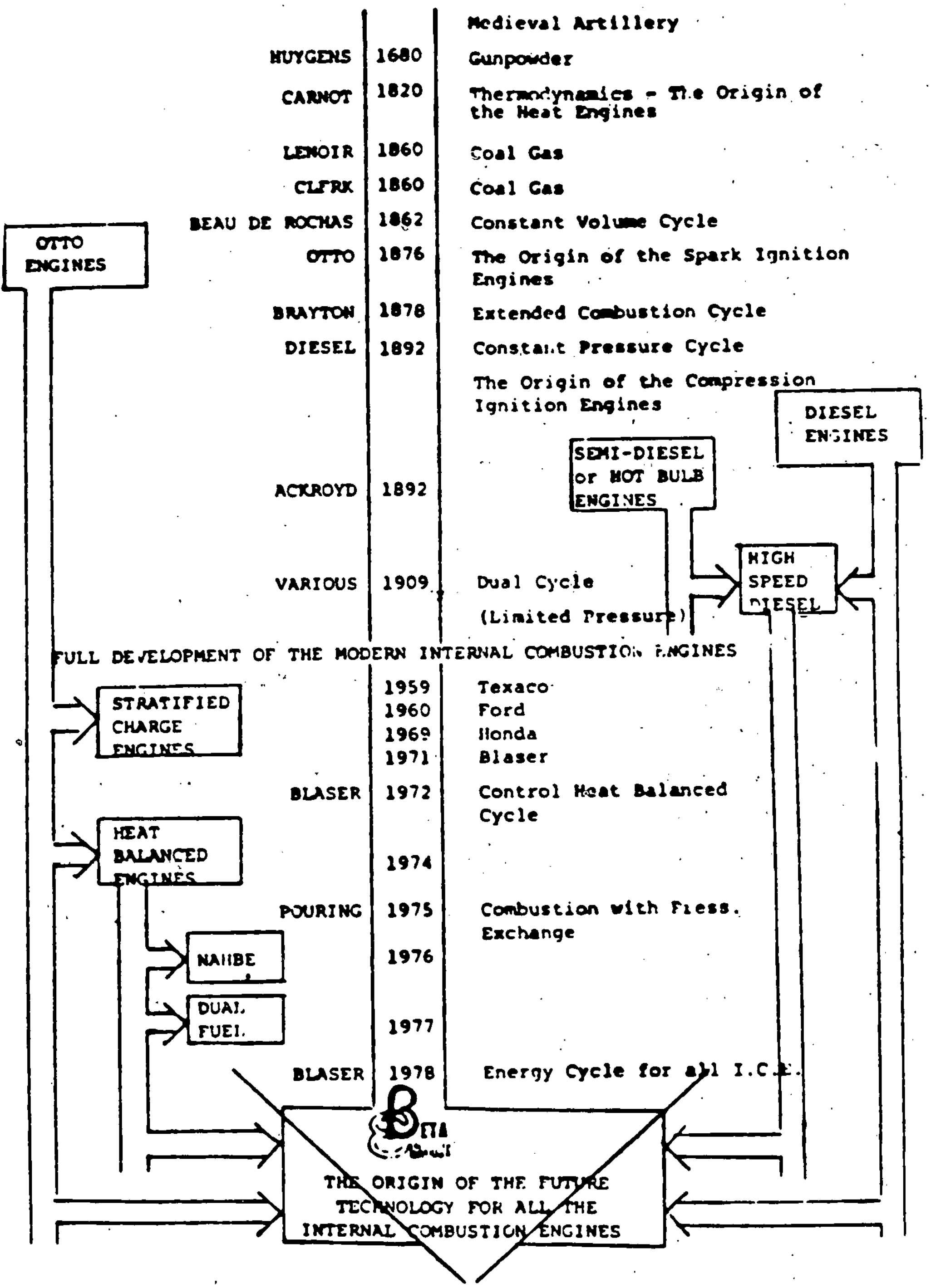
For the Internal Combustion Engines using the volume variation of their working chambers and, the related contributions of auxiliary hardware for the fulfillment of the events of their operative power cycles. "A REFINING IMPROVEMENT OF THEIR COMBUSTION CHAMBER GEOMETRIES AND THEIR AUXILLARY HARDWARE WHICH EXPECTATIONS ARE DIRECTED FOR THE ACHIEVEMENT OF THE EVENTS OF THE BETA CYCLE AN ENERGY CYCLE FOR THE INTERNAL COMBUSTION ENGINES."

The BETA cycle, with its approach using "Micro Coordinates" for the description of the energy related events, is allowing the required TIME considerations for weighing the contributions of the enormous quantity of minute discrete events through which the molecular bonds are broken and energy is allowed to flow for converting an existing chemical potential into an expected availability of thermal energy.

This approach is permitting the evaluation of COMBUSTION AND HEAT using the required micro-coordinates of position and momentum for describing the events in the micro domain of the energy fluxes and the weighing of the contributions of reactants availability and distribution, the control capabilities of the auxiliary hardware and the envelop constrains of the working chamber geometries. Furthermore, the engines operating in the BETA Energy Cycle mode with no compromises or distortions for their real combustion process are less sensitive to fuel characteristics as octane number, cetane number, flash point, viscosity, etc., and their broad multifuel capabilities are encouraging the use of man-made bio-fuels, as alcohol.

INTERNAL COMBUSTION ENGINES (I.C.E)

CHRONOLOGY



		Medieval Artillery
HUYGENS	1680	Gunpowder
CARNOT	1820	Thermodynamics - The Origin of the Heat Engines
LENOIR	1860	Coal Gas
CLERK	1860	Coal Gas
BEAU DE ROCHAS	1862	Constant Volume Cycle
OTTO	1876	The Origin of the Spark Ignition Engines
BRAYTON	1878	Extended Combustion Cycle
DIESEL	1892	Constant Pressure Cycle The Origin of the Compression Ignition Engines
ACKROYD	1892	
VARIOUS	1909	Dual Cycle (Limited Pressure)

FULL DEVELOPMENT OF THE MODERN INTERNAL COMBUSTION ENGINES

	1959	Texaco
	1960	Ford
	1969	Honda
	1971	Blaser
BLASER	1972	Control Heat Balanced Cycle
	1974	
POURING	1975	Combustion with Press. Exchange
	1976	
	1977	
BLASER	1978	Energy Cycle for all I.C.E.

INTRODUCTION

At the start ofthe industrial revolution, the atomic nature of matter was not yet understood and the mathematical model developed to represent the relations between thermal and mechanical behavior had to be put together with the guidance of the crude experiments that could be made.

The controversial and severl times revised Thermal Theory today called Classic or Equilibrium Thermodynamics was concerned itself only with the macroscopic properties of aggregated matter with molecules having completely random distributions of position and velocities and it can work only those state of maximum disorder called the states of Thermodynamic Equilibrium and for the calculations of changes from one to another Equilibrium State, it was unavoidable the use of the socalled quasistatic processes. This constrains and the general pattern of the interrelation of the state variables have been summarized on the Thermodynamic Laws which deal only with equilibrium states and from which one can predict the complete thermal behavior of any aggregate of matter given a relatively few empirically relationships obtained by macroscopic measurements.

When the atomic nature of matter began to be understood the foundations of the Classic Mechanic were revised and its law refined for accommodating <u>Time</u> as new weighing value descriptive dimension and scolars pioneering in the subject dedicated their efforts for defining how the macroscopic properties of matter deal by the equilibrium thermodynamic could depend on the assumed behavior of theconstituent atoms.

The first successes were concerned with gases and they supply the means for expressing pressure temperature and other macro properties of the system in terms of average values of molecular properties. Those works origin the Kinetic Theory of gases.

A most general effort, origin of the Statistical mechanic, was done by Gibbs, Boltsman and others to provide a statistical correspondence between the atomic substructure of any piece of matter and its macroscopic behavior and relationship.

From there and with the contributions of statistical Mechanics and Quantum Theory, statistical thermodynamics was started and the relationship between pressure, temperature volume and heat capacity in function of the properties of the molecules forming the Micro system of theagiomerated matter have been derived.

Those scientific advances in the understanding of the laws of Nature have deeply clarified and expanded the capabilities for the description and analysis of the state of a thermodynamic SYSTEM.

A system is a separation of a restricted region of space or a finiteportion of matter from its surroundings. For describing the system in terms of quantities related with its behavior, or its interaction with the surroundings, we need to define the permitted interactionsthrough the ideal divider and accept a <u>macroscopic</u> or <u>microscopic</u> point of view for defining the properties to be examined.

The Macroscopic point of view refers to the gross characteristics or large scale properties and its supply macroscopic description and macroscopic coordinates.

The Microscopic point of view considers the system as an aggregate of an enormous number N of molecules, each of which is capable of existing in a set of states of independent energy.

Recalling that Thermodynamics deals with the interior of the system, if a macroscopic point of view is adopted, the macroscopic quantities having a bearing on the internal state of the system are called thermodynamics coordinates and they serve for determining the internal energy of the system.

Heat is the macrocoordinate for the internal energy of the system and it was logic for the early investigators to think of heat as a "fluid" and that it can be produced and furthermore the entity heat can have inertia, velocity and also thermal oscillations as the acoustic oscillations. The driving force equivalent to pressure was temperature and from there heat has the characteristics of a state variable of the macrosystem. This approach was for many years part of the development of the thermal science until advanced understanding of energy proved that mechanical work can be added to asystem for creating heat, proving that heat must be treated as energy potential with the same characteristics of the other known used names, chemical, electrical, solar, etc.

Those advances in the understanding of Thermal behavior of the system and the acceptance of the macro and micro point of view as cooperative approaches have refined the laws ofthe Classic Thermodynamics clarify illogical resultsof extensions of its empirical mathematical models and permitted a new insight for explaining, describing and defining the system coordinates required for the solving and the understanding of yesterday empty, unsolvable loops of the natural non-equilibrium situations of no quasistatics processes as laminar flow, viscosity, heat conduction, diffusion, browniam motion, reversibility rate of chemical reactions, etc.

Despite those factsthe technology of the modern internal combustion engines remain nurtured by the assumption of their old originators and because the Thermodynamic power cycles for the heat engines; Otto, Diesel, Brayton, Stirling, Ericson, etc., only deal with equilibrium states in a "macro" thermodynamic system, which follows quasistatic processes for achieving their fundamental function, "Transformation of HEAT into WORK", no accommodation is offered for the application of the energy conversion events micro coordinates. From there, all the endeavors aimed for the betterment of the perfor mances of the actual internal combustion engines remain limited to the macro congributions of the system and their fundamental event, the supply of Heat, called combustion, explosion or simply "BANG" cannot benefit from the blindly ignored capabilities of the state-of-the art of modern science and technology.

The BETA Energy Cycle for the internal combustion engines is intending to start filling the gap. It relates specifically with the introduction and use of the time dimension and its microdomain as part and weighing factor for the energy related events of the power cycles of those engines. The proposed refinements for the working chamber, geometrics and contribution of the auxiliary hardware are aimed for accommodating the operation to the time-bounded micro coordinates governing the natural process of combustion. The microdomain proposed by the BETA cycle is a sound scientific foundation for the development of the BETA Engine technology and from there the scientific updating of the I.C.E. theoretical foundations and the refinement on Method and Apparatus technology for accommodating the time-bounded requirements of the micro-processes converting chemical into thermal energy are opening the expectations of the full use of our actual technological state-of-the-art for the betterment of the performances of those engines in critical areas, such as , fuel economy, fuel limitations, pollution abatement, noise and vibration control and weight reduction.

Scope of the Project

As a balanced planning for organizing the expected contributions, the scope of scientific technical and operative inferences are defined as:

BETA Energy Power Cycle - The refining of the original power cycles by allowing the use of the "micro point of view" for the description of the system and the micro coordinates for the evaluation of the non equilibrium non quasi-static energy events.

BETA Engine Method of Operation - The handling, proportioning and mixing of the reactants for accommodating the overall objectives to the requirements of distribution, availability and activity of the charge, before and during the energy conversion events in the working chamber.

BETA Engine Apparatus - Refinements and improvements in the working chamber envelope geometry to accommodate its macro contribution for the sustaining of the molecular interaction and the rate of reaction which are unavoidably related to the availability of heat required for fulfulling the operative expected performance of the engines.