



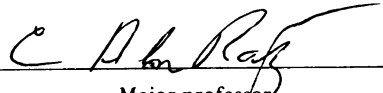
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ETHANOL FUEL FOR SPARK IGNITION TRACTORS

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M.S. degree in AGRICULTURAL ENGINEERING


Major professor

C. Alan Rotz

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ETHANOL FUEL FOR SPARK IGNITION TRACTORS

By

Harold McClure Swarr

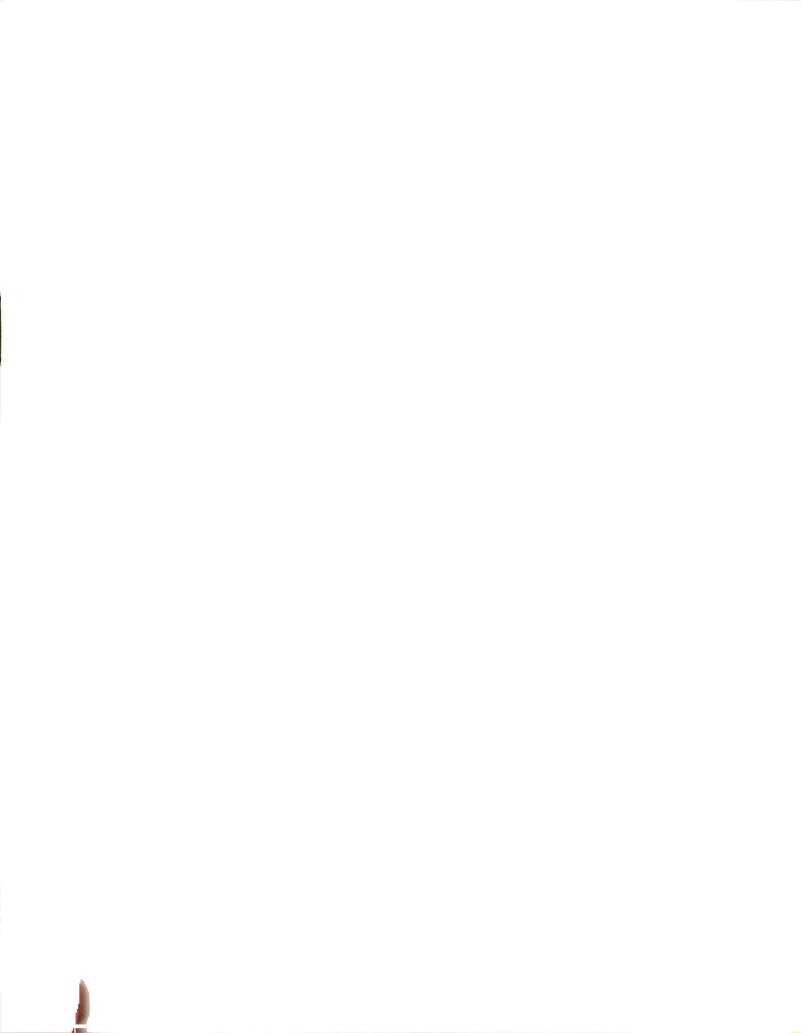
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ABSTRACT

ETHANOL FUEL FOR SPARK IGNITION TRACTORS

BY

Harold McClure Swarr

The unknown supply and cost of crude oil has created interest in developing alternate energy sources. Since the 1973 oil embargo, ethanol has been promoted as a partial or complete replacement for gasoline fuel should the need arise.

A Ford 2000 tractor was converted to operate on straight ethanol fuel. Necessary engine modifications were performed to achieve adequate vehicle operation. Ethanol fuels with up to 25% water content were tested. Fuel consumption, power, engine temperature and driveability were measured. Higher compression pistons were then installed to optimize ethanol fuel performance.

Ethanol fuels produced greater thermal efficiency and higher power output than gasoline. Fuel consumption was always higher with ethanol than with gasoline due to the lower energy content of ethanol. Ethanol fuel containing 10% water content produced equal power, better thermal efficiency and only slightly less fuel efficiency than 100% ethanol.

Approved


Major Professor

Approved


Department Chairman



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I INTRODUCTION

Petroleum fuel prices rapidly increased following the oil embargo of 1973. Gasoline prices more than tripled, reaching a current maximum price level of approximately \$1.35/gallon in Michigan. The United States has become far too dependent on imported petroleum. Growth of the automotive industry since World War II has been the primary reason for this large petroleum consumption. The low cost, abundant supply, and superior qualities of petroleum derived fuels such as gasoline and diesel fuel, forced America to fill the wide gap between domestic demand and supply with imported petroleum. As more cars were sold, more oil was imported, and briefly, in February 1976, imports exceeded 50 percent of total petroleum use (18).

The impact of the embargo led to a conscious effort to reduce the amount of imported oil. Americans quickly realized that the world petroleum supply was not infinite and that their supply could be cut off or priced up at any time by the politically unstable OPEC countries. Finding and exploiting alternate energy sources and utilizing the available energy much more efficiently became national goals. No longer could Americans afford to thoughtlessly spend money on energy wasting products such as the large gas-guzzling cars that were America's trademark.

A detailed analysis of the world petroleum supply has led many to come to the following two conclusions (18, 26, 34, 38, 32). First, the world petroleum supply will peak around the year 2000 at the going rate of world consumption. A definite end to the once seemingly boundless supply will take place in the not-too-distant future. The second conclusion implies that no one knows what or if a single energy source will eventually dominate the market the way petroleum has for such a long time. This

required the implementation and perfection of every possible energy source.

Many energy experts (18, 27, 32) feel that there will never be another energy resource such as petroleum and that the only way to prevent an energy catastrophe by continued heavy petroleum usage is to supply a larger portion of the total energy demand from each of the other known energy resources. Perfection of all the alternative energy sources such as solar, wind, and electric as well as making better use of petroleum is seen as being the best solution for cutting down our dependence on petroleum. Realizing this, the last 7 years has produced significant gains in the perfection of many energy resources.

Perhaps the most difficult task for energy researchers is finding non-petroleum alternative fuels for use in internal combustion engines. The difficulty arises from the fact that America's dependence on automotive transportation was made possible only because of the abundance of low cost gasoline and other petroleum products. Indeed, during the early years of automotive development, the oil and automotive industries became inseparably interlocked, with mutual problems requiring complete cooperation for their solution (37). Modern automobiles have been designed with gasoline as fuel. These designs have taken years to perfect, and introduction of alternative fuels cannot be made suddenly. Time is needed to develop engines which can best utilize the fuel properties of a different fuel. This is why future fuels, which will be widely used around the year 2000, must be thoroughly researched within the next few years.

Alcohols, particularly ethanol and methanol, are leading candidates for future use as fuels for internal combustion engines. Their properties are generally similar to those of gasoline, although significant differences do exist. Another factor influencing their candidacy is that

they can be produced from a variety of substances and their production technology in most cases is quite well known. Economic production is the major factor which has kept alcohols from being considered as primary automotive fuels. However, with rising petroleum prices and better alcohol production technology, alcohols must be considered as fuels for internal combustion engines.

Future fuels need to be gradually added nationwide as replacements for gasoline. This helps lessen our dependence on petroleum fuels, rather than facing the impossible task of suddenly replacing our total petroleum supply in a short time. Long term (after the year 2000) future fuels appear to be supplied from synthetic gasoline and distillate oils produced from coal and oil shale (18, 43). However, increased efficiency of production and more advanced processing technology is required to bring down the operating costs before these fuels can exist and be used nationally. Eventually, synthetic fuels will become economical, and our future fuels will have similar compositions to the liquid hydrocarbons used presently, but of the alternative fuels available to supplement the petroleum supply until then, alcohols appear to be the best (18, 20).

Methanol appears to be the alcohol best suited for nationwide fuel use in the United States (35, 38). It can be efficiently produced from our vast supplies of coal as well as any type of cellulose material and natural gas. Known economically recoverable coal alone is equivalent to about five times the proven reserves of oil worldwide, and over 30% of it is in the United States (20). This solid fuel resource, along with oil shale and tar sand, will produce our synthetic future fuels. Any alternative fuel that could receive widespread national use in the United States would have to be produced from one of these solid resources

(39, 56). The main problem involved with converting these solids to liquid hydrocarbon fuels is the expensive need to add hydrogen to them. This process is known as hydrogenation and the more hydrogen needed, the more expensive the conversion process. Hydrogenation will become more economical in the future and the process of bringing the lower hydrogen-to-carbon ratio of oil shale and coal up to that of current petroleum fuels will be performed at a much lower cost (29, 43). For now, however, the less hydrogenation needed, the less the conversion cost. Methanol synthesis is the first stage in producing fuel from coal and its production technology has been well known for a long time (9).

Ethanol fuel is an alternative for use in agricultural production. Non-petroleum production of ethanol is best accomplished by the fermentation of any carbohydrate-containing agricultural feedstock or suitable biomass waste material (28). Some feedstocks commonly used to produce ethanol are corn, grain, potatoes, sugar beets, sugar cane, wheat, and sorghum. Corn is usually considered the cheapest and most abundant source in the United States for ethanol production for fermentation (43). Production from the fermentation of renewable feedstock creates an advantage in that there will always be a supply from which to produce ethanol. The biggest disadvantage of counting on ethanol as a future fuel is that it could never replace a very large part of the petroleum demand in the near future. Indeed, it is projected the United States would have to increase its current industrial ethanol production approximately 29 times by 1990 in order to produce a nationwide 5% ethanol-gasoline blend (18). The production costs of shipping and producing ethanol feedstocks and getting the final product fermented, distilled and in the gas tank just simply cannot be lowered enough in the next 20 years for ethanol to be

taken seriously as a nationwide fuel in the United States (28).

However, when looked at as a localized fuel, ethanol may be the best alternative fuel available to help reduce petroleum consumption. The renewable resources used to produce ethanol create a distinct advantage when production occurs in the proper environment. If transportation costs of the feedstock and final product can be minimized, and the feedstock is not bought on the open market, the overall ethanol production costs can often be significantly lower than the current price of gasoline in Michigan (45). The actual price depends on the price, if any, of the feedstock. Thus stretching the nation's fuel supply with ethanol could possibly be best achieved by operation of localized fleets of vehicles, such as all the vehicles on a farm or airport, where the production of fuel is near and the vehicles can be designed for optimum ethanol utilization.

Ethanol is actually a very good fuel for internal combustion engines, and has been used as a fuel in many countries (42). It has many properties, such as a higher octane rating and cleaner burning characteristics, which make it a better fuel than gasoline. Ethanol also has a few properties, such as lower volatility and lower energy content which create problems with engine use.

The work presented in this paper is part of a larger project dealing with the economic assessment of ethanol production from a small farm still using surplus farm crops as feedstock. The alcohol fuel project, funded through the Michigan Department of Agriculture, was designed to research the most efficient means of producing ethanol and then using it as an on-farm fuel. A small-scale alcohol still was constructed at the Michigan State Beef Cattle Research Barns where the production of ethanol from corn

was evaluated. This location enabled the use of the ethanol byproduct of distillers grain to be used as a supplemental feed for the university's beef cattle. The part of the project reported here, dealt with utilizing the still-produced ethanol as a straight fuel for gasoline powered tractors used on the farm.

II OBJECTIVES

The overall objective of this research was to evaluate the feasibility of converting a gasoline fueled farm tractor to operate on ethanol fuel. Specific objectives were:

1. To extensively review the results of previous studies conducted on alcohol-fueled engines including design requirements and potential problems.
2. To compare engine performance of a gasoline-fueled tractor to the performance of the same tractor converted through minor carburetor changes to burn ethanol.
3. To measure the increased engine performance obtained by increasing the engine compression to further optimize the tractor for ethanol fuel.

III LITERATURE REVIEW

A. Alcohol Fuel History

The use of alcohol as a motor fuel is an old concept. Ever since the first internal combustion engines were developed, ethanol and methanol were considered as primary fuels. In 1907, the USDA published a report comparing alcohol fuel properties to those of gasoline (3). At this point in time, internal combustion engines were first developing as major sources of power, and it was not certain whether gasoline or alcohol would be the future supply of fuel. In 1909, a similar study was conducted by the United States Geological Survey, as actual engine tests were performed to determine and compare specific fuel properties (2). Steam produced from low cost coal had long been the major source of power, but engineers realized that petroleum fuels were superior to any other source of power for mobile engines. The chief controversy, which led to extensive fuel and engine tests, was that ethanol could be produced from a variety of renewable plants, seemingly creating an inexhaustible supply, while gasoline had to be refined from the unknown supply of crude oil. Ethanol was generally considered the best alcohol fuel before World War II because of its supply and well known production technology. Methanol was considered as a primary fuel source when production technologies were perfected to produce synthetic methanol from coal in the 1930's (38).

Alcohol use as a motor fuel soon became inferior to gasoline as these early tests proved gasoline to be better suited for internal combustion fuels. Alcohol fuel properties provided problems such as much higher fuel consumption and trouble with cold starting. In addition, gasoline

soon became endorsed by the oil companies as larger crude oil supplies were discovered and better, less expensive refining methods were developed. Since large scale alcohol production plants had not been developed at this time, gasoline prices decreased considerably compared to alcohol. Thus, better engine performance, lower cost, better fuel economy, and plentiful supply made gasoline the obvious fuel of the future for spark ignition engines and virtually excluded any major nationwide use of fuel alcohol in the United States.

Historically, whenever petroleum supplies were threatened, alcohols were again recognized as possible temporary fuels. The period of time from the beginning of World War II through the end of World War II was characterized by the possibility of threatened oil imports. This time period produced a wealth of engine test data in which a variety of fuels were used to fuel spark ignition engines (42). Because of their history as engine fuels, alcohols were considered first when oil imports were threatened. During World War II, research continued on how alcohol fuels could be best utilized in the existing internal combustion engine design. Alcohol was used in a few cases as an emergency fuel.

Ethanol fuels have long been a more favorable alternative to gasoline in those countries where the costs of petroleum fuels greatly exceed those in the United States, and in those countries with great excesses of certain renewable plant materials such as corn, sugar cane, and cassava which can be economically converted to ethanol. Because of this, much of the literature published on alcohol fuels is not printed in English. Some of the countries and territories throughout the world which used ethanol blends in gasoline during the decades of the 1920's and 1930's include: Argentina, Australia, Cuba, Natal, South Africa, and Sweden. In the 1930's

the United States Chrysler Motor Corporation produced cars which operated on 100% ethanol for exportation to New Zealand. International Harvester also made trucks for export to the Philippines which were powered with engines designated to burn 100% ethanol (43). Both Japan and Germany researched and utilized ethanol more heavily than the United States during World War II because their heavy dependence on imported petroleum was harder felt during periods when imports were cut-off (42). Germany fueled many of its vehicles on ethanol made from potatoes (21). Brazil has always had the available land for a great surplus of crop production from which large quantities of ethanol can be fermented and used nationally to operate their automobiles (19, 31).

After World War II, foreign oil imports were no longer threatened in the United States and the world supply of petroleum seemed inexhaustible. Low cost petroleum prices led to the virtual exclusion of any fuels other than petroleum distillates for nationwide use after 1945. Gasoline became the fuel which has perfected the design of the modern day spark ignition engine.

As the population grew and more cars were sold, the demand for fuels became excessive and the United States became more and more dependent on imports from the Middle East. The heavy population increase throughout the world in the last 15 years has created tremendous crude oil demands, and consequently had caused major price increases in petroleum fuels over the last few years. These price increases, fuel shortages of recent years, and political instability in the Middle East again threaten the security of United States dependence on foreign imports for a large supply of our fuel. Americans now realize that the world's crude oil supply is not endless, and that nonrenewable petroleum fuels will someday no longer

exist (19, 20, 32, 38). The 1973 oil embargo sparked an energy consciousness in the United States that has led to a national effort to both conserve our existing resources and to develop every alternative to its full potential. Congress approved the formation of the Department of Energy to head the development of these alternate energy sources in 1977.

Since 1973, renewed interest has been bestowed in the use of alcohol as a nationwide fuel, both in its neat form and as a gasoline blend. Alcohol fueled spark ignition engine performance testing has provided current data which to a large extent is simply verification and reworking of the research performed with ethanol between 1920 and 1945. Much of the data collected 55 years ago can be applied to alcohol use in modern internal combustion engines (42). Thus, the use of alcohol as a fuel for internal combustion engines is not a new concept. There has been a wealth of information collected regarding the performance of alcohol as a fuel, and the conditions for optimum performance are relatively well known (29).

B. Alcohol Production for Fuel

The majority of current alcohol fuel research has dealt with the economic feasibility of implementing ethanol and methanol as nationwide fuels (43). Production costs have always been higher for alcohol than gasoline. However, as research continues to develop and perfect cost effective methods for producing alcohol, the rising costs of imported petroleum make alcohol a more suitable alternative fuel.

The technology for producing ethanol is well known. In the United States there are two types of ethanol, each with its own production method. Ninety-three percent of all industrial ethanol is made by the hydration of ethylene which is a petroleum derivative (20). This is

approximately 75% of the total U.S. production (28). The other 25% is mainly used as beverage alcohol and can be produced by the fermentation and distillation of any biomass feedstock whose carbohydrate content can be easily fermented. Biomass resources with this carbohydrate type are all food sources such as grains (corn, wheat and barley), sugar crops (sugar cane and sugar beets), and potatoes. The carbohydrate feedstock is first ground and cooked with water to convert the starch to sugar with the enzyme amylase. Yeast is then used to ferment the sugar. "Fermentation is the decomposition of organic compounds into simpler compounds through the use of enzymes, which act as catalysts in the conversion of sugars with six carbon atoms, or six sugars, to ethanol by yeast" (43). The product of this conversion contains 6 to 12% ethanol which is drawn off by a distillation process. A high protein material known as distillers' dried grain is also a fermentation product. Distilled ethanol can be made 95% pure with a conventional distillation process. Production of ethanol with less water increases production costs (6). Ethanol forms an azeotrope with 5% water, causing the production of anhydrous ethanol to require the expensive process of further distillation with benzene. Thus, the cost of producing alcohol with a given water content must be compared with any advantages or disadvantages of having water in the internal combustion engine alcohol fuel. This ethanol production process has been known for centuries and improved upon with the art of brewing beer, whiskey and all other alcoholic beverages.

Ethanol can also be produced by using other biomass materials such as wood and corn fodder. These feedstocks contain cellulose which requires the highly complicated front-end solubilization step called hydrolysis. The cellulose is first hydrolyzed by acid treatment or enzymatic action,

and then processed in a manner similar to that for simple sugars (28).

Methanol can be produced from almost any carbon source - petroleum, natural gas, coal, corn, garbage. It can also be produced by the destructive distillation, or pyrolysis, or wood (26). Nearly all methanol is currently made from natural gas (28). The process for converting solid material to methanol requires the pulverized, dried feedstock to be fed through a steam/oxygen-blown gasifier to produce a synthesis gas consisting of CO and H₂. Contaminants such as H₂S and CO₂ are removed before methanol synthesis with a Co/Zn/Cr catalyst is performed. This process is similar to ethanol fermentation in that it is relatively simple and has been known for a long time (38).

The problem with using alcohol fuels lies partly in creating better production technology, but mainly in deciding when, how and possibly if alcohol fuels should be used to supplement petroleum fuels. The economics involved and the political decisions which must be made are quite complex, and several factors must be considered before any decision can be made. Further complications arise from the different methods used to predict future costs, the assumptions made within these methods, and the guidelines used to interpret the results.

The major obstacle blocking the path for alcohol fuels is simply production cost. Methanol and ethanol costs differ because of different production methods and resources used. The most cost-effective processes are those which supply not only one product but a number of products related with one another (32). In the United States, ethanol costs are higher than methanol costs when the two fuels are considered for nationwide use (20, 38). Most studies conclude that ethanol will not play a major role as a motor fuel (43). The primary reason is the high cost of the cheapest

possible feedstock, which is corn (28). Ethanol from cellulose materials is currently quite a bit more expensive, due to hydrolysis rather than fermentation of carbohydrate food resources (20, 43).

An idea of the uncertainty involved in trying to accurately predict future costs of a potential fuel can be seen with ethanol. One fact is certain; the price of corn will need to be lower for the ethanol fuel producer but higher for the farmer producing the corn. The higher the corn price, the higher the ethanol price. The potential market for the huge quantities of distiller's grain by-product would affect other feed markets such as soybean meal, while gradually losing its own market due to overproduction. Besides the high raw material cost, the total energy consumption during ethanol production is rather high. "When the energy used in growing corn and the energy used in drying the distiller's grain are included, the efficiency is only 56 per cent, meaning that 1.8 BTU are consumed for every BTU produced as ethanol, other alcohols and distiller's grain" (28). Along with the high cost of raw materials and the high energy consumption, there is a shortage of feedstock for ethanol production. Most economic feasibility studies on possible ethanol fuel usage have come to conclusions such as: "If the entire U.S. production of corn, wheat, barley, oats, and grain sorghum, amounting to 329 billion liters in 1977, rather than just the surplus, were fermented, it could theoretically, provide 253 million ℓ /day of 200 proof alcohol, equivalent to 166 million ℓ /day of gasoline. Fermentation of the entire sugar crop of 6.6 million metric tons could provide ethanol equivalent to another 7.6 million ℓ /day of gasoline. This 174 million ℓ /day of gasoline-equivalent from the entire fermentable U.S. farm product comes to 15% of the gasoline consumed in 1977" (20). The outlook for increased ethanol production from

land currently not farmed is not very good either. "The United States Department of Energy has estimated that if all practically available farm land were used for farm crop plantings in excess of those required for food production, the ethanol produced from the crops and residues would satisfy no more than 8% of today's total liquid fuels energy demand" (20). Thus, the use of straight ethanol as a national motor fuel is impossible.

Ethanol/gasoline blends are viewed by most economists in much the same light as straight ethanol fuel. The only real difference lies in the fact that with an all-out national effort, the potential volume of ethanol from farm products could possibly be sufficient for blending with gasoline at a 10% blend level. The high raw material cost and energy consumption affect blends in the same way. More energy and money are spent on the ethanol produced than on the petroleum saved. "One farm-state economist likened blending fermentation alcohol with gasoline to stretching hamburger with filet mignon, 'a losing economic proposition'" (20).

The economic factors involved in methanol production are much more favorable than those of ethanol. The principle difference is that the number one raw material for methanol production is coal, which is much more abundant than ethanol raw materials. If all the U.S. energy consumption was furnished by coal, proven reserves of economically exploitable mineral deposits would last 120 years, while potential reserves might bring this figure up to 1300 years (48). Coal reacts with oxygen or air, steam and/or H_2O to form mainly combustible gases (CO , H_2 , CH_4), which through catalytic reduction of the carbon monoxide yield $MeOH$ or methanol (21). Methanol production from wood/bark biomass sources such as underutilized standing forests, logging residues and mill residues as well as specially designed silvacultural biomass farms represent potentially

significant sources of fuel (43). However, their potential is generally considered long term as much development is needed before they can be used for large quantities of fuel. Coal, both lignite and bituminous, is generally considered the primary feedstock for methanol production (18).

Even though alcohol fuel consumption may not become cost effective on a national basis, the use of alcohol in a local environment can be economically feasible. Ethanol appears to be well suited for small scale production in a centrally located facility where the local surplus of biomass feedstock can be used to fuel a fleet of optimally designed ethanol vehicles (20, 28). A prime example of this environment exists on the farm. An on-farm still could produce enough ethanol to fuel all the engines used on the farm. The high cost raw material, usually corn, would be produced within the system, consequently lowering the overall operating costs. Ethanol would then be produced at a much lower cost than if the feedstock had to be purchased at market value.

C. Alcohol Properties and Ethanol Fueled Internal Combustion Engine Characteristics

Alcohol and gasoline exhibit different properties because of their chemical structure. Gasoline is considered a hydrocarbon fuel which means its molecular structure consists entirely of carbon and hydrogen atoms. Ethyl alcohol, or ethanol, is derived from the hydrocarbon ethane (C_2H_6), while methyl alcohol, or methanol, is derived from the hydrocarbon methane (CH_4). These are the two simplest alcohols in terms of production efficiency and molecular structure. Their production consumes the least energy and they offer some advantages over other alcohols in automotive applications, such as a comparatively low boiling point (25). The

Table 1. Properties and characteristics of alcohol, diesel and gasoline fuels.

Source	Gasoline	Diesel	Ethanol	Methanol	Gasohol**	Diesohol**
Formula	Petroleum	Petroleum	Agricultural products, petroleum	Forest products, natural gas, coal	--	--
	C ₄ -C ₁₂ mix	C ₆ -C ₁₄ mix	C ₂ H ₅ OH	CH ₃ OH		
Specific weight (grams/cc)	0.743	0.827	0.802	0.791	0.743	0.827
Energy content (kj/l)	33,727	38,746	23,580	18,006	32,723	37,210
Energy content (kj/kg)	45,820	54,659	29,772	22,678	44,192	52,170
Pump octane	87-98	20-30	98-102	99-102	90-91	--
Intake air/fuel ratio	14.9	15.0	9.0	6.5	14.0	14.6
Heat of vaporization (kj/kg)	409	156	921	1,176	419	--
Boiling point (°C)	-0.5-2	198-338	78	65	-0.5-216	78-338
Vapor pressure (Pa at 38°C)	345	--	120	220	392	--
Cetane	--	50	8	3	--	--
Reactions with materials	--	--	Some plastics, rubber, lacquer, paint, epoxy	Some plastics, rubber, copper, brass, terneplate***	--	--

* Defined as 10% anhydrous ethanol and 90% gasoline.

** Defined at 10% anhydrous ethanol and 90% diesel oil.

*** A lead-tin coated steel used in automobile fuel tanks.

Sources: (References 4, 5).

substitution of an OH radical for one of the hydrogen atoms in each of the hydrocarbons gives the formula for ethanol (C_2H_5OH) and methanol (CH_3OH), and has the effect of bestowing waterlike characteristics on what was once a volatile but inert hydrocarbon (48).

Ethanol and methanol exhibit similar fuel properties when used in internal combustion engines. The viscosity and density of alcohol fuels are similar to those of gasoline and permit the use of present carburetor and injection systems (25). Some properties are better with methanol while others are better with ethanol. Perhaps the best way to view the two fuels is that when ethanol is used in place of methanol, the performance data universally falls between that obtained with gasoline and that from use with methanol. Thus, if advantages are obtained with alcohol, they are not as great with ethanol as they are with methanol, and if there are disadvantages, they are less with ethanol than methanol (18). This understanding can be beneficial in estimating engine characteristics with ethanol fuel from the vast majority of current alcohol research that has been performed with methanol.

A large advantage of using ethanol as a motor fuel is that it can be used in many gasoline engines with little engine modification (25). Certain design alterations are necessary to take full advantage of ethanol's fuel properties when designing a true alcohol engine, but the cost of converting most gasoline engines for ethanol use is quite low compared to almost every other fuel (49). Thus, a readily available alternative fuel for gasoline can be distilled for use in internal combustion engines. When comparing the adaptability of an alternative fuel such as alcohol to that of an existing fuel source like gasoline, there are three major areas of comparison: 1) Fuel efficiency - the quantity of the alternative fuel used

to produce equivalent power output; 2) Performance or Driveability - the quality of engine and vehicle operation and 3) Emissions and Materials Compatibility - how the alternative fuel affects both the environment and the vehicle itself.

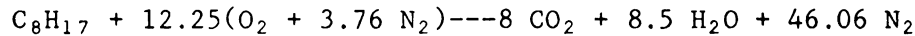
C.1 Fuel Efficiency

The OH radical attached to each ethanol molecule produces fuel properties which, in many cases are not as beneficial for internal combustion engine performance as gasoline fuel properties. Hydrocarbon fuels burn when ignited in the presence of oxygen and emit a certain amount of energy, referred to as the heat value or heat of combustion of the fuel. Gasoline molecules contain a mixture of at least 4 carbon atoms (C_4H_{10} which is n-butane) and may contain up to 12 ($C_{12}H_{26}$ which is dodecane), each molecule being able to be fully oxidized to produce CO_2 and H_2O , the major products of combustion. The amount of heat energy given off during the combustion process of converting the carbon-hydrogen molecules to CO_2 and H_2O increases as more carbon atoms are present in the charge (3). Each ethanol molecule contains only two carbon atoms while carrying an OH radical that increases both the molecular weight and size. This causes ethanol to produce less heat energy per given weight of fuel (1, 48). Average heating values for gasoline, ethanol and methanol are 43,500 KJ/Kg, 26,300 KJ/Kg, and 19,700 KJ/Kg respectively (19).

When a fuel undergoes oxidation or the burning process in an internal combustion engine, there is a theoretical optimum mixture of air and fuel just sufficient to produce complete combustion (46). This air-fuel ratio is termed the stoichiometric ratio and can be determined by knowing the molecular formula and weight of the fuel and writing an equation which

presumes that all the carbon is oxidized to carbon dioxide and all the hydrogen to water (8). Since alcohols already contain an oxygen atom, they are in essence already partly oxidized or burned, and consequently need less air for complete combustion (28). The difference in the required amount of air is determined by the oxygen content of the fuel (25). Methanol requires 44% as much air as gasoline for combustion while ethanol requires 61% (20). This can be observed in the lower air-fuel ratio for alcohol compared to gasoline. Calculations (8) for determining the air-fuel ratio on a weight basis for gasoline, ethanol and methanol are shown below:

Gasoline:

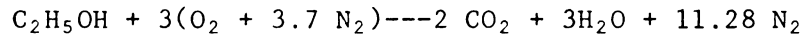


$$\text{Air/Fuel Ratio} = \frac{\text{Weight Air}}{\text{Weight Fuel}} = \frac{(12.25 + 4.76) \text{ mol air}}{\text{mol fuel}} \times$$

$$\frac{13.15 \text{ Kgm air/mol}}{51.25 \text{ Kgm fuel/mol}} = 14.9 \text{ Kgm} =$$

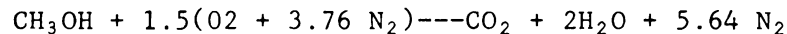
molecular weight (weight of 1 mole of substance)

Ethanol:



$$\text{Air/Fuel Ratio} = \frac{(3 \times 4.76) \text{ mol air}}{\text{mol fuel}} \times \frac{13.15 \text{ Kgm air/mol}}{20.9 \text{ Kgm fuel/mol}} = 9.01$$

Methanol:



$$\text{Air/Fuel Ratio} = \frac{(1.5 \times 4.76) \text{ mol air}}{\text{mol fuel}} \times \frac{13.15 \text{ Kgm air/mol}}{14.5 \text{ Kgm fuel/mol}} = 6.47$$

Thus, the chemically correct air-fuel ratios are: 14.96 Kg of air/Kg of gasoline 9.01 Kg of air/KG of ethanol and 6.47 Kg of air/Kg of methanol.

To develop a given power level, an engine must utilize a certain amount of energy (47). From the previous calculations of heat energy content and air-fuel ratio, the lower alcohol values imply that a greater amount of fuel must be used to provide the same total energy in the combustion chamber (15). Although the actual fuel consumption has been reported in virtually every study (1, 2). Many studies have reported methanol and ethanol fuel consumption increases of approximately 1.70 and 1.35 times the normal gasoline consumption (21). However, fuel consumption depends on many engine and operator dependent variables, leading to a wide range of reported alcohol consumption rates from the literature (46). Proper carburetor adjustment is one major factor for optimum fuel economy. Methanol and ethanol fuel consumption in recent multicylinder engine tests was reported to be approximately 2.00 and 1.65 times the optimum gasoline consumption respectively (29, 43).

In addition to the air-fuel ratio and energy content, alcohols differ from gasoline with respect to how the mixture is burned in the combustion chamber. Fuel mixture burning characteristics such as flame speed, detonation, octane rating and combustion chamber design are all interrelated and all affected by the OH radical of each ethanol molecule. Knowledge of these factors and their effect on other engine operating variables such as ignition timing and compression ratio is essential for obtaining the optimum economy for a given fuel.

When the fuel-air mixture in the combustion chamber is ignited, it does not simultaneously explode, but the flame in the form of a disc or cap travels throughout the mixture burning as it goes (3, 36). Flame

speed, or rate of propagation, is the velocity with which the flame cap travels through the mass of the fuel-air mixture once it is ignited (2). Slightly rich mixtures tend to produce the fastest flame speeds, but less fuel efficiency than slightly lean mixtures (15).

At a given air fuel ratio, the flame speed is a primary determining factor for proper spark advance. Slower burning mixtures need to be ignited sooner to complete the proper combustion process. A flame speed comparison of two fuels can be made by determining the MBT (minimum spark advance for best torque) spark advance of each fuel tested under identical engine test conditions (66). Many engine tests performed with straight ethanol fuel advocate spark advances much greater than for gasoline (8, 62, 63). This indicates that ethanol has a slower flame speed than gasoline. However, more recent engine tests using very accurate test equipment and keeping proper control over factors affecting the comparison have shown that the smaller MBT spark advance with ethanol compared to gasoline reflects faster burning with neat ethanol (10, 21, 25). Ethanol containing water burns at a slower speed than pure ethanol (2, 3). Ethanol fuels containing small percentages of water will need a greater spark advance than neat ethanol fuels.

Besides being influenced by the fuel type, the rate of propagation also depends on the cylinder pressure and mixture temperature (35). The higher the mixture pressure before ignition, the faster it will burn, and the higher the temperature of the mixture before ignition, the faster it will burn (46). This leads us to consider ethanol's higher octane rating, perhaps the largest advantage of using ethanol as a fuel.

Octane ratings are simply a measure of a fuel's antiknock quality, or its ability to resist the premature explosion known as detonation as

the mixture temperature is raised (46). The knock limit of a fuel is distinctly a function of the mixture temperature (25). As the fuel air mixture is compressed during the compression stroke, both its temperature and pressure increase. The burning of a mixture in a closed container causes a pressure increase, the increase being proportional to the initial pressure and temperature of the mixture (48). If the compression is contained indefinitely, a temperature is reached where the mixture self ignites or detonates.

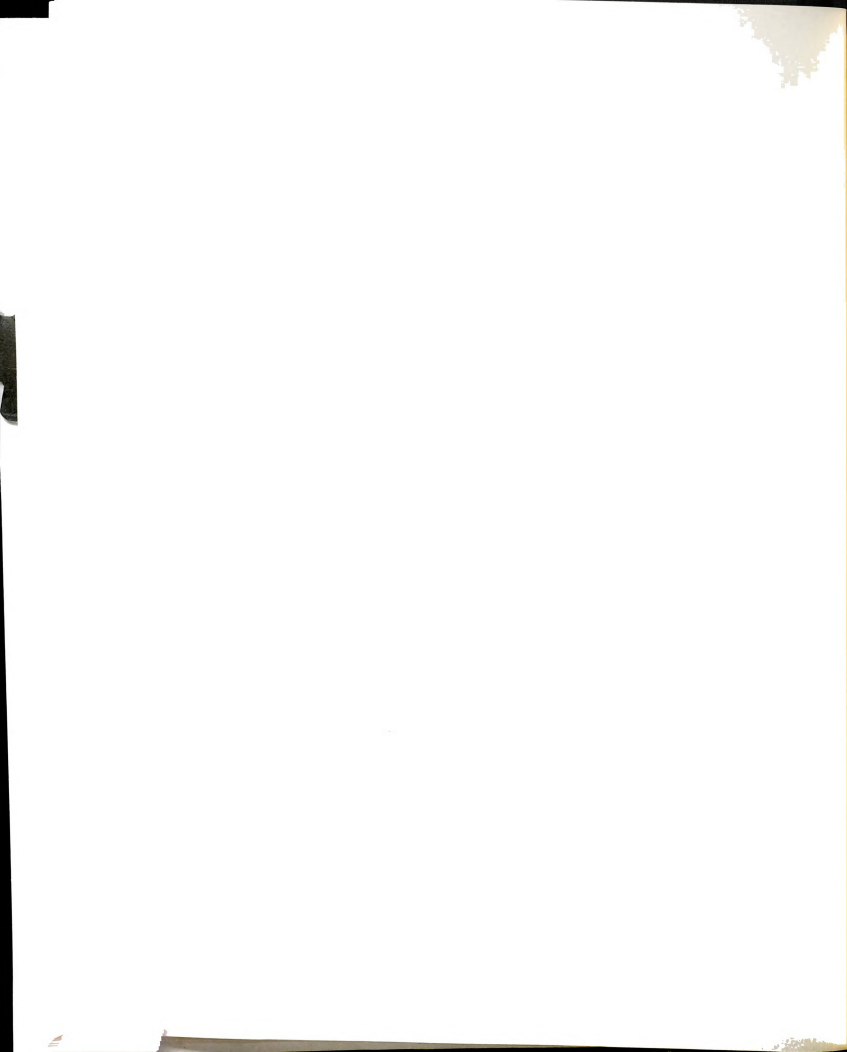
The rate at which the pressure rises in a cylinder after ignition is dependent on the relation between the rate of propagation of the mixture and the piston speed of the engine (3). The faster flame speed of ethanol results in higher peak pressures during combustion than those from gasoline (66). The outward piston motion lowers the pressure while the propagation of the mixture raises pressure. Low piston speed in proportion to the rate of propagation causes rapid cylinder pressure increases. Too high piston speed may cause a decrease in pressure during mixture burning and consequent power decreases. Gasoline engines are usually designed so that the mixture is ignited at top dead center or slightly on the downward stroke of the piston following compression, because the octane rating of most gasolines are low while their flame speed is high. If the timing is advanced too far with gasoline, causing the mixture to be burned for a long time at high compression, the temperature of the unburned fuel will soon reach the point of explosion, causing engine knock. Maximum flame temperatures for gasoline, ethanol and methanol at 1 atmosphere of pressure are 478°C, 392°C and 370°C respectively (21, 43). The higher temperatures for gasoline reduce its knock resisting ability and thus its octane rating.

The octane rating of a fuel is expressed in terms of a number which is based on the hydrocarbon fuel, octane, whose ability to resist detonation

is given a value of 100, and the gas n-heptane which cannot be compressed very much without detonation which is given an octane rating of zero. The octane number of a fuel is based on the percentage volume of a mixture of octane and n-heptane that matches the preignition characteristics of the fuel (6). There are two different ways of measuring the octane value of a fuel. The research octane number is determined from measurements taken on a single cylinder laboratory engine, while the motor octane number is calculated for a hot engine under full load conditions (8, 21). The market oriented octane rating usually consists of an average of these values. A typical market octane rating for unleaded gasoline is 86 or 87 (6). Modern engine designs require fuels with an octane number of 89-90, requiring the addition of lead or other anti-knock chemicals which can have an adverse effect on pollution levels.

The market-oriented octane values for methanol and ethanol are approximately 102 and 100 which are considerably higher than gasoline. In addition to eliminating the need for adding the pollution causing knock suppressant tetraethyl lead, alcohol's higher temperature of premature detonation enables their use at higher cylinder compression pressures. A fuel that is used at a higher compression ratio provides greater power per piston stroke, because the burning of a mixture at a higher compression causes much higher cylinder pressures which push the pistons down with more force (46). Thus, using ethanol at a higher compression ratio enables the engine to produce more power than is possible with gasoline fuel. Properly designed gasoline engines using a compression ratio between 7 and 9:1, depending on the octane rating of the gasoline, while a true alcohol engine using ethanol has a CR of 12 or 13:1 (8).

When optimizing the utilization of a particular fuel, one often over-



looked design element that greatly effects fuel efficiency and detonation and thus overall engine performance is combustion chamber shape (55). Improper design greatly affects the combustion rate (36). If the combustion rate is too high, detonation occurs. If the rate is too slow, incomplete combustion resulting in power loss and wasted fuel occurs. Engine knocking is directly influenced by the ability of the mixture to burn uniformly. Uniform flame cap propagation occurs when the mixture is free to expand while burning, thus letting the flame cap evenly heat the successive mixture layers and ignite them (55). Improper mixing may create slow burning causing unwanted pressure build-ups due to the compression of the unburned fuel and pressure from the burned mixtures, thus resulting in an explosive mixture. Proper combustion chamber design creates a turbulent mixture so that a smooth, even burning process occurs. Turbulence tends to decrease detonation by increasing the heat flow through the combustion chamber walls which help keep the last part of the mixture cooler (37).

Burning the mixture in a confined space such as the combustion chamber may cause a pressure wave to propagate back and forth through the mixture, causing the flame cap to oscillate as it burns. The improper relationship between the combustion chamber design, the piston compression and the heat generated by combustion can cause these pressure waves (46, 55). If these waves through the mixture become improperly synchronized with the waves of combustion, a momentary high pressure and corresponding high temperature may occur in the remaining unburned mixture resulting in an extremely fast rate of propagation or virtual explosion known as knocking. The combustion chamber design may also leave unwanted pockets or isolated masses of the air-fuel mixture near the exhaust chamber which quickly increase pressure

once ignition occurs and cause a flow of gas (pressure wave) towards the flame cap and a possible synchronization and explosion. These explosions happen too quickly to cause a significant increase in engine power. In fact, they are quite hard on the engine bearings and metal parts and can ruin an engine very quickly (36).

Greater thermal efficiency, or more work from the same amount of fuel due to more complete burning, is obtained with a high compression ratio (14, 32). More complete burning occurs because of the higher combustion temperature, pressure and greater burning time due to longer piston travel at higher compression (36). At the same compression ratio ethanol produces slightly higher thermal efficiency because during combustion, alcohol has a faster flame speed and higher peak pressures which produce more work from the burning charge while during expansion ethanol's lower burned gas temperature provides reduced heat transfer to the cylinder walls and therefore less waste (19, 32).

Alcohol fuels provide higher thermal efficiency not only through their ability to use higher compression ratios, but also because of their ability to operate well with lean fuel-air mixtures (30, 35). Engine tests have shown and most alcohol researchers agree that ethanol and methanol maximize fuel economy at lean fuel air mixtures and that for a given load, alcohol fuels can operate at leaner air-fuel mixtures than gasoline before misfires occur (2, 3, 43). The lean misfire limit for alcohol engines is usually found to occur with mixtures about 20 percent leaner than lean limit gasoline-air mixtures (16, 50). The higher burning rate of ethanol compared to gasoline and the high compression operation of alcohol fuels contribute to this extended lean mixture operation (66).

Disagreement exists as to what air-fuel mixture provides the optimum vehicle performance in terms of fuel economy and driveability. A variety of conclusions based on experimental engine data have been reached. The API study of 1976 (1) based their straight alcohol test results on the 1975 SAE meetings in Detroit, where detailed performance tests on a single cylinder engine fueled with straight methanol were presented. The conclusion was drawn that the use of alcohol fuels in internal combustion engines extended the lean misfire limit considerably, and this lean burning ability was treated as the major reason for alcohol fuels providing better thermal efficiency. A recent alcohol manual (6) provided data from straight fuel tests and concluded that the lean misfire limit was the same for straight ethanol as for gasoline. A third study presented at the 1979 symposium for alcohol fuels in California agreed that adjustment of the air-fuel ratio shows that straight alcohol combustion can occur at a much leaner mixture than in the case of gasoline, but maximum economy at partial load was similar to that of gasoline and occurred at mixtures that were 10 to 20% leaner than the stoichiometric mixture (25). A similar study presented at the same conference gave the test results for fueling a passenger car with pure ethanol, and concluded that lean air-fuel ratios quite often lead to poor driveability because of the excess heat needed for keeping the mixture vaporized. Even when this heat was provided, the alcohol mixtures which provided the best driveability were not as lean as the gasoline mixtures (13).

This conflicting data on alcohol's lean misfire limit represents a major problem with the vast amount of experimental data reported for alcohol fuels. Many engine tests have been performed without proper control over engine operation, leading to misinterpretation of test results (66).

Different operators have drawn different conclusions from the same test data based on their idea of optimum performance. Most of the conflict comes from deciding which conditions are truly equivalent for the two fuels. The large difference in such properties as flame, speed and latent heat of vaporization affect the choice of the proper spark advance and the fuel-air mixture strength to be selected in running comparative tests (1). There is a need for more standardized test procedures and recording of test data in the future (27, 29).

Thus, ethanol's molecular structure provides fuel properties such as faster flame speed at all compression ratios and higher octane ratings, which must be exploited when designing an engine to optimize fuel utilization. Engine operation at a higher compression ratio increases the importance of proper engine design. The flame speed of ethanol at 12 or 13:1 compression is much higher than the flame speed of gasoline at its optimum compression (10, 21). Therefore, higher compression ratios lead to further retarding of the spark advance than is appropriate at lower compression (31, 66).

The higher combustion temperatures and flame speeds lead to the possibility of preignition, which is the ignition of the air-fuel mixture before its proper time. Preignition can lead to detonation and rapid engine destruction. There has been experimental evidence that engine operation above the load limit produced preignition, especially with methanol, which results in rapid engine destruction (25, 38). However, a fuel that preignites can still be a good knock suppressor (64, 37). Proper combustion chamber design can prevent such causes as localized hot spots and improper exhaust gas diluents from producing preignition and possible engine damage (37). Major engine modifications such as increasing the compression ratio



for maximizing ethanol as a fuel must be done with care. Each engine component and fuel property must be considered and integrated into the total engine operating cycle.

C.2 Engine Performance - Driveability

The most obvious problems encountered with gasoline engines using straight ethanol or methanol fuel are the difficulty in cold starting and greatly deteriorated driveability once the engine is started. There are two basic causes for these problems. The first is a result of ethanol's lower energy content which produces a very lean fuel-air mixture. The second lies in the difference in volatility between alcohol and gasoline. These problems must be corrected before satisfactory engine performance can be achieved with straight alcohols.

Conventional cars are simply undriveable on straight ethanol or methanol because the stoichiometric air/fuel ratio of these fuels is so low that the mixture delivered by a carburetor designed for gasoline is too lean to fire (20). Therefore, the first step involved when replacing gasoline with alcohol is to correct the air-fuel ratio problem either by enlarging the jet sizes in the original carburetor or replacing the carburetor with one designed for alcohol fuel. The former process can be difficult and time consuming, especially with carburetors of complicated modern design. All the jets in the carburetor must be enlarged by the correct ratio in order to provide more fuel to enter the cylinders under all operating conditions. These ratios are 1.5 for methanol and 1.27 for ethanol (8).

Unless one has considerable experience working with carburetors and is familiar with shop procedures such as operating a drill press, the

best alternative is to replace the carburetor with one designed specifically for either ethanol or methanol. Replacing the carburetor alleviates the possibility of incorrectly drilling the carburetor jets and perhaps not including all of them in the process. Also, the correct air flow and fuel flow are assured by the proper matching of the various spark timing and carburetion curves involved in their design for best power and best efficiency (7, 15, 53).

In addition to the air-fuel mixture leaning effect, the volatility of ethanol and methanol presents a number of difficulties. Volatility pertains to a fuel's ability to vaporize. The three major components determining a fuel's volatility include its boiling point, vapor pressure and latent heat of vaporization (19). In order for the air-fuel mixture in the combustion chamber to be ignited and burned, the fuel must be in the gaseous state (46). This requires that the liquid fuel receive enough heat to overcome the attractive forces between neighboring molecules and disperse into the higher state of entropy (48).

As the temperature of a liquid is raised, the molecular energy becomes greater causing more frequent and violent molecular collisions resulting in more molecules entering the gaseous state. When the boiling temperature is reached, there is an additional amount of energy the liquid must absorb before it can freely vaporize. This additional heat is known as the latent heat of vaporization and is a direct function of the liquid's molecular attractive forces. Thus, the ability of a fuel to evaporate or be taken up by the incoming air is determined by both the boiling point and latent heat of vaporization.

Vapor pressure is simply a measure of the amount of liquid fuel that is entering the vapor state at a given temperature. The higher the vapor

pressure the more molecules leaving the liquid state and becoming a gas. Gasoline consists of a mixture of different hydrocarbons, some with very low boiling points and some with very high boiling points. Most gasolines contain between 6 and 10% n-butane which has a boiling point of 31°C (8). These low boiling hydrocarbons provide a high vapor pressure which when coupled with gasoline's high air-fuel ratio creates a combustible mixture even at very low ambient temperatures.

The attractive forces between alcohol molecules are considerably greater than those of gasoline because of the hydrogen bonding between the OH hydroxyl groups (10). The uniform molecular structure of ethanol and methanol eliminate the benefit of gasoline's low boiling hydrocarbons. Thus, the vapor pressure of alcohol fuels is considerably lower than the vapor pressure of gasoline.

Methanol boils at 65°C and ethanol boils at 78°C (18). Approximate values for the latent heat of vaporization for gasoline, ethanol and methanol are 328, 824 and 1104 KJ/Kg, respectively (19). At 100°F, the vapor pressure of gasoline varies from 7 to 15 psi while methanol and ethanol have lower vapor pressures of 4.6 and 2.5 psi respectively (18). These figures show that for a given volume of fuel, gasoline provides a higher percentage which enters the vapor phase at a given temperature. Vapor lock can only be a problem with straight alcohol fuel if the fuel pump or carburetor reach a temperature equal to or greater than the fuel's boiling point (1, 15, 20).

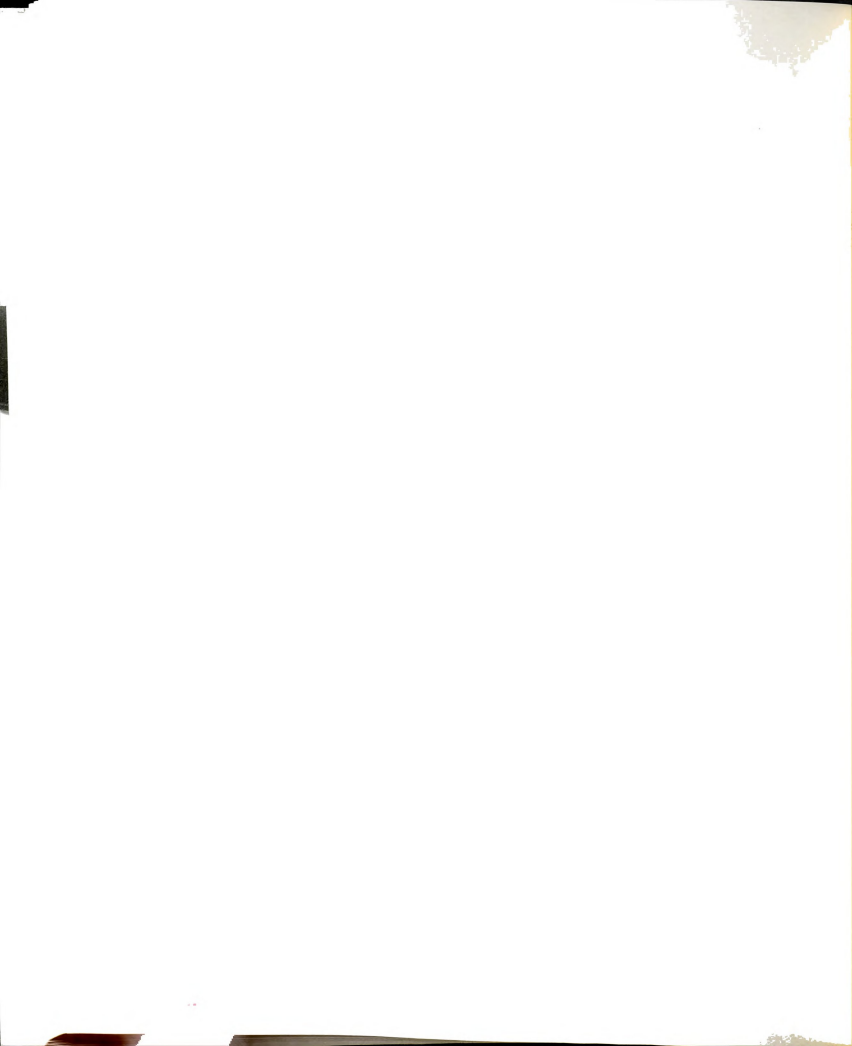
Ethanol's low vapor pressure, high latent heat of vaporization, and the greater fuel volume utilized by the engine to produce a comparable gasoline power output make it impossible to cold start an ethanol fueled engine below approximately the 5-12°C temperature range without some form

of starting aid (15, 30). Ethanol fuel containing water content will raise the cold start temperature due to the extremely high latent heat of vaporization of water (18). Three primary methods have been used to alleviate this problem when converting gasoline engines to ethanol. The first solution involves mixing a small portion of highly volatile fuel with ethanol. A 10% gasoline mixture reduces the cold start temperature to approximately 0°C (15) while an 8 to 10% pentane mixture dropped the temperature to -10°C and 16 to 18% volume pentanes dropped the temperature to -30°C (22). The second solution involves injecting this same volatile fuel into the air stream. Propane and ether have been used with much success (1, 7). A separate metering system must be added to the vehicle if this method is used. This system should be easily switched on and off and be used only for engine warm up before switching to the straight alcohol fuel.

A third method involves heating the engine block or intake manifold by using a heating element shunted across the battery. This method is hoped to provide the optimum cold starting aid for future cars designed for straight ethanol use, but adding a system to present gasoline engines tends to drain the battery (7, 14). Straight ethanol fuel injection directly into the cylinders helps alleviate warm-up driveability problems, but cold starting has been reported to remain difficult (29, 38).

Methanol's lower boiling point and higher vapor pressure cause less difficulty in cold starting than ethanol (25). However, methanol's higher latent heat of vaporization caused greater problems during warm-up driveability once the engine was started (1).

Once the cold start problem is solved, the more difficult problem of poor driveability must be solved. Ethanol's higher latent heat of vaporization keeps the large amount of alcohol fuel entering each cylinder from



adequately being vaporized. A cooling effect on the intake air occurs as heat is drawn out to vaporize the fuel. When either the lower alcohol energy values or lower air-fuel ratios are used to determine the extra amount of alcohol per power stroke needed to provide equivalent gasoline power outputs, the product of multiplying the excess amount of fuel by the greater heat of vaporization indicates that ethanol and methanol require respectively from 4 to 5 and 7 to 8 times the normal amount of heat for similar gasoline mixture quality (8, 15, 34). The latent heat of vaporization must continuously be supplied to the mixture until it reaches the cylinder or the fuel may condense back to the liquid state. The greater the latent heat, the more the mixture is cooled and the greater the amount of heat needed to keep the fuel vaporized. Condensation of the fuel in the intake manifold causes improper air-fuel mixture distribution to the cylinders and creates the problem of maldistribution. Maldistribution causes misfires resulting in poor engine operation due to the lack of fuel in the mixture (29).

Maldistribution of the fuel-air mixture is a problem with gasoline engines converted to operate on ethanol (2). Most gasoline engines are not designed to provide sufficient additional heat to the intake manifold because of gasoline's low latent heat of vaporization which requires very little heat to keep the mixture vaporized. Some engines having short, well designed intake manifolds and perhaps an air preheating system provide enough heat to prevent maldistribution once the operating temperature is reached, but a large percentage do not (61).

Fuel injection systems alleviate the problem of maldistribution because each cylinder receives the proper mixture of fuel injected directly into the combustion chamber. Once the engine is started, the heat of compression

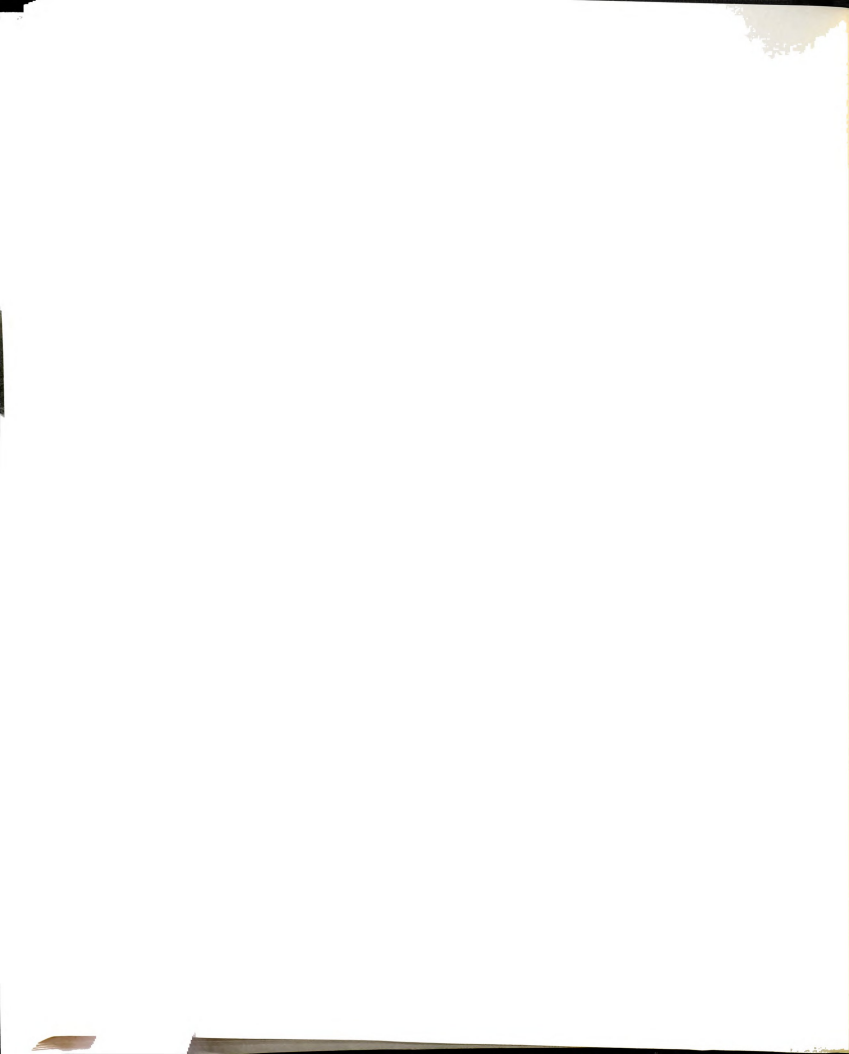


and the hot exhaust residue combine to vaporize the fuel. However, converting carbureted spark ignition engines to fuel injection is very expensive (49).

Heating the intake manifold of conventional spark ignition engines is necessary to prevent condensation of ethanol and methanol (51). The most efficient way of providing this heat is to utilize the waste heat produced by the engine. Exhaust manifold heat can be utilized in many cases by constructing sheet metal shields to transfer the heat from the exhaust to intake manifold. Perhaps a better method of using the exhaust is to directly heat the intake air rather than the manifold (4). Here, a thermostat can be used to control the temperature by allowing colder ambient air to be mixed with the hot air coming from the exhaust manifold. This method is used in many modern designs (46).

A second alternative is to use the engine coolant as a heat source. Sometimes a higher temperature thermostat may provide enough additional engine heat to warm up the intake manifold. Another way to utilize the coolant heat is to surround the intake manifold with a water jacket, creating a heat exchanger from the coolant to the fuel mixture. However, water jacketed intake manifolds are not readily available and it can be quite expensive to have a new intake manifold designed for alcohol conversion.

Preheating the intake air can have an adverse effect on the amount of power that can be produced by the engine. As the air is heated, its volume expands and the total amount of mixture that can enter each cylinder decreases. Engine tests have verified that preheating the intake air can cause significant decreases in the maximum horsepower produced (2, 4). Also, the hotter mixture reduces the maximum degree of compression and spark advance



that can be used without knocking. Since the object of preheating is primarily to prevent precipitation of the liquid on the walls of the induction system, it is necessary only to raise the temperature of these walls to above the boiling point of the fuel (36). Tests have been reported verifying that ethanol powered engines were destroyed when the intake air was heated excessively and engine-knock occurred (31). Care must be taken to prevent the mixture from overheating and possibly producing detonation.

Even though ethanol's high latent heat of vaporization may create the unwanted problem of maldistribution, it also can be quite beneficial. The heat absorbed by the fuel as it vaporizes causes the air-fuel mixture to become cooler. If pressure is constant, the cooler the gas, the smaller its volume (48). Vaporization of a stoichiometric air fuel gasoline mixture results in a temperature drop of about 15°C whereas an ethanol mixture causes a temperature drop of about 35°C (6). Higher heat range spark plugs may help to increase the combustion chamber temperature causing more fuel to vaporize and the engine to warm up faster (7). Therefore, since the ethanol fuel mixture is over twice as cold, it is considerably higher in mass density than the gasoline mixture. This means that if an equal volume of each mixture is drawn into a cylinder, the ethanol mixture will contain over twice the amount of fuel by weight. This is the same as saying that the volumetric efficiency of an engine using the ethanol fuel would be over twice as great as the same engine using gasoline fuel.

The increased amount of fuel in the combustion chamber helps to offset the lower heat value of ethanol and produce an energy stroke equivalent to that of gasoline (51). Thus, ethanol and methanol produce as much power as gasoline when used at normal gasoline compression ratios even though

the alcohols have a much lower heat value than gasoline. Coupling ethanol's higher volumetric efficiency with an increased compression ratio, a further increase in the energy output can be obtained. This increase means that ethanol can actually produce more power than gasoline when used in an internal combustion engine (3).

Methanol has a greater latent heat of vaporization than ethanol, causing a further cooling of the mixture and higher volumetric efficiency. At high compression and rich fuel-air mixtures, methanol creates more power than ethanol and has been used for many years as fuel for racing cars, where fuel economy is not of primary interest.

The beneficial results of a high latent heat of vaporization can be observed in straight alcohols containing various water contents. Because of the very high costs involved in producing pure ethanol, engine operation with straight ethanol containing a small water percentage is desired. Water has a latent heat of vaporization that is much higher than ethanol or methanol and consequently produces a higher volumetric efficiency than pure ethanol (50). Also, water added to a pure alcohol has a positive influence on engine knock resistance by raising the octane rating of the fuel (21). Thus, the lower energy content of ethanol containing a small percentage of water is heavily offset by the fuel's higher volumetric efficiency and higher octane rating.

In conclusion, ethanol's volatility plays the major role in offsetting the fuel's low energy content by producing comparable power outputs to gasoline. The high latent heat of vaporization gives ethanol the advantage of packing more of its mixture into the cylinder while the lean misfire limit enables ethanol engines to operate at a mixture ratio that utilizes a high percentage of the available fuel energy. The disadvantages

caused by ethanol's volatility include starting and operating difficulties which must be overcome by fuel and/or engine modifications.

C.3 Emissions

The enactment of automotive exhaust emission standards in the early 1970s has caused a great deal of research in this area. Concern over automobile exhaust pollutants led to the creation of pollution control devices such as exhaust gas recirculation and the catalytic converter which have become standard equipment on modern automobile designs. Indeed, the exhaust emission characteristics of any potential future fuel will merit heavy consideration and be a determining factor on how the fuel will be used (39).

If a hydrocarbon fuel is completely burned in the combustion chamber, the exhaust would contain nothing but CO_2 and H_2O . The hydrocarbon fuel molecules would be completely oxidized to these products. Unfortunately, this complete oxidation process does not occur during the combustion cycle. Combustion of a hydrocarbon fuel always produces a certain amount of emissions which are simply products of incomplete combustion or partial oxidation.

The major exhaust emissions produced by the burning of hydrocarbon fuels are nitrogen oxide (NO_x), carbon monoxide (CO) and unburned hydrocarbon (UBF) (35). All three of these are federally regulated. The amount of each of these pollutants produced by a specific engine is determined by a number of parameters such as spark advance, internal carbon and overall engine wear. However, by far the most important factor determining the quality of exhaust emissions is the engine's fuel-air ratio (29). The term equivalent ratio (ϕ) has been developed for comparing different fuels

under different air-fuel ratios. Equivalence ratio is defined as the actual fuel-air ratio divided by the stoichiometric fuel-air ratio. A stoichiometric mixture will have an equivalence ratio of 1.0 ($\phi = 1.0$). Rich mixtures will have $\phi > 1.0$ and lean mixtures will have $\phi < 1.0$.

Improperly mixed fuel and air simply do not burn properly. Rich mixtures contain an excess amount of fuel which cannot be burned due to the absence of sufficient oxygen. If mixtures become so lean that strong, self-sustaining flame cannot be established or cannot propagate through the entire combustion volume in the time available, partially or completely unburned fuel will escape through the exhaust valve. Both very high and very lean mixtures produce unwanted emissions (46).

In theory, the stoichiometric fuel-air mixture is the optimum in terms of flame speed and emissions production (18); however, test results show that slightly leaner fuel-air mixtures produce better fuel economy and emissions while slightly rich mixtures produce maximum power and flame speed (46, 47). The concern of the American public, and therefore the goal of automotive designers is to maximize fuel economy and minimize fuel emissions. Thus, automobiles are designed with the fuel-air mixture in the lean direction (20).

The vast amounts of research performed on alcohol fueled engine emissions has produced a wide variety of results and conclusions. The sophisticated equipment and calculation procedures involved is one possibility for experimental error. Improper calibration of the measuring equipment designed for use with pure hydrocarbon fuels is another. The problems involved with determining accurate aldehyde and unburned fuel levels from equipment designed for measuring the unburned hydrocarbon content of gasoline is often explained (15, 17, 66). Improper control of the air-

fuel ratio and comparisons of two different vehicles whose air-fuel ratios are not controlled will definitely lead to misleading results. Maldistribution often adversely affects the validity of actual exhaust emissions from properly heated multicylinder engines. Specific assumptions and procedures must be stated in order for test results to be meaningful. Also, the research performed on stationary, single cylinder engines cannot necessarily be accurate for multicylinder vehicles.

Some publications (6, 44, 45) praise alcohol as being a highly clean-burning fuel. Statements are made about how alcohol will require no emission controls at all (6). Other research has found that the emissions of neat alcohol fuel are fairly close to those of gasoline and that certain emission controls will be necessary (29, 66). Nevertheless, recent research (13, 15, 17, 29, 30, 66) using accurate equipment and proper control over operating variables has produced fairly consistent results and conclusions.

Most research (29, 30, 19, 66) indicated the carbon monoxide emissions depended primarily on equivalence ratio rather than on the fuel or compression ratio. Both gasoline and neat ethanol produced low CO values at $\phi \leq 1.0$. Ethanol produced CO values in this range that varied from being nearly equal to gasoline (15, 66) to being 30 to 60% less than gasoline values (13, 30). At $\phi > 1.0$, there was generally a significant increase in CO values but ethanol still produced lower values than gasoline. Ethanol's lower rich CO emissions were attributed to a higher hydrogen-to-carbon ratio and lower burned gas temperature (66).

Nitrogen oxide emissions seemed to receive the most consistent conclusions. They are produced when nitrogen contained in the mixture air becomes oxidized. This procedure takes place under very high temperatures ($> 1080^{\circ}\text{C}$) and consequently reach a maximum at high combustion temperatures

(30). Virtually every study (17, 19, 29, 30, 66) agreed that the lower combustion temperatures of ethanol decrease NO_x emission levels. All these results indicated that nitrogen oxides reached their maximum at slightly lean ($\phi = .9$) mixtures indicating that the increase in free oxygen exerts a stronger influence on NO_x formation than the slowly falling combustion temperatures (51).

At the same compression ratio, the average peak ethanol NO_x emissions were approximately 30-50% lower than gasoline. As the ϕ was moved away from the peak value, NO_x emissions fell rapidly due to lower combustion temperatures, creating a bell shaped curve. Above $\phi = 1.0$, gasoline and ethanol produced very close values, while below $\phi = 0.8$ gasoline produced significantly higher values (19, 66). Higher compression ratios produced higher NO_x values for ethanol, but at $\phi = .9$, ethanol still produced lower values than gasoline. Only one study (13) produced average NO_x values that were higher for ethanol than for gasoline. Excessive heating of the intake air was believed to have caused this. This raises the possibility of cold weather alcohol engines providing a higher NO_x level than determined from the literature, depending on the method used to heat the air.

The most inconsistent emissions results produced by the literature comparing ethanol to gasoline were for unburned fuel and aldehydes. Since unburned ethanol is not a real hydrocarbon, the nomenclature of unburned fuel (UBF) emissions is generally used to represent unburned ethanol and all other hydrocarbons in the exhaust excluding aldehydes (19). Methanol forms formaldehyde and ethanol forms acetaldehyde during the first step of their oxidation and are consequently much higher for alcohol fuels than with gasoline. Aldehydes (HCHO) are not regulated emissions because of gasoline's low production level, but they are reactive in the photochemical

smog forming process and may require future regulation due to alcohol's high output level (20).

The variety of test results measuring UBF and HCHO emissions was in large part due to the difficult procedures used for measuring them. The flame ionization detector (FID) commonly used for exhaust hydrocarbons does not respond fully to either alcohols or aldehydes (15). Complicated additional procedures are necessary for accurate results, greatly increasing the possibility of error and invalid data.

The conclusions drawn for neat ethanol UBF and HCHO values were generally consistent in their increase or decrease with changing ϕ values, but a discrepancy lies in whether the values were greater or less than equivalent values. Aldehyde emissions were unquestionably greater with ethanol fuel at all ϕ . The amount of increase ranged from 2 times (15), to a maximum of 10 times the gasoline value (29). Aldehyde emissions appear in most studies to be lowest at stoichiometric air-fuel mixtures and increase when the mixture was either leaned or made rich (19, 20). Aldehyde emissions decrease as exhaust temperatures increase because of their decomposition at higher temperatures (48). When the compression ratio is increased, aldehydes also increase. This is probably due to the lower exhaust temperatures produced at higher compression ratios (19, 66).

Unburned fuel emissions varied even more than aldehydes. Minimum values were generally found to occur between $\phi = .8$ and $.9$ with increases in both leaner and richer fuel mixtures. Some studies found UBF values for neat ethanol to be nearly equal to gasoline values (29, 66). Others found UBF to be much lower (25, 53) and some much higher (15, 30). The majority of research found neat ethanol UBF emissions to be at least equivalent to or greater than gasoline. One researcher (66) stated that

he was surprised to find the UBF emissions of ethanol nearly equal to gasoline since the ethanol fuel-air charge, and thus the unburned mixture in the combustion chamber crevices, contain about 60% more fuel mass than that of gasoline. Increases in the compression ratio produced higher UBF values in all these studies. The reasons for these higher compression UBF levels were attributed to the increased fuel density in the combustion chamber crevices due to higher pressures and the reduced amount of UBF oxidized in the exhaust system due to the lower exhaust temperatures of higher compression (66).

Alcohol water content has also been claimed for helping increase quench layer emissions (17). The quench layer is the layer of mixture between the cylinder wall and flame cap which does not get burned due to the very hot flame (1080-2746°C) being quenched by the heat extracted from the relatively cool (79-135°C) combustion chamber wall. Water cooling of the incylinder gases can have a negative effect by slowing down the combustion process and promoting quench layer growth and increased unburned fuel emissions (35). Flame quenching has been proposed as a very important UBF producing mechanism (10, 17, 30). Also, it has been hypothesized that the majority of exhaust aldehydes are formed when unburned quench layer gases are removed from cylinder walls and mixed with bulk cylinder exhaust gases during blowdown and exhaust (22). Other research tends to reject this idea (54).

The majority of literature comparing methanol, ethanol, and gasoline exhaust emissions seemed to indicate methanol as the best fuel (18, 29, 38). Most studies found NO_x and UBF emissions to be significantly lower with methanol than with ethanol. HCHO emissions were found to be nearly the same for both fuels, while CO emissions were reported as being both lower

(17) and higher (30) than ethanol.

Because of alcohol's higher octane rating, any high level use of alcohol fuel will call for engine designs with significantly higher compression ratios than modern gasoline engines to take advantage of higher thermal efficiency and higher power outputs. The general concensus of this recent research on neat ethanol indicates that higher compression ratios tend to increase UBF, HCHO, and NO_x while CO remain fairly unchanged. This research provides ample evidence that even at similar compression ratios, ethanol fuels may produce similar or worse exhaust emissions than gasoline under certain operating conditions. As with gasoline, the optimum equivalence ratio for low production levels from all the emissions except NO_x appears to be between $\phi = .8$ and $.9$ (1, 66). Thermal efficiency is also nearing its maximum value in this range. However more research needs to be performed to optimize exhaust emissions from alcohol fuels before any claims of no exhaust control devices can be made.

C.4 Materials Compatibility

Just as alcohol fuels have come to generally be regarded as cleaner burning fuels than gasoline with respect to emissions, they also have been categorized as more harmful with respect to engine materials (43). The research done on the materials compatibility of alcohol fuels, however, has drawn many inconsistant conclusions (29). Some of the results tend to contradict other research conclusions. Some data claim that alcohol-gasoline blends are more harmful than straight alcohol fuels, while other studies indicate the opposite (33, 35). One study indicates using straight methanol fuel causes a very high rate of engine wear (33), while another claims long engine life with little or no engine wear (14). Improperly



controlled operating conditions and a lack of standardized interpretation of experimental data may produce these results (29).

Nevertheless, there is ample evidence in the literature that indicates ethanol and methanol are not compatible with some materials commonly used in modern gasoline engines (42). Corrosion and chemical attack of many plastics, polymers and metal alloys is widely reported (35, 38, 50). One factor that seems constant throughout the literature is that the effects of ethanol on engine parts is much less detrimental than methanol (30).

The subject of materials compatibility can be broken down into deterioration from fuel content and engine wear caused by combustion process. As a polar material, alcohol is more active chemically than gasoline (1). Many materials, especially those in newer model cars, are affected by the increased solvent power of alcohol. Viton, used in critical parts of some carburetors, swells excessively while cork and leather shrinks and polyester-bonded fiberglass softens, blisters and deteriorates (20). Many elastomers used in the fuel system tend to get hard and crack (1). Polyurethane impregnated fuel pump diaphragms have been reported to fail when using ethanol fuel (35). Neoprene softened and eventually deteriorated (38). Racing cars using methanol use more expensive plastic parts to avoid swelling or hardening of seals and diaphragms (1).

Ethanol and methanol were heavily reported as being excellent solvents for loosening dirt, rust and partially dissolved gum deposits (24). Replacement of gasoline with alcohol frequently causes fuel filter clogging because the alcohol released deposits which draw them into the filter. Both alcohols also attack the lead-tin coated steel known as terneplate from which automobile fuel tanks are fabricated (1). The steel exposed

after this lining is removed is subject to heavy corrosion. Steel, zinc, copper, aluminum and magnesium have been reported to be corroded by ethanol and methanol, especially if water is present in the fuel (20, 24, 29). Alcohol corrosion causes pits and provides sites for fatigue crack initiation (48).

The subject of engine wear caused by alcohol fuel combustion had only been studied in depth in recent years. Before 1975, alcohol fuel research was mainly concerned with fuel economy and performance, no highly structured analysis of the potential problems of engine wear was undertaken until the Department of Energy commissioned the U.S. Army Fuels and Research Lab to conduct an on-going study in 1977 (29).

Several factors are involved concerning the diversity of information gathered on engine wear. Wear may be caused solely by the effects of combustion products on the metal parts, or the combustion products may react with the lubricant and keep it from protecting the engine. The engine temperature must be considered as well as the manufactured oil composition and additives (38). The precision instruments needed for accurate engine and oil analysis prevent the novice from accumulating accurate, meaningful data.

The chemical and physical properties of alcohol fuels produce some undesirable combustion properties when used in gasoline engines. The single boiling point and high latent heat of vaporization cause more liquid alcohol to condense on the cylinder walls than gasoline. The higher the water content of alcohol fuel, the greater its probability for increased engine wear (2, 3). Since alcohol is immiscible with oil, but is miscible with water, condensates of unburned alcohol and water in the engine form an emulsion with oil (58). Blowby gas of an alcohol fueled engine contains

higher concentrations of components expected to contribute to corrosion and wear than gasoline blowby. These components include acetaldehyde, formaldehyde and formic acid (33).

Wear in an alcohol engine can occur in several ways. An emulsion can restrict the supply of oil for boundary lubrication. Alcohol and water droplets in the emulsion may flash to vapor on contact with hot surfaces, leaving insufficient oil in the area to be lubricated. The pits and fatigue cracks caused by corrosion generate abrasive particles which wear down sliding surfaces. Alcohol may also decrease the effectiveness of oil additives by changing their chemical structure (65).

The U.S. Army at their Southwest Research Institute has made extensive tests on the lubrication system and lubricant formulations that have evolved during the past 70 years of hydrocarbon fuels (24, 33). SRI is continuing to develop better fuel and lubricant compatibility to optimize the use of alcohol fuels in engines designed originally for gasoline or currently for alcohol.

In a series of tests conducted on a single cylinder Coordinating Lubricants Research engine, The SRI found astonishingly high rates of wear using neat methanol fuel (22, 33). Low engine operating temperatures were tested for by simulating short trip service under typical winter conditions and low speed, low temperature stop-and-go city driving. These results showed that severe lubricant dilution occurred and the lubricant contained large quantities of both methanol and water as a stable emulsion. This emulsion could lead to rapid rust formation and engine failure. The iron piston ring wear rate increased by almost a factor of ten and copper wear rate increased by a factor of three. The hydraulic valve lifters started sticking sporadically as did the piston pin bushings. The blowby gas

analysis showed large concentrations of formaldehyde and formic acid. Low temperature ethanol operation showed the same results but to a less severe degree. Higher temperature engine operation analysis showed greatly diminished engine wear and a high degree of evaporation of the methanol and water in the emulsion.

Low temperature engine tests conducted by Ford Motor Co. and Exxon Oil Co. using a 2.3 liter Ford Pinto engine produced similar results (58, 65). Engine wear with straight ethanol fuel was increased slightly at normal operating temperatures but substantially at low temperature. The oil showed loss of lubricity and contained substantial emulsions. Special oil formulations were tested and found satisfactory for ethanol but not for methanol. These tests, along with those done at SRI, conclude that cold weather alcohol operation can create substantial engine problems. Other tests have concluded that there is little or no difference between the wear rates of iron, lead and chromium for methanol and gasoline fueled vehicles (14, 29). The Bartlesville Energy Research Center reported no obvious engine component damage or wear for two vehicles operating on neat methanol over a 16 month period where the vehicles were operated over a controlled duty cycle involving two trips per day of only 10 miles per trip with the remaining time spent "soaking" at ambient conditions (53). One researcher contends that the addition of benzol or acetylene to ethanol will prevent any corrosion from occurring in the engine (49).

As with other conditions previously mentioned, no clear consensus concerning the effects of ethanol and methanol on engine wear is apparent. Because most farm produced, small-still ethanol will contain 5-10% water, more extensive field tests need to be performed to determine the long range effects that the water has on engine wear, especially during low

temperature operation (50). The tremendous number of cars in Brazil that are operating on straight ethanol suggests that if cars are not going to experience compatibility problems, their original designs must be for alcohol and not for gasoline. It is only reasonable to expect some problems to occur when alternating fuels so different in chemical and physical characteristics as are gasoline and alcohol (50).

D. Alcohol/Gasoline Blends

The majority of the vast amount of alcohol research performed in the United States has not been on straight alcohol, but on a 10% ethanol and 90% unleaded gasoline blend known as gasohol. Gasohol was made available to the public in certain sections of the country during 1980 at competitive gasoline prices which were the result of a \$.40/gallon federal subsidy (28).

Most modern vehicle designs commonly used in fleet systems have been tested with gasohol (53). Few problems have been found affecting engine operation and vehicle performance which are caused by very small concentrations of ethanol ($\leq 10\%$) in the fuel. The most common problems found include slight materials incompatibility requiring possible replacement of engine parts containing certain substances, and the need for slight adjustment of the air/fuel ratio due to the leaning affect of the ethanol (43).

The effects produced in vehicle performance by adding a 10% ethanol mixture to the fuel seem to be the same, but only about 10% as great as those produced by direct gasoline substitution from neat ethanol (30). Laboratory tests of well-tuned, late-model vehicles have shown that the blended fuel provides 2 to 4% lower fuel economy than gasoline, approximately

equal to the difference in energy content of the fuels (53). The lower energy content of the ethanol creates a slight leaning effect from gasohol. Generally, hesitations on accelerations are experienced in late-model vehicles because of this leaning effect (20). The lower lean misfire limit of ethanol usually permits the leaner mixture to operate with no carburetor adjustments. Thermal efficiency increases proportionally. The higher octane rating of ethanol increases the octane rating of gasohol and often helps eliminate the pinging noise common to many engines using unleaded fuel. The higher latent heat of vaporization of ethanol increases volumetric efficiency slightly and thus cancels out the power reduction normally resulting from leaner mixtures. Exhaust emissions are slightly increased or decreased in the same direction as found from neat ethanol operation. Leaning the air-fuel mixture may either increase, decrease or essentially have no effect on exhaust emissions, depending on the original state of adjustment of the engine (18).

There are two potential major problems that may occur with the use of gasohol fuel that do not occur with neat ethanol. These are separation of the ethanol and gasoline caused by the presence of water and vapor lock. Alcohols exhibit unusual physical properties in that pure ethanol is miscible with water in any proportion, and pure ethanol is also miscible with gasoline in any proportion, however, gasoline, water, and ethanol will only mix in very small water proportions (20). When ethanol and gasoline are blended together, the ethanol may absorb water and cause fuel separation into two phases. The upper portion of the fuel will be primarily gasoline with some ethanol and water. The lower portion will be primarily ethanol and water with some gasoline. The phase separation is also temperature dependent with separation more likely to occur in colder temperatures.

Also, corrosion due to the water can occur to some fuel system components (50). Thus, water must be removed from the gas tank before gasohol is used.

The addition of ethanol to unleaded gasoline may increase the vapor pressure of the gasoline depending on the formulation of the particular gasoline (53). This, coupled with a substantial reduction in front-end boiling points for certain gasoline hydrocarbons, gives concern for the possibility of vapor lock (18). Fuels with a "higher than normal" vapor pressure generally result in easier cold starting, due to the greater amount of fuel in the vapor state. However, higher engine temperatures may create too much fuel entering the vapor state before reaching the mixture point, thus resulting in vapor lock. Vapor lock can be prevented by mixing the 10% ethanol with gasoline having proper distillation characteristics (20). Certain slow boiling gasoline components such as butane may need to be retained (18).

E. Alcohol Fuels in Diesel Engines

The national use of alcohol as a motor vehicle fuel in diesel engines is not of major concern due to the low percentage of diesel fueled cars. However, when considering alcohol as the primary source of fuel on a farm, the great majority of modern farm mobile machinery powered by diesel engines demands that future fuels be compatible with diesel engine design.

Diesel engines present both advantages and disadvantages for ethanol fuel. Diesel engines are designed to operate by compression ignition where the increase in combustion chamber temperature and pressure causes an eventual self ignition of the fuel-air mixture. This requires a fuel with a high cetane rating or high ability to ignite under diesel pressures.

The cetane rating of ethanol is very low, meaning that the complete substitution of ethanol for diesel fuel is impossible. Therefore any use of ethanol fuel in a diesel engine without a major engine overhaul requires ethanol to be used as a fuel supplement.

The advantages of diesel engine design for ethanol fuel use are complementary to the advantages a spark ignition engine provides. In fact, a true alcohol engine or an engine specifically designed to optimize ethanol fuel performance, appears to be a uniform mixture of diesel and spark ignition designs (15). The higher compression ratio of diesel engines take advantage of ethanol's octane rating. The fuel injection helps alleviate evaporation and mixture distribution problems. Several methods for utilizing ethanol fuel in diesel engines have been researched and tested. Two of the more promising methods include dual-fueling a diesel engine with ethanol by either spray-injection or carburetion of the air-fuel mixture into the intake manifold. (5) Other methods of supplementing diesel fuel with ethanol include blending the fuels into an aqueous mixture known as diesohol (50). This blend suffers from the same problems exhibited by gasohol (4).

Perhaps the best means of using ethanol in diesel engines is to convert the diesel engine into a true alcohol engine. This alleviates the often small savings gained by supplemental fueling (50). The major drawback is that the process is irreversible. Several studies (14, 40, 49) have explained this conversion. The University of Illinois (40) made significant changes in an International Harvester diesel tractor for straight ethanol fuel operation which included replacing the fuel injection system with a spark ignition system. Optimum operating conditions were sought to provide the maximum benefit of the ethanol fuel. The electronic ignition distributor was mounted in the injection pump body. Long reach spark plugs

were used in place of the injectors. An auxillary heating plate was used to increase vaporization of the mixture. An auxillary fuel pump was needed to provide a cold starting fluid. A redesigned intake manifold providing more heat to the mixture was also installed. An aircraft pressure carburetor was mounted between the turbocharger and intake manifold and an extra head gasket was added to decrease the compression ratio from approximately 16:1 to 13:1. Nichols (14) used direct injection by using a self lubricating injection pump and drilled holes in the cylinder heads to place spark plugs.

F. Alcohol Fuel in Spark Ignition Engines

A number of universities have been involved with alcohol fuels testing. Most have been affiliated with federal agencies or major companies. Perhaps the university performing the greatest amount of alcohol fuels research is the university of Santa Clara in California, under the direction of Dr. R. K. Pefley (22, 27, 30). This research team has done extensive research with both pure and blended alcohol fuels since 1968. They have been sponsored heavily by the DOE and have studied a wide variety of areas such as exhaust emissions analysis, the environmental effects of alcohol spills, and the assessment of end uses of alcohol fuels (27). They have operated vehicles on both pure and blended alcohol since 1970, while researching and developing fuel systems and engine modifications that exploit the properties of alcohol fuels (27). The department has operated a 1972 Plymouth Valiant and a 1970 American Motors Corp. Gremlin on neat methanol for 4 and 5 years as of June 1976 (29).

Other universities have performed alcohol fuel engine tests, quite often to determine the operating characteristics of the fuel and provide

their results to a curious and interested local public. The University of Illinois (40) typifies research conducted at many universities with their conversion of an International Harvester IH3388 diesel tractor to operate on straight ethanol. The tractor was operated, tested and publicly displayed during the University of Illinois field day in 1980.

Other countries have performed considerable research on alcohol fuels technology. West Germany has undertaken an extensive research program (9) to evaluate the possibilities of using alcohol to help reduce their extremely high levels of imported oil. The German Federal Ministry for Research and Technology is similar to the United States DOE and has devised a comprehensive alcohol fuels research program to operate from 1979 through 1982, ending with a heavy series of fleet tests. The Volkswagenwerk AG Company research division has performed an extensive amount of alcohol fuel research and engine testing, providing results and data comparable to the work done at the University of Santa Clara. Winfried Bernhardt (19, 32, 51) and Holmer Menrad (25, 51) are two Volkswagenwerk researchers supplying West Germany with the same type of research data that Dr. R. K. Pefley has supplied to the United States.

Brazil has performed the most research with ethanol fuels (50). The abundant supply of sugar cane and the year-round warm temperatures assure a constant low-cost supply of fuel that gives optimum engine performance (31). Dr. G. K. Chui of Ford Motor Co. heads the Engineering and Research staff which teamed with F.D.P. Pinto from Ford of Brazil to help optimize Brazilian engines to operate on neat ethanol. Early test results, published in 1979 (15), tested engines with the minimal changes necessary to accept ethanol fuel before engine tests were run to develop optimum calibrations. Their results showed that good driveability was

displayed by a 1978 1.4 L engine operated at an equivalence ratio of $\phi = 0.67$. Cold start was not possible below 5°C. Emissions tests showed increased aldehydes and UBF, similar CO values, and decreased NO_x . Driveability of this vehicle suffered from maldistribution of the air-fuel mixture due to improper heating. Subsequent studies were made with engine revisions designed to optimize fuel economy and vehicle performance.

Volkswagen of Brazil (13, 31) has performed many engine tests utilizing ethanol in both its neat and blended forms. Their research continues to improve neat ethanol performance as Brazil is rapidly increasing the number of cars using the fuel. By 1985, Brazil expects to fuel approximately 1/3 of national motor vehicles with straight ethanol (7). Ford Motor Co. feels that future improvements to engine designs and fuel metering systems, along with possible fuel modifications, will eventually eliminate all driveability problems and maximize fuel economy in Brazilian engines operating on neat ethanol (7).

The California Energy Commission (CEC) has been operating fleets of pure alcohol fueled automobiles for quite some time. Extensive tests performed on a fleet of three Ford Escorts driven in the Los Angeles area using a straight ethanol-methanol fuel mix showed that they passed the California Air Resources Board's 1982 emissions standards for NO_x , HC and CO by 37, 55 and 44 percent respectively. A methanol fueled Volkswagen Rabbit has been added to this fleet of Escorts and has performed equivalent to or better than its gasoline powered counterpart (45). This Rabbit will be the blueprint for 37 cars, the first pure-alcohol automobiles manufactured on a U.S. assembly line.

Future engines, designed to utilize a high percentage alcohol fuel will use many well-developed means to maximize engine performance.

These include such things as optimizing the compression ratio, ignition timing, spark plug heat range, and lubricant and materials compatibility. But the main thrust of future research will be devoted to perfecting air-fuel metering and induction systems which improve driveability and fuel economy. Air-fuel mixture preparation, particularly as regards fuel droplet size, droplet size distribution and vaporization is needed for further improvements in vehicle performance and exhaust emissions (29). Poor nebulization of the fuel and poor mixing with the combustion air are the factors limiting alcohol fuel and spark ignition (19).

Pefley (22, 29) describes test results for several different fuel preparation systems with the objective of maximizing fuel economy, engine performance and exhaust emissions. One system which essentially eliminated maldistribution but did not provide optimum exhaust emissions, consists of a pressure wave generated by the intake valve opening to meter and nebulize the fuel of each intake charge. This acoustic carburetion system produced an indicated thermal efficiency of 41% at equivalence ratio $\phi = .9$. A sonic flow carburetor (presserator) using a high stream velocity, open plenum intake manifold produced higher power output and thermal efficiency than the stock venturi carburetor but did not reduce maldistribution. Electronically controlled fuel injection allows management of equivalence ratio for each cylinder as well as injection timing. This system provides optimum mixture distribution and sufficient thermal efficiency and power outputs, but unburned fuel emissions were three times that of gasoline.

Perhaps the optimum future carburetion technique will be that of electrostatic carburetion. The potential for electrostatic carburetion of alcohol is unique, in that the hydroxyl group that leads to the problems associated with lowered calorific values and high latent heats, also



provides the means whereby alcohols may be atomized electrostatically (10). Because of the difference in electronegativity of oxygen and hydrogen, the OH radical in alcohols is electrically polarized, making them amenable to electrical atomization. If the surface of a liquid becomes charged, forces are established (on electrical pressure) on the surface opposing the surface tension forces of the liquid holding it together. The excess charge is removed from the surface by it disrupting and emitting streams of charged droplets. These droplets are evaporated in the charge air with no heat transfer across boundaries such as the inlet manifold and piston crown. Electrostatic carburetion must be considered as a primary method for achieving optimum fuel particle sizes if future research determined that optimum fuel spray sizes for propagation rates, fuel economy and pollutant emissions do exist.

A number of systems have been designed to improve the warm-up characteristics of engine induction systems so that a cold engine can be started and utilize its exhaust gas enthalpy to heat the intake manifold (19). One such approach involves localized augmentative intake air preheating to promote fuel evaporation during cold start by utilizing a number of electrical heating elements inside the intake manifold. These elements are heated by the battery and stop working when normal engine operating temperatures are reached. Another system uses a heat pipe vaporizer unit consisting of a small compact heat exchange unit which is a sealed vertical metal tube containing a specific liquid. Waste heat from the exhaust gases heats the lower part of the tube causing the liquid to boil and recondense in the upper cooler part of the heat pipe. The heat given off by the condensing liquid is available to evaporate fuel in the incoming air.

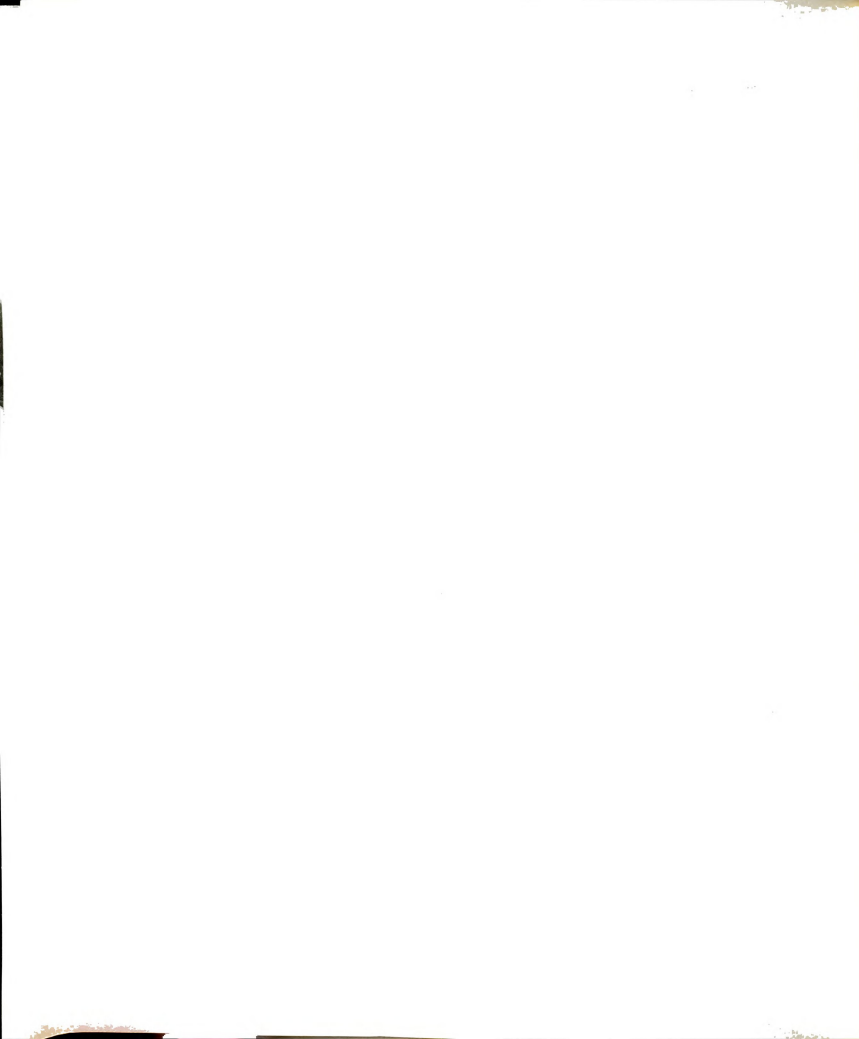
An innovative design for starting straight methanol fueled engines in cold weather has been developed by Geiner and Likos (11). The object was to thermally decompose methanol to products that include hydrogen in order to start an internal combustion engine at very low temperature. A small methanol combustor was developed to supply thermal energy to decompose methanol passing through tubes near the combustion chamber. An engine cooled to -30°C was rapidly started but carbon buildup in the methanol tubes and slow conversion from gas to liquid methanol requires further design modifications.

A group of Brazilian engineers has developed a very successful fuel control system which allows fuels of various stoichiometries to be used interchangeably without economy penalty (59). The system is known as lean limit control (LLC) and is a technique of air-fuel management which involves detection of incipient over-lean combustion based on information regarding combustion quality of each discrete combustion event. A magnetic sensor picks up continuous signals from the flywheel and through the use of micro-electric signal processing, a digital output signal describing each combustion pulse as good or bad is generated. Based on this feedback of combustion quality data, the system's servo portion maintains the air-fuel ratio at the best fuel economy. Tests have been highly successful with gasoline blends up to 50% ethanol. Future work will be based on neat ethanol fuel and possibly include spark timing and knock suppression.

Future research needs to continue until an eventual optimized control system can be developed. Maximizing fuel economy, power output and vehicle performance while producing minimum exhaust emissions is the goal of researchers in the future. Through the exploration of improved hardware design such as optimum compression ratio, camshaft design, high swirl



combustion chambers, high energy ignition and systematic exploration of possible engine control strategies, an optimum control system will be developed for future straight alcohol engine design (22).



IV EXPERIMENTAL PROCEDURE

A. Assumptions

The primary purpose of this research was to determine the feasibility of straight ethanol fuel when substituted for gasoline in a farm tractor with a spark ignition engine. The comparison of ethanol to gasoline was made under two separate sets of criteria. Both comparisons were made with the assumption that the ethanol fuel would be produced in a small-scale farm still and used on the farm.

For the first comparison, the assumption was made that the farmer would want to utilize the ethanol fuel with only those engine changes which were absolutely essential for adequate ethanol operation. This viewpoint is the one shared by the majority of farmers (50). The engine modifications made enabled the farmer to convert back to gasoline fuel in the future if he so desired.

The second comparison assumed that the farmer was interested in permanently utilizing ethanol as a primary fuel. He would be more willing to make the conversion changes that take advantage of ethanol's fuel properties that are not optimized by gasoline engine design. These modifications are not only more expensive but they eliminate the possibility of using gasoline fuel without the high cost of engine remodification. The specific engine modification that was made under this comparison was the replacement of the gasoline pistons with diesel pistons that take advantage of ethanol's high octane rating and thus increase the power output. Modifications more complex and expensive than replacing the pistons, such as installing a direct injection fuel system, were felt to be beyond the desire of almost every farmer and likewise beyond the scope of this research.

This research was not intended to produce a true alcohol engine, where every design detail was chosen to optimize ethanol fuel. Nor was the intent to completely overhaul a spark ignition engine to make the maximum number of possible modifications for ethanol fuel optimization. Rather, the intent was to obtain an adequate replacement fuel for spark ignition engines which could be produced on the farm.

Three basic parameters were determined to be of importance to any farmer considering ethanol fuel usage. These parameters are power output, fuel economy and vehicle driveability. They represent the basis for comparison between ethanol and gasoline fuel performance. Modifications or adjustments were made to maximize these parameters.

Ethanol water content is an important factor for anyone producing ethanol on a small-scale still. A 95% pure ethanol product may be obtained from this method. The higher the percentage of water to be removed during ethanol distillation, the greater the amount of time and money needed. Therefore, ethanol fuels containing from 0% to 20% water were tested and engine performance was compared to that of gasoline.

An additional concern of farmers considering an alternate fuel is how this fuel will affect the repair and maintenance of the tractor. The lack of ethanol fuel damage to internal engine parts after many hours of engine use makes information on this area of vital concern. An important part of this research lies in the results of component examination after an extended time period of normal machinery use.

Ethanol fuel emissions were not considered a part of this research.

B. Tractor Modifications

A Ford 2000, 3 cylinder, 8 speed, gasoline powered tractor with 2.6 l displacement was donated by the Michigan State Beef Cattle Research. This tractor had been heavily used and then stored for a long period of time before conversion was undertaken. A complete tune-up was required before any gasoline tests could be performed. The internal engine component condition was not evaluated prior to performance tests with gasoline although low cylinder compression readings indicated that major internal wear had occurred. The decision was made to evaluate the gasoline test results with those of ethanol at the original 8:1 compression ratio since similar internal engine component conditions would allow a direct comparison. Optimum conventional gasoline tractor performance would be determined from the Nebraska Tractor Test data (67) and compared to the ethanol test results after the higher compression pistons were installed and any internal component damage repaired.

After the performance testing was completed with gasoline fuel, a number of significant engine modifications were necessary before ethanol could be used. The most essential change required altering the carburetion system due to ethanol's lower energy content. Two carburetion system alterations were evaluated for overcoming ethanol's lower air/fuel ratio. The first design involved using the original carburetor designed for gasoline and drilling all the jets and vent holes to a proportional larger size. This alternative carried a high probability for error, not only in improperly drilling each item, but in failing to include all the necessary jets and vents. The second solution which was chosen involved replacing the gasoline carburetor with one specifically designed for ethanol. Ford Motor Company donated a carburetor similar to the design used at their

test facilities in Brazil (7). This carburetor was a single stage, up-draft Economaster, (model number 267LWX) with a #18 venturi. According to Mingle (8), the lower stoichiometric air/fuel ratio of ethanol at approximately 9 to 1 compared to gasoline at approximately 15 to 1 coupled with ethanol's lower heat value of 3,200 KJ/liter compared to gasoline at 5,300 KJ/liter produces an increase in the jet and vent diameters in the ethanol carburetor of approximately 1.27 times those of the gasoline carburetor. The main jet size of the gasoline carburetor was .043 inches while the alcohol carburetor measured .055 inch. This was the size increase of 1.28 which correlated quite closely to Mingle's calculations.

The new carburetor also contained an adjustable needle valve to the main jet which permitted the testing of various air/fuel ratios. The goal of maximizing fuel economy and thus minimizing fuel cost could be achieved by burning the leanest possible air/fuel mixtures that could give adequate engine performance. The adjustable main jet was also necessary to test different ethanol-water mixtures to determine the effect of the various percentages of water content on fuel economy and engine performance.

A second problem in straight ethanol fuel operation was that of cold weather starting and engine warm-up. Ethanol's higher latent heat of vaporization and lower vapor pressure combine to create difficulty in engines designed to operate on gasoline. The low vapor pressure of ethanol makes starting an ethanol fueled spark ignition engine at temperatures below 10°C practically impossible without a starting aid. The high latent heat of vaporization requires that heat be provided to the intake manifold to keep the vaporized ethanol from condensing and causing uneven fuel distribution between the cylinders. This maldistribution problem can be solved after sufficient engine warm-up by utilizing the engine heat to keep the

air/fuel mixture vaporized. Spark plugs designed for a hotter heat range were used to replace the regular plugs. This change provided more heat in the combustion chamber to help burn the fuel mixture more completely, especially in cold weather.

Many methods were considered to provide the intake manifold with heat and to get the engine started in cold weather. Preheating the intake air, heating the total engine block with a heating element, injecting a more volatile fuel such as ether or propane into the air tube or mixing this same fuel in a smaller percentage with the straight ethanol in the fuel tank, are all methods for starting an ethanol engine in cold weather. Careful evaluation of each alternative was made before a final decision was determined. Preheating the intake air leads to problems of proper control. Too hot a mixture leads to power loss and eventual detonation and rapid engine wear. If this method is used to heat the intake manifold as well as start the engine, temperature control devices must be installed to keep the mixture at the proper temperature. Heating the engine block leads to rapid battery drainage if an outside power source is not used. This method is more favorable and would be appropriate in many cases if a block heater is plugged into an outside electrical outlet. However, cold weather operation producing quick engine cool down necessitates carrying an extension cord on the tractor and always remembering to stop the tractor within cord distance of an electrical outlet. Mixing a volatile fuel with the ethanol in the fuel tank meant that our test results would always be influenced by this additional fuel. Possible mixture separation as well as the time consumed in having to mix every tank full were factors which hindered this solution.

A final decision was made to inject either propane or ether into the

air stream as the method for starting the cold engine. Both fuels are gaseous under ambient temperature and pressure conditions and thus alleviate the need for vaporization. Upon recommendations from engineers at Ford Motor Company (7), the decision was made to use propane rather than ether. Lower cost, greater availability and less consumption were all reasons for choosing propane over the commonly used diesel engine ether starting aid.

A small propane canister, commonly purchased in most hardware stores, was strapped to the tractor within easy reaching distance of the seated operator. A line was attached from the propane tank to a fitting on the intake manifold following the carburetor. The intake vacuum produced the mixing of the mixture of ethanol fuel with propane in the intake manifold just above the carburetor. When the outside temperature was 20°C or less, the operator started the tractor by first turning the propane valve to inject a small amount of propane into the intake manifold as the engine was started. The propane valve was gradually closed as the engine warmed up with a complete shut off once normal operating temperature was attained. During extremely cold temperatures, the engine was operated almost exclusively on the air/propane mixture until engine warm up was reached. With warmer ambient temperatures, less propane was needed and a shorter time interval for propane use was required. In the summer, when the temperature was usually higher than 20°C, this starting aid was not necessary.

The problem of intake manifold heating to keep the mixture vaporized once the engine was started was not a problem in this research due to the particular engine design of the Ford 2000 tractor. This design incorporated an intake manifold surrounded by a water jacket producing a heat exchange between the engine coolant and the incoming fuel-air mixture. The intake manifold was designed as a separate engine component attached to the

cylinder head in a position where little utilization was taken from the engine's heat. The heat exchanger design indicates that fuel distribution problems would occur with gasoline fuel, and would be certain to occur with ethanol fuel. The higher latent heat of vaporization of ethanol caused more heat to be drawn from the air to vaporize the fuel and thus a decrease in the air/fuel mixture temperature with a high probability of condensation. The water jacket surrounding the intake manifold was a very efficient means of using engine heat to keep the mixture vaporized. This design would probably be a standard feature for any engine designed specifically for alcohol fuel. No modification was made to this design.

An area requiring careful attention when replacing gasoline with ethanol fuel is the replacement of any materials which are incompatible with the ethanol. The only problem observed in this area was the need to install an electric fuel pump because the mechanical pump's diaphragm was not compatible with ethanol. Each engine requires a thorough inspection to replace any noncompatible parts.

Another concern was the selection of the proper ignition timing for ethanol fuel mixtures. Ethanol's different burning characteristics indicate that the ignition timing setting to optimize ethanol performance may be different from the optimum gasoline setting. The literature indicated a wide range of recommendations for ignition timing, from very early to very late settings. In order to prevent any undue wear on the engine and provide consistency in interpretation of our engine results when comparing ethanol fuels with varying water contents, a standard ignition timing setting was chosen. The decision was made to set the ignition timing slightly advanced from 3 to 6° BTDC at idle speed. This decision was based primarily on the advice from engineers at Ford Tractor (7), as their tests

showed this to be the optimum setting. During the testing procedure, the effect of ignition timing on power output and fuel consumption was tested at 90% ethanol fuel by varying the timing to different settings and then measuring the effect on power and fuel economy at different loads.

After completion of the ethanol tests at the 8:1 compression ratio, the engine was rebuilt and pistons producing a 12:1 compression ratio were installed. These pistons were standard diesel pistons with the combustion chambers milled to provide a 12:1 compression ratio. The purpose of this replacement was to take advantage of ethanol's higher octane rating and provide optimum fuel economy and power output.

At this time, a complete internal engine examination was performed to determine the engine condition. Excellent engine condition was essential not only to provide optimum ethanol performance, but to provide an accurate data base for any future comparisons to determine long term engine wear. Measurements included piston clearance, cylinder taper and out-of-roundness, valve clearance, valve margin width, and valve seating. It was discovered that all three cylinders were badly worn and out-of-round. The piston clearance in each cylinder was at least 3 times the maximum specification. Most of the valves were not seating properly, and most of the bearings needed replacement. The decision was made to replace the cylinder sleeves, main and rod bearings, and reface and reseal the valves before the higher compression pistons were installed. Measurements taken after this work was completed indicated that the dimensions for each of the above engine wear points were well within their specifications.

C. Test Procedure

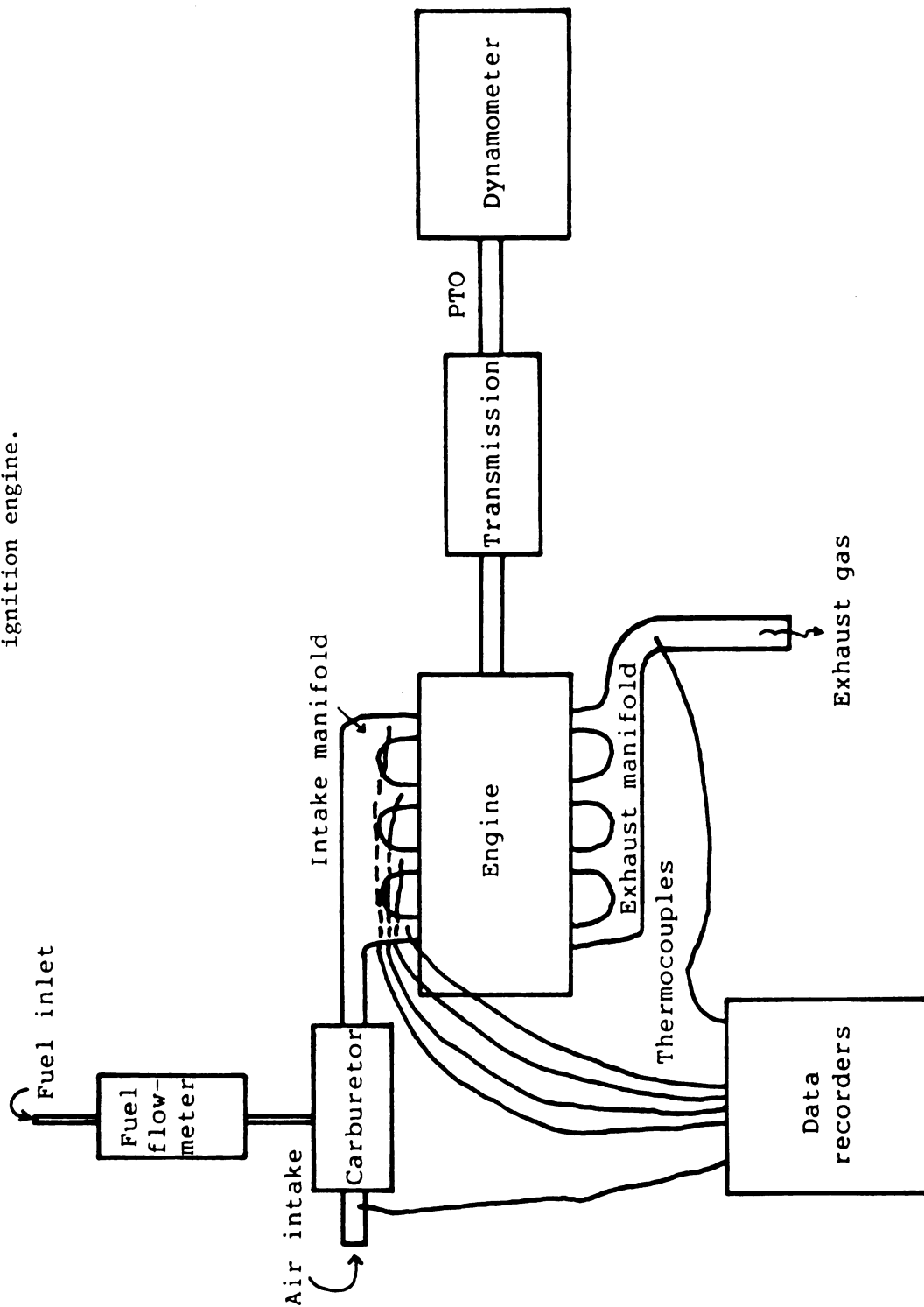
Laboratory engine tests were first performed with gasoline as a fuel. Engine performance was then tested using 7 ethanol and water mixtures. The test procedure remained the same for each fuel tested. At least three separate test runs were performed for each fuel to determine an accurate average for each measurement. Tests were conducted for gasoline and ethanol at 8:1 compression ratio before being conducted for ethanol at 12:1 compression. Tests were conducted with ethanol and distilled water solutions of 100, 95, 90, 85, 80, 75, and 70 percent ethanol by volume.

During the laboratory tests, three measurements were taken: power output, fuel consumption and engine temperatures. To measure power for gasoline and 8:1 compression ratio ethanol tests, the tractor was coupled through its pto drive to an electric-cradle dynamometer which provided a constant load to the tractor. For the 12:1 compression ratio ethanol tests, a portable hydraulic dynamometer was used due to a breakdown of the electric dynamometer. Fuel consumption was measured by feeding the ethanol into the carburetor from a 50 ml graduated cylinder. A stop watch was used to time the fuel flow through the cylinder. The intake fuel-air mixture temperatures, recorded both before and after the water jacketed intake manifold, and the exhaust temperature were all monitored during the tests by using thermocouples connected to a digital data recorder. The temperature of the fuel-air mixture was recorded just as it entered the combustion chamber of each cylinder. The intent of these three measurements was to test for possible cylinder maldistribution. The exhaust temperature was recorded by placing a thermocouple in the exhaust manifold. One purpose

of this measurement was to determine the effect that the various water contents of the ethanol fuel mixtures had on combustion temperatures. The exhaust temperature measurement also revealed the effect of the increase in compression ratio on combustion temperatures. A further benefit of this temperature measurement involve comparing combustion temperatures between ethanol and gasoline. The literature produces conflicting evidence for this comparison. Most studies confirm that ethanol combustion temperatures are lower than gasoline's, but some studies indicate the opposite (30, 43, 66).

The test procedure consisted of starting the engine and allowing sufficient warm-up time before the engine was loaded down to a pto torque of 203 N-m. This load was approximately 2/3 of the anticipated maximum load and served as a reference point for adjusting the carburetor for optimum fuel economy. The adjustable needle valve in the main jet was then screwed in until the engine speed began to slow down, then backed out 1/2 turn. This provided the leanest air/fuel mixture that could be used to provide proper engine performance, and was considered to provide maximum fuel economy. Fuel consumption and engine temperatures were recorded as the pto torque was increased at intervals of 40.7 N-m from 0 to 339 N-m. At each torque level, the pto speed was kept constant at 540 rpm. Maximum power was found when an engine speed of 540 rpm would not be maintained under the load. Fuel and temperature measurements were taken at each load level.

Schematic of test stand used to evaluate ethanol fuel in a Ford 2000 with a spark ignition engine.



V EXPERIMENTAL RESULTS

As previously mentioned, torque level, fuel consumption and engine temperatures were the only data recorded during the engine tests. From these values, the following categories were calculated. Torque levels were recorded in ft-lbs and then converted to N-m. With the constant PTO speed of 540 rpm, these values were used to determine power in KW. Energy consumption in KJ/sec was determined by knowing the fuel consumption in ml/sec and using the average energy values for gasoline (33,720 J/ml) and 100% ethanol (23,580 J/ml). The assumption was made that the water content of the ethanol fuel decreased the energy content by the percentage of water. Thermal efficiency was calculated by dividing the power produced by the energy consumed. Fuel efficiency was power obtained divided by fuel consumption.

A. Power

The comparison of performance results at 8:1 compression ratio to those obtained at 12:1 compression ratio must be done while considering the engine condition. The poor engine condition at the lower compression produced values that were less than optimum in many cases. However, some measurements were not affected by the worn internal engine components, and a direct comparison of gasoline and ethanol results can be made because of the similar engine conditions under which they were performed. According to the Nebraska tractor tests, the maximum power a gasoline fueled Ford 2000 tractor can produce at 1800 engine rpm with a standard pto speed of 540 rpm is 22.4 KW (30.04 HP) (67). This data will be used as optimum gasoline engine performance from which our results will be compared.

At an 8:1 compression ratio, gasoline fuel produced a maximum power output of 19.3 KW. This is approximately 86% of maximum available power with this engine design. Straight ethanol fuel with up to 30% water content was tested at this compression ratio. The maximum power produced by 100%, 95%, and 90% ethanol fuels was 19.7 KW, 19.7 KW, and 19.6 KW, respectively, which were all greater than that produced with gasoline. Maximum power outputs for ethanol fuels with a water content greater than 10% were lower than with gasoline fuel. The maximum power produced by 85%, 80%, and 75% ethanol fuels was 18.56 KW, 18.40 KW, and 18.17 KW, (Table 1) respectively. With 70% ethanol fuel, low load engine operation was quite difficult. Below approximately 150 N-m torque the engine speed could not be maintained at a constant level. The rpm reading varied uncontrollably at all carburetor settings. At loads greater than 150 N-m, engine operation became stable with a maximum power output of 15.07 KW.

At a 12:1 compression ratio, ethanol fuels with a water content of 20% or less could be used to operate the engine. Ethanol fuels of 75% or lower caused engine surging and hesitation at all speeds and loads. The maximum power output of each ethanol fuel tested was greater than or equal to the maximum power produced by gasoline. Engine tests with 100% ethanol fuel easily produced 22.37 KW. As the engine load was increased further, engine knock began to occur. At the maximum load with pto speed maintained at 540 rpm, severe engine knock necessitated engine shutdown. The same result occurred with 95% ethanol fuel. Because of the engine knock, both 100% and 95% ethanol fuels produced a maximum power output of approximately 24.6 KW. When 90% ethanol fuel was tested, only slight detonation occurred at maximum load at 540 pto rpm. This led to a maximum power out of 26.10 KW which was 35% greater than the maximum power produced by gasoline at 8:1

compression, and 16.7% greater than the maximum power obtained from the Nebraska tractor tests. This high power output is a result of the water content of the 90% ethanol fuel. The octane rating of water is much higher than ethanol, and the 10% water was enough to allow operation at a 12:1 compression with no engine knock. The second beneficial property of the water content was its high latent heat of vaporization which cooled the air-fuel mixture during vaporization and thus further reduced the mixture volume below the mixture volumes of 95% and 100% ethanol. This cooler mixture packed the cylinder very efficiently, increasing the volumetric efficiency and therefore, the power output. Maximum load for 85% and 80% ethanol fuels caused no detonation and produced maximum power outputs of 25.36 KW and 22.37 KW respectively. The higher water content of these fuels could not produce the power of the ethanol they replaced. Thus, at a 12:1 compression ratio, the maximum power output of ethanol fuel was significantly increased over the gasoline and ethanol test results at an 8:1 compression ratio. Ethanol fuel with 20% water content produced the same maximum power output that gasoline produced under optimal engine conditions.

B. Fuel Consumption and Thermal Efficiency

The large difference in energy content between gasoline and ethanol resulted in substantial differences in the fuel consumption rates. Table 2 reveals that by volume, much more ethanol was consumed at a given load than gasoline. These figures also reveal that as ethanol water content increased, fuel consumption increased. These results were expected and confirmed the majority of test results in the literature indicating the higher consumption rates of ethanol fuels with greater water contents.

Table 2. Maximum Power in KW

Fuel	Fuel Content (% by volume)	Compression Ratio	
		8:1	12:1
Gasoline	100	19.32*	--
Ethanol	100	19.71	24.6
	95	19.71	24.6
	90	19.55	26.1
	85	18.56	25.36
	80	18.40	22.37
	75	18.17	--
	70	15.07	--

*Nebraska tractor test results report a maximum power output of 22.4 KW. Difference due to engine wear.

Table 3. Fuel Consumption in ml/sec at 8:1 Compression Ratio

Torque (N-m)	Gasoline	% Ethanol					
		100	95	90	85	80	75
6	.98	1.23	1.33	1.35	1.52	1.52	1.67
40	1.11	1.45	1.56	1.59	1.77	1.79	1.96
81	1.32	1.77	1.79	1.92	2.0	2.20	2.25
122	1.54	2.0	2.17	2.17	2.27	2.44	2.56
162	1.71	2.33	2.35	2.44	2.63	2.78	2.94
203	1.91	2.56	2.56	2.70	2.94	3.13	3.33
244	2.13	2.86	2.9	2.9	3.23	3.45	3.57
284	2.25	3.23	3.23	3.33	3.7	3.7	4.0
325	2.67	3.7	3.85	3.85	4.17	4.17	4.55
Max.	2.78	4.17	4.17	4.26	4.76	--	--

Table 3 presents the fuel consumption data for the tests at the 12:1 compression ratio. The same pattern was found in these results pertaining to ethanol water content. The individual test results were very similar to those produced at an 8:1 compression ratio. From these results, we conclude that increasing the compression ratio had little effect upon fuel consumption rates. The results displayed in Tables 2 and 3 show a very uniform reduction in fuel consumption time from low to maximum load and from 0 to maximum water content. Very few results deviated from this uniform pattern, indicating a sufficient system for measuring fuel consumption and determining maximum fuel economy.

Two calculations which provided information more beneficial than the fuel consumption were thermal efficiency and fuel efficiency. These measurements reveal the use of the energy which is contained in the fuel. Alternate energy sources must be viewed in terms of how their energy content is utilized. Thermal efficiency was considered to be the ratio of the energy output, or power produced, to the energy contained in the fuel. An examination of Table 4 shows that for a given load, ethanol used less

Table 4. Fuel Consumption in ml/sec at 12:1 Compression Ratio

Torque (N-m)	% Ethanol				
	100	95	90	85	80
0	1.11	1.15	1.19	1.39	1.13
19.78	1.56	1.58	1.70	1.89	1.92
131.88	2.06	2.11	2.27	2.54	2.53
197.83	2.38	2.44	2.62	2.81	2.89
263.77	2.73	2.78	2.92	3.31	3.29
329.71	2.98	3.09	3.27	3.55	4.13
395.65	3.33	3.36	3.62	4.17	4.24
Max.	Knock	Knock	3.85	4.31	

energy than gasoline to produce the same power. This means that much of gasoline's higher fuel energy content is never utilized and is simply wasted. Figure 1 confirms this observation by showing the results of thermal efficiency calculated for ethanol fuels and gasoline at 8:1 compression. This figure reveals that 90% ethanol produced the highest thermal efficiency for almost every load, indicating that a higher percentage of the energy in the fuel was used to produce power. Table 4 also shows that 90% ethanol gave lower values for energy consumption than ethanol fuels with greater or lesser water content. Both sets of data show 90% ethanol fuel as the most beneficial volume of water for producing maximum volumetric efficiency and thermal efficiency. Ethanol fuel with a water content of less than 10% does not fill the cylinder enough to utilize more of its energy, while a water content greater than 10% replaces too much ethanol to utilize the energy contained in the fuel.

Table 5 and Figures 2 and 3 show the results obtained from operation at the 12:1 compression ratio. The energy consumption values in Table 5 showed the same pattern and similar values for each ethanol fuel as in Table 4. Figure 2 shows the close thermal efficiency values for 90% ethanol fuel at 8:1 and 12:1 compression ratio with gasoline at 8:1 compression. A major difference between the ethanol fuel values at 12:1 compression ratio versus those at 8:1 compression was that the 12:1 compression values did not peak during high load and then begin to decline until the fuel produced maximum power. Instead, there was consistent positive slope from no load to maximum power. At maximum power, 90% ethanol produced a thermal efficiency slightly over 31% while 100% ethanol fuel exhibited a value of approximately 28.5% and gasoline only 20.5%.

Fuel efficiency is also a measure of fuel utilization by an engine.



Table 5. Energy Consumption in KJ/sec at 8:1 Compression Ratio

Torque (N-m)	% Ethanol Fuel						
	Gasoline	100	95	90	85	80	75
6.10	33.05	29.48	30.02	28.86	30.47	28.67	29.71
40.68	36.75	35.13	34.95	33.96	34.87	33.01	34.66
81.36	43.16	41.27	40.32	40.75	40.09	41.89	39.26
122.04	52.27	47.16	48.61	46.05	46.10	46.03	45.27
162.72	56.31	54.94	52.64	51.78	52.71	52.44	51.99
203.40	62.38	60.36	59.81	58.15	58.93	59.04	58.89
244.08	71.15	67.44	64.96	61.54	63.54	66.21	63.14
284.76	74.86	76.16	73.48	73.22	72.96	71.12	70.74
325.44	91.04	85.83	86.24	81.70	83.58	76.97	78.52
Max.	93.74	96.21	93.41	88.50	83.58	--	--

This calculation is represented in terms of power and time per unit of fuel volume, KW-hr/L. This value indicates the maximum power a unit volume of fuel could produce for one hour under a given load. The higher the value, the more efficiently the fuel is utilized. Figure 4 represents the results of fuels tested at the 8:1 compression ratio. Because of the vast difference in energy content between ethanol and gasoline, the values of gasoline far exceed those of ethanol. The greater the load, the greater the difference between gasoline and ethanol. All fuels exhibited results in the positive direction. Greater loads produced higher efficiency. The increase in ethanol fuel efficiency at increasing loads could not match gasoline's increase in efficiency. The greater quantity of ethanol entering each cylinder at high load could not be burned and therefore utilized as well as the greater quantity of gasoline entering the cylinders during high load. Figure 4 also shows the relationship ethanol fuels displayed in terms of fuel efficiency. Ethanol fuels with higher water contents have less energy per gallon and consequently lower fuel efficiency results. Thus, to produce a constant power for a certain time period required a

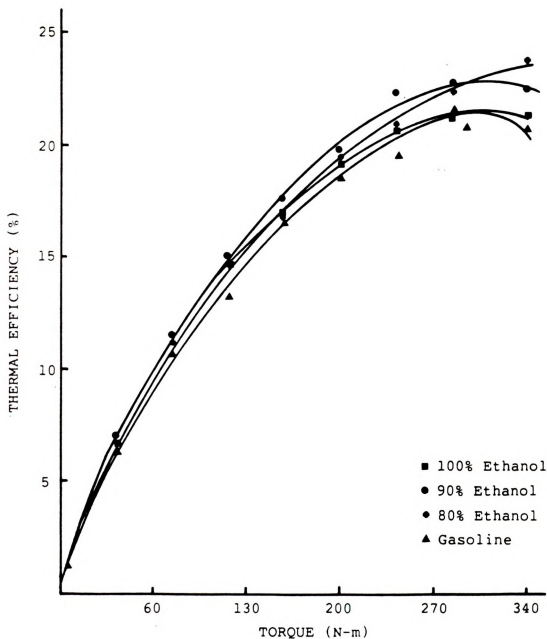


Figure 1. Thermal efficiency of Ford 2000 fueled with gasoline or ethanol/water mixtures operated with a PTO speed of 540 RPM at 8:1 compression ratio.

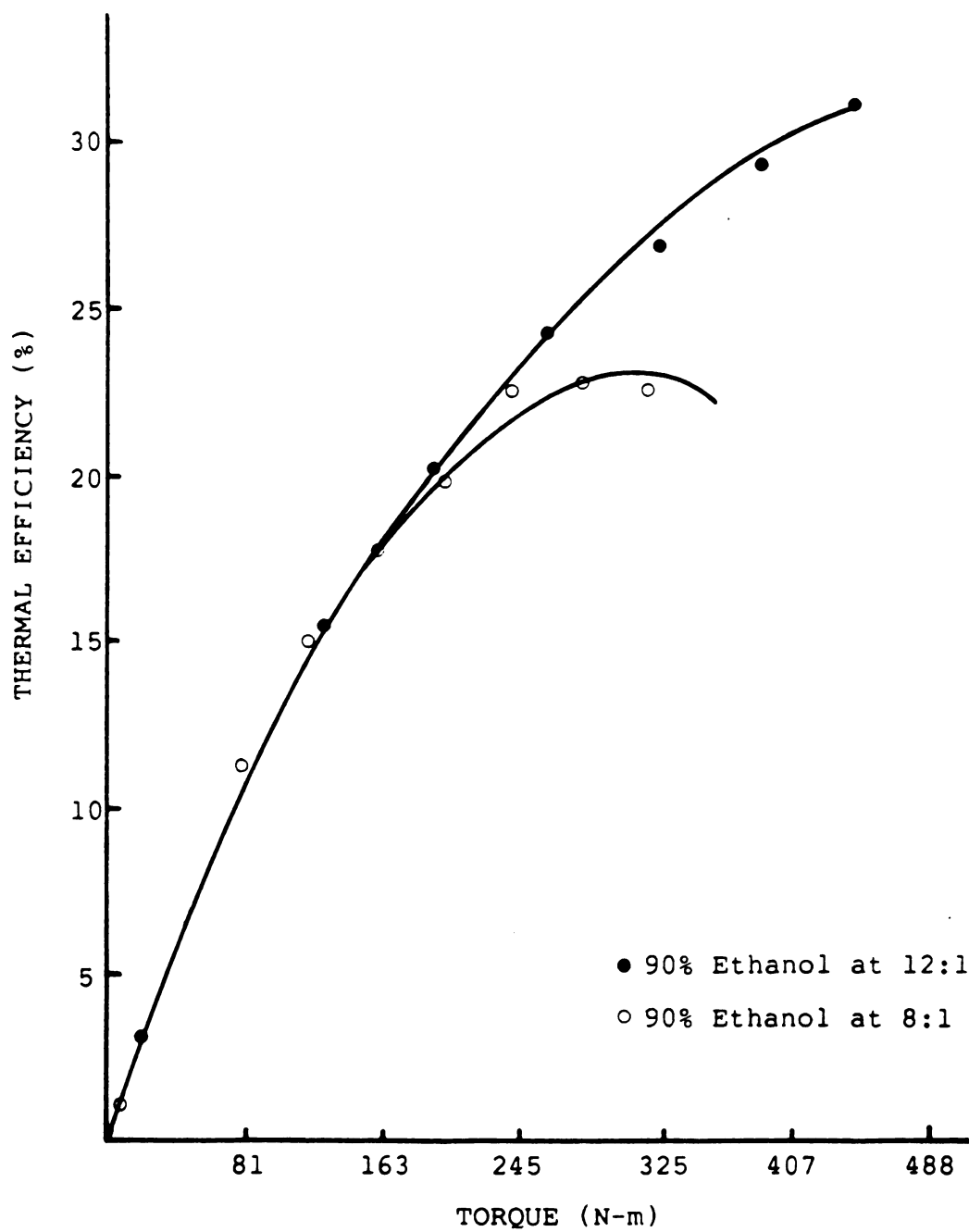


Figure 2. Thermal efficiency of ethanol fuel at 12:1 vs. 8:1 compression ratio.

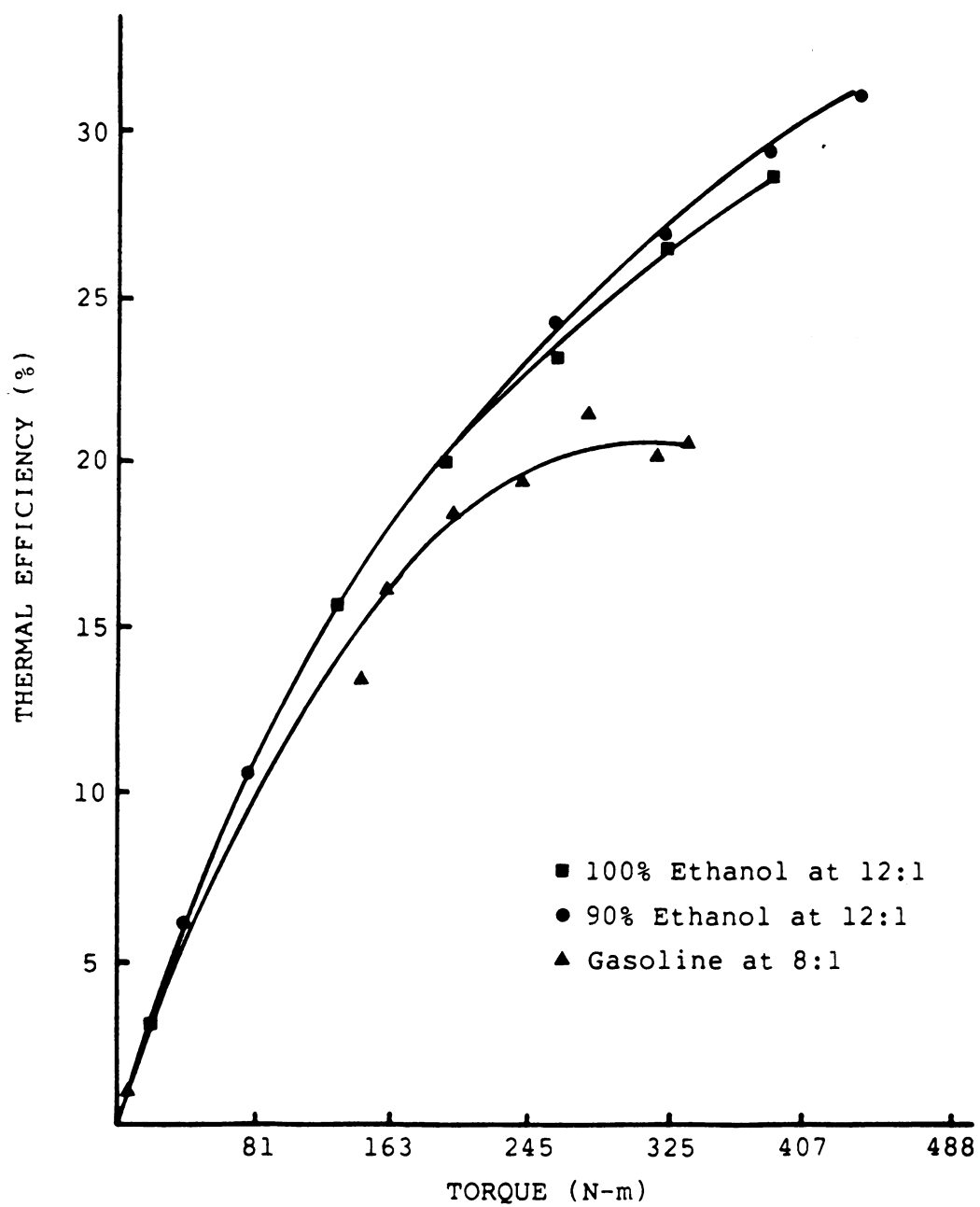


Figure 3. Thermal efficiency of ethanol fuel at 12:1 compression ratio vs. gasoline at 8:1.

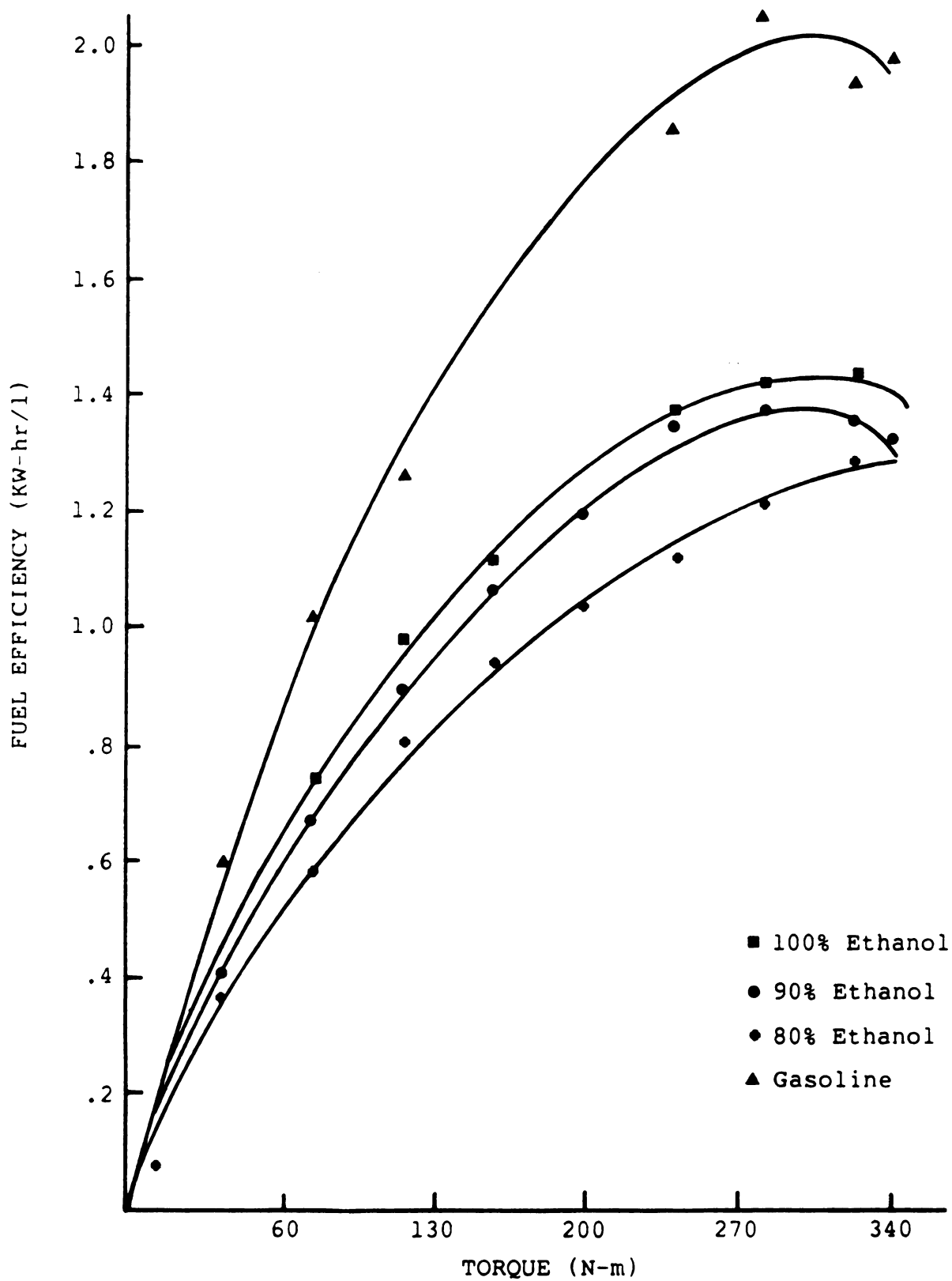


Figure 4. Fuel efficiency of ethanol fuel vs. gasoline at 8:1 compression ratio.

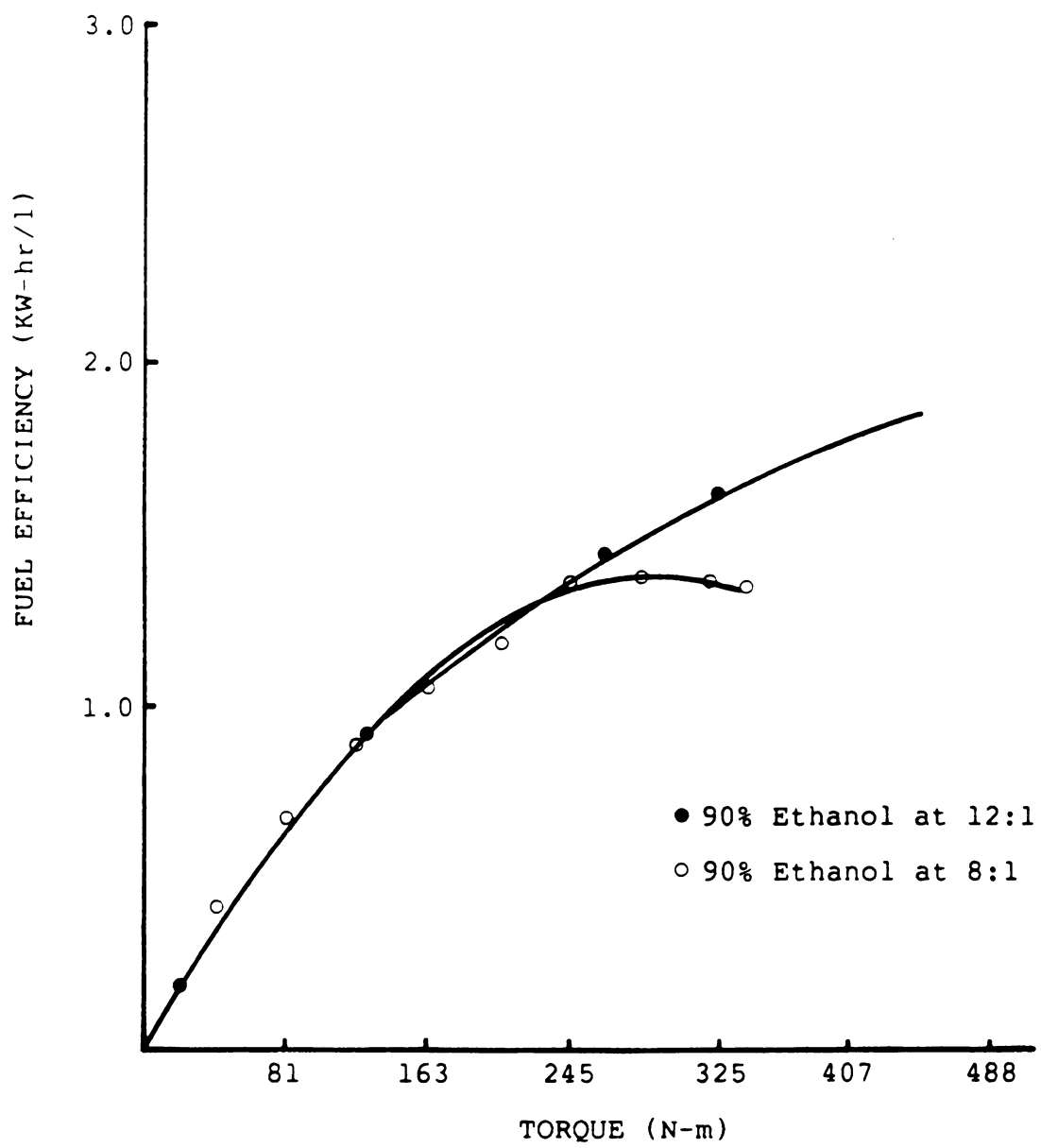


Figure 5. Fuel efficiency of ethanol fuel at 12:1 vs. 8:1 compression rate.

higher volume of ethanol fuels with greater water contents. Maximum values for both gasoline and ethanol occurred just before maximum load was reached. Gasoline produced a maximum fuel efficiency of 2.03 KW-hr/ℓ while 100% ethanol produced 1.39 KW-hr/ℓ.

Figure 5 shows the comparison of 90% ethanol fuel efficiency at 8:1 and 12:1 compression ratios. The higher compression produced much better utilization of the ethanol at high loads. Higher combustion temperature and pressure created better mixture burning and a constant increase in fuel efficiency from no load to maximum load. Fuel efficiency values for 8:1 compression reached a peak at about 3/4 load and then began to decrease. Figure 6 compares the fuel efficiency of 100% and 90% ethanol fuel at 12:1 compression with gasoline at 8:1 compression. The increased performance at the higher compression ratio yielded maximum ethanol fuel efficiency values that were much closer to the gasoline's maximum fuel efficiency. The maximum fuel efficiency for 100% ethanol fuel at 12:1 compression was 1.88 KW-hr/ℓ compared to gasoline's maximum fuel efficiency of 2.03 KW-hr/ℓ. These values compare favorably to the maximum fuel efficiency of 2.14 KW-hr/ℓ produced by the Nebraska Tractor Tests (67). The lower gasoline fuel efficiency produced in our tests was the result of worn internal engine components.

C. Intake Temperatures

Intake temperature measurements were made to determine the effect of ethanol's high latent heat of vaporization on air-fuel mixture formation. Four thermocouple temperature readings were recorded. One reading measured the air-fuel mixture temperature between the carburetor and the water jacketed intake manifold. The other three readings measured the air-fuel

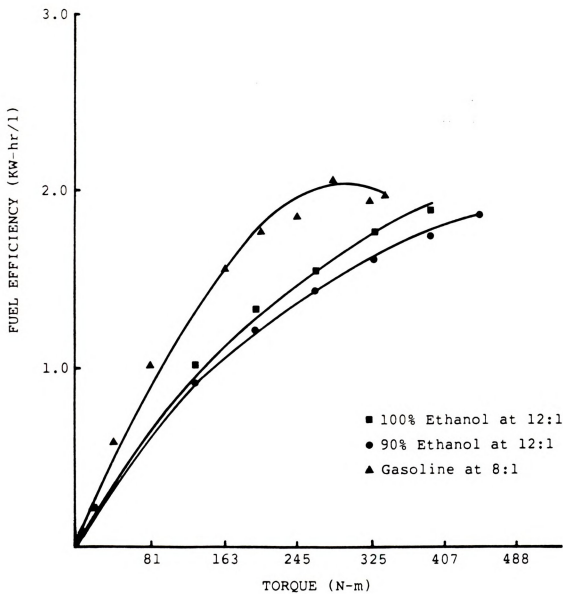


Figure 6. Fuel efficiency of ethanol fuel at 12:1 compression ratio vs. gasoline at 8:1.



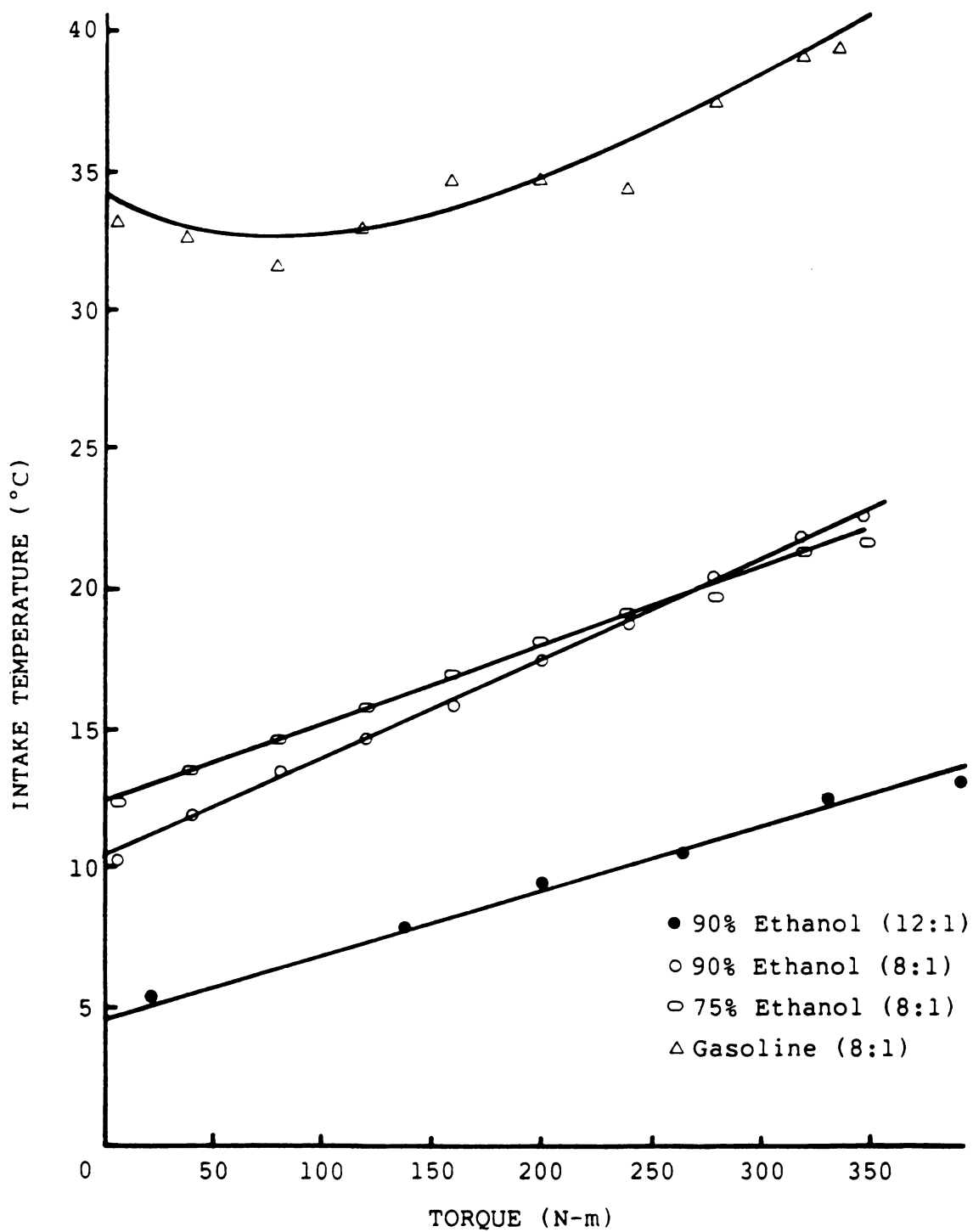


Figure 7. Intake air temperature following the carburetor for ethanol fuel vs. gasoline.



mixture temperature between the intake manifold and the combustion chamber. Figure 7 displays a comparison of the temperature reading above the carburetor at various torque levels. This comparison can be made between ethanol at 8:1 compression. These results reveal potential mixture distribution problems and the effect that water content has on increasing or decreasing this problem. Interpretation of these results is difficult due to the many variables involved.

At 8:1 compression ratio, ethanol fuels produced much lower carburetor temperatures than gasoline. These results verified our expectations based on ethanol's higher latent heat of vaporization. As higher loads were tested and more fuel used by the engine, carburetor temperatures increased due to incomplete fuel vaporization. This resulted in a positive uniform slope for each ethanol fuel tested. Carburetor temperatures for ethanol fuels with increasing water content were similar and in most cases slightly higher than fuels with lesser water contents. It was anticipated that the greater water content would decrease the intake temperatures considerably; however, the extremely high latent heat of vaporization of water apparently caused a balance between increasing the volumetric efficiency and reducing the amount of fuel vaporized in the mixture.

Figure 7 shows the substantial decrease in carburetor intake temperature at 12:1 compression ratio. These results are much more significant when considering the ambient temperature during these fuel tests. The tests conducted at 8:1 compression ratio were performed during the middle of the month of June with an ambient temperature of approximately 24°C. Tests performed at 12:1 compression ratio were conducted during the middle of the month of August with an ambient temperature of approximately 30°C. Thus, significantly higher ambient temperatures still provided for a 5-10°C

drop in intake air temperature following the carburetor. The low temperature readings at low load for ethanol fuels with low water content were close to the freezing point. Repeating the tests at temperatures much cooler than those attained during warm summer days would probably lead to carburetor icing. Year round operation using ethanol fuels would quite possibly require a controllable air preheater that would heat the air before entering the carburetor.

In addition to recording the intake air temperature following the carburetor, three temperature measurements were made after the fuel-air mixture passed through the intake manifold. A thermocouple detected the temperature between the intake manifold and combustion chamber of each cylinder. The primary purpose of this measurement was to determine the effectiveness of the water-jacketed intake manifold in providing adequate cylinder distribution of the air-fuel mixture. The drop in mixture temperature following the carburetor made a heat source essential for keeping the ethanol from condensing before it reached the combustion chamber. Our test results indicate that the heat exchanger method of heating the air-fuel mixture was adequate in keeping maldistribution from being a problem. For both 8:1 and 12:1 compression ratio tests, the temperature difference between cylinders for a certain load was usually within 5°C. Lower loads produced less variation in cylinder temperature than heavy loads. The increase in fuel consumption during heavy loads caused a greater variation in the intake temperature readings. Maximum load usually produced the greatest variation in cylinder temperatures, sometimes as high as 10°C.

Table 6 provides the average cylinder temperatures at the 8:1 compression ratio. The water content of ethanol fuels proved to be a

Table 6. Energy Consumption in KJ/sec at 12:1 Compression Ratio

Torque (N-m)	% Ethanol Fuel				
	100	95	90	85	80
0	26.17	25.76	25.25	27.86	26.60
19.78	36.78	35.39	36.08	37.88	36.22
131.88	48.57	47.27	48.17	50.91	47.73
197.83	56.12	54.66	55.60	56.32	54.52
263.77	64.37	62.27	61.97	66.34	62.06
329.71	70.27	69.22	69.40	71.15	77.91
395.65	78.52	75.27	76.82	83.58	79.98
Max.	N.T.	N.T.	81.70	86.39	--

very important factor. Gasoline intake cylinder temperatures increased with the increase in engine load, as did 100% and 95% ethanol fuels. Increasing water contents of ethanol fuel produced lower initial starting temperatures and a decrease rather than increase in cylinder temperature as the load increased. 90% ethanol produced near constant temperature readings throughout the entire range of loads. Table 7 contains the average cylinder temperatures at 12:1 compression ratio. A comparison with Table 5 shows that the initial no load starting temperatures for each fuel were similar for both compression ratios, but as the load was increased during the higher compression tests, a much higher drop in average cylinder temperature was the result. Every ethanol fuel produced a significant drop in cylinder temperature with increasing load. 90% ethanol fuel produced a temperature drop of 12.3°C from no load to maximum load at a 12:1 compression ratio.

D. Exhaust Temperature

Exhaust temperature measurement was performed in a similar manner to intake temperature measurement. A chromel-alumel high temperature

Table 7. Average Cylinder Temperatures at 8:1 Compression Ratio (°C)

Torque (N-m)	Gasoline	100	95	% Ethanol Fuel			
				90	85	80	75
6.10	64.1	56.7	63.8	62	60.9	56.0	54.1
40.68	64.4	56.8	62.1	61.9	61.1	55.6	53.3
81.36	64.5	57.5	62.0	61.4	60.3	54.9	51.5
122.04	64.7	57.2	62.6	60.9	59.7	53.1	50.6
162.72	66.2	57.2	63.5	61	58.9	51.3	48.3
203.40	67.4	57.6	64.5	61.5	58.9	49.7	46.9
244.08	69.1	58.4	66.5	61.9	57.6	48.3	46.9
284.76	71.1	59.9	64.8	62.8	56.2	48.8	47.3
325.44	76.1	61.6	62.5	60.2	54.0	48.7	48.0
Max.	79.0	63.0	64.8	62.0	54.8	50.4	51.1

Table 8. Average Cylinder Temperatures at 12:1 Compression Ratio (°C)

Torque (N-m)	100	% Ethanol Fuel			
		95	90	85	80
0	64.2	61.0	59.0	54.6	51.3
19.78	59.9	57.7	55.2	48.5	47.9
131.88	58.2	57.2	54.6	41.5	42.7
197.83	57.7	56.1	52.7	40.1	40.4
263.77	57.7	55.7	50.1	38.4	38.6
329.71	57.6	54.9	47.6	36.7	36.7
395.65	57.8	52.8	45.8	36.3	36.7
Max.	N.T.	N.T.	46.7	36.0	--

thermocouple was placed between the exhaust manifold and exhaust pipe and coupled to a date recorder. Lower exhaust temperatures were expected for the ethanol fuels since alcohol burns at a lower temperature than gasoline. As the water content of the ethanol became greater, it was felt that the cooling process of the water vaporization would create lower exhaust temperatures for the higher water content ethanol fuels.

Figure 8 shows that the difference in exhaust temperature between ethanol and gasoline was not great. At 8:1 compression ratio, ethanol



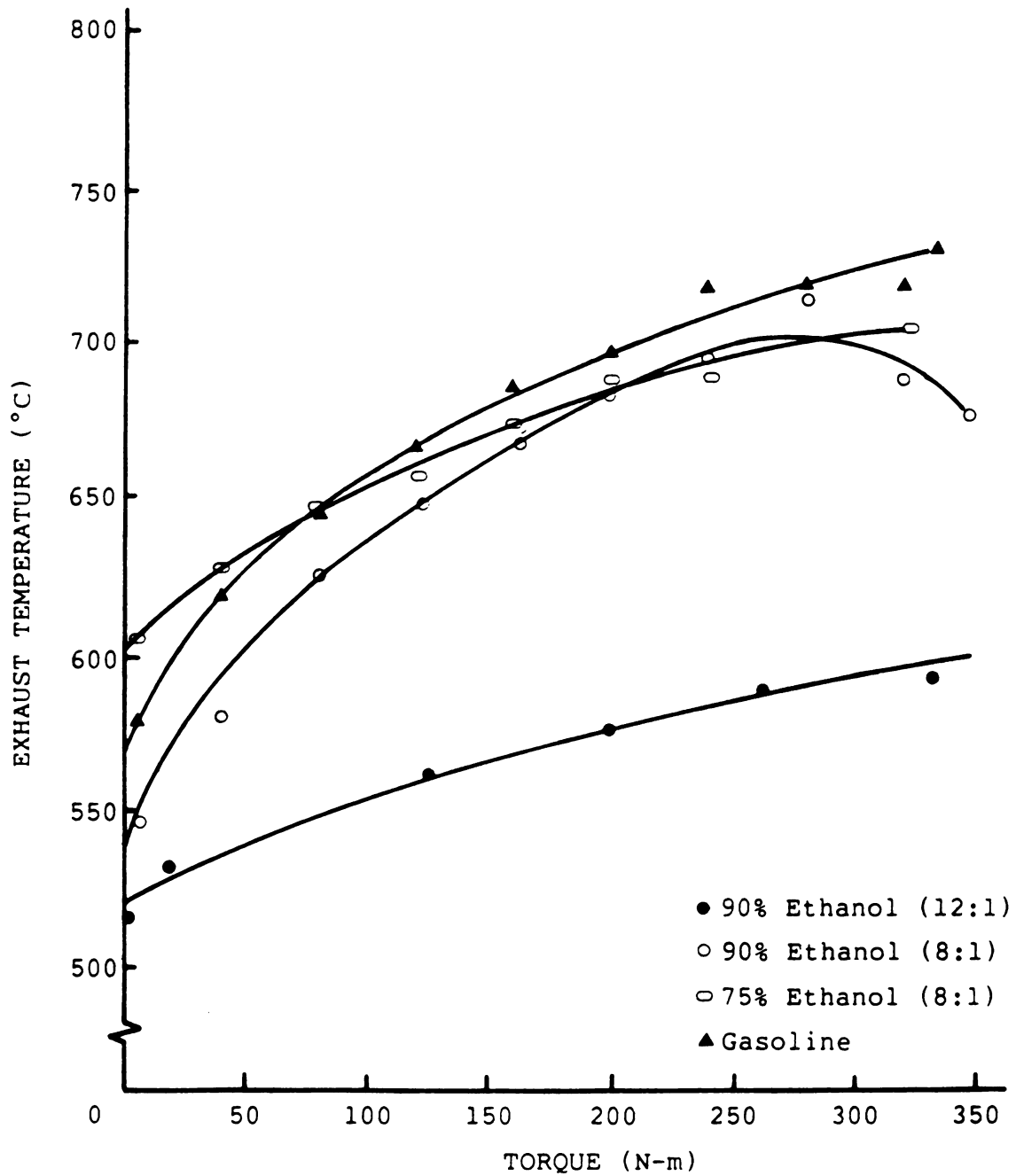


Figure 8. Exhaust temperature as a function of load for a Ford 2000 fueled with gasoline or ethanol/water solutions.



fuel with 15% or lower water content produced exhaust temperatures that were lower than gasoline at every load with an average decrease in exhaust temperature of approximately 20°C. As the ethanol water content was increased above 15%, the exhaust temperatures became greater and closer to gasoline values. The low load values for ethanol fuels with high water contents were actually higher than gasoline values for the same load. Higher loads produced temperatures with ethanol which dropped below the corresponding gasoline load value. This trend can be seen with the 75% ethanol fuel values on Figure 3. Ethanol fuels with higher water contents produced higher exhaust temperatures. This surprising result is most likely the product of incomplete fuel mixing and burning, similar to operating an engine on a lean air/fuel mixture which produced a hotter combustion temperature. Figure 8 also shows the effect that the higher compression ratio had on exhaust temperatures. A substantial decrease in exhaust temperature values resulted from the compression increases in the water content producing only slight differences in exhaust temperature values. These differences were generally slight increases in exhaust temperature rather than the expected decrease.

E. Ignition Timing

After a complete series of tests had been performed to record engine data at 12:1 compression ratio, a series of tests were performed to determine the effect of changes in ignition timing on engine performance. The standard ignition timing used for testing ethanol fuel mixtures was set at 4-5°BTDC at an idle speed of 600 rpm. The ignition timing tests consisted of operating the engine with 85% ethanol fuel and performing the standard power and fuel consumption tests at different ignition timings. Tests



were performed at idle speed ignition timings of 0°BTDC, 5°BTDC, 8°BTDC and 13°BTDC.

Fuel consumption figures remained quite stable throughout the tests; however, substantial changes in power output occurred. At 0°BTDC, severe engine surging at approximately 200 N-m torque prevented any measurements from being recorded. Also, the maximum power that could be attained was 24.6 KW, compared to the 25.36 KW of power produced at the idle speed ignition timing of 5°BTDC. The idle speed ignition timing of 8°BTDC achieved a maximum power output of 25.36 KW, but severe engine knocking prevented any measurement recording. Further ignition timing advancement to 13°BTDC caused severe engine knock and rapid engine shutdown when only 22.4 KW of power was produced. Thus, the engine performance results at the idle speed ignition timing of 5°BTDC proved to be optimal for both power and fuel consumption.

As mentioned in the test procedure, each fuel was tested at a given torque level for at least three test runs. The average of these values was used for the graphs and the tabled values. To determine the accuracy and reproductibility of these averages, the variance fuel consumption for a sample of torque levels from various fuels was calculated. Results of these calculations indicated that the normal for the gasoline and the 8:1 compression ratio ethanol tests was $\leq 3.0\%$. The variance in fuel measurements for the rebuilt engine tested at 12:1 compression ratio were significantly improved. The normal variance for these results was less than 1.0%.

F. Driveability

Perhaps the most important part of this research was an evaluation of the performance of the Ford 2000 tractor under normal, everyday usage. The tractor was driven under several different conditions at both 8:1 and 12:1 compression ratios. A wide variety of performance characteristics resulted from these conditions. The tractor was driven for a short time under the 8:1 compression ratio using 90% ethanol fuel during warm August afternoons with the temperature near 30°C. The air-fuel ratio was not controlled during this driving period. No driveability problems were apparent as a result of the ethanol. The idle speed was smooth and no hesitation during slow speed acceleration was observed. In fact, the acceleration rate seemed to be even better with the ethanol fuel than with gasoline.

Operation with the 12:1 compression ratio produced poor performance under some conditions. Cold weather operation caused a long delay, to allow engine warmup, before the tractor could be used. A 5-minute engine warmup was required when the temperature was approximately 15°C. Temperatures dropping to 0°C would probably require a 10-15 minute engine warmup period. Cold weather starting at 15°C was no problem with the propane starting fuel, but any change in engine speed before the engine was at full operating temperature produced a quick engine stall. The cold engine simply had to be left idling at a constant speed until it was at operating temperature. The colder the temperature, the longer this waiting period and the more propane utilized to keep the cold engine running.

Engine operation with no load at 12:1 compression ratio produced sig-



nificant hesitation upon fast acceleration from a slow engine speed. If the throttle was opened very slowly, the engine would stall. A rapid closing of the throttle would usually prevent stalling and allow a slower throttle opening. An average throttle opening from medium speed to high speed would often produce hesitation followed by rapid acceleration to the high speed. Wide open throttle operation with no load produced alternating surges and hesitations changing the engine speed by approximately 100 rpm.

The best engine operation occurred when a sufficient load was applied to the tractor engine. During the engine tests, 90% ethanol fuel was being tested with a load of 15 KW. The engine speed was reduced to 900 rpm before the throttle was quickly pulled wide open. No hesitation occurred and quick engine acceleration resulted. This exercise was repeated several times with the same result. No surging or hesitation was evident at wide open throttle. From this result, the most beneficial operation that could be performed with this tractor would be constant speed, high engine load field operations. A large percentage of the work performed on the farm, such as plowing, fits into this category. The tractor was used to windrow a field of cut hay. No difficulties were encountered in completing this task.

After all the engine tests were completed, the tractor with the 12:1 compression pistons was used at the beef cattle research barns for feed handling and other minor daily farm jobs. During cold weather, the farm workers found the lengthy engine warm-up and poor driveability to be unacceptable. The curtailing of the ethanol production from the farm still caused an inconsistent fuel supply. These factors led to the decision to replace the 12:1 compression pistons with 8:1 compression pistons and

operate the tractor on gasoline.

G. Problems Encountered

During the process of engine conversion and the subsequent operation with ethanol fuel, there were basically two types of problems encountered. One was the effects which ethanol had on the engine material and drive-ability of the tractor. The other deals with the mechanical problems that occurred during installation of the 12:1 compression pistons.

The materials compatibility problems would affect engine operation if nothing was done. Probably the most serious of these was the chalk-white creamy-like deposits which covered the bottom of the float bowl of the carburetor and seemed to be mixing with the fuel. Continuous operation with no removal of these deposits could lead to clogging of the main jet and eventual engine stalling.

A similar problem occurred with the fuel filter. After a few months of using ethanol, the paper filter element turned a dark brown color and needed to be replaced. It was not determined whether this was caused by impurities in the ethanol or by ethanol's reaction with the filter element. The solution to the latter would be replacement of the filter with one more suitable to ethanol.

Two other problems, which resulted from the 12:1 piston installations, were the residue found in the combustion chamber and the high level of oil dilution. The residue produced by the ethanol combustion was a sticky, brown, tar-like substance which coated the cylinder wall above the top compression ring travel, as well as the top of the piston and the face and seat of each valve. The only real harm these residues could produce is possible valve damage. Too much residue build-up on the valves may lead



to hot spots causing preignition and eventual valve destruction due to valve burning.

Severe oil dilution occurred with engine operation at the 12:1 compression ratio. The reason for this problem was eventually tracked down to bad valve timing, rather than bad valve seating or blowby past the piston rings. Installation of a different camshaft would curtail this problem.

The two major driveability problems that were encountered with ethanol fuel were cold starting and low speed hesitation and surging upon acceleration. The use of propane as a starting aid helped the cold starting problem considerably, but cold engine idling at constant speed was still difficult in less than 15°C ambient temperature. The idle speed would gradually decrease necessitating pulling the manual choke on and off until the engine reached operating temperature. Once the engine began to warm up, the idle speed became constant and the amount of propane needed for engine operation was slowly reduced to zero. Perhaps a better intake manifold or carburetor design would provide better mixture heating and distribution and reduce the amount of propane and time needed for engine warm-up. With the present fuel system, even after the engine was at normal operating temperature, severe hesitation occurred with acceleration. If the throttle was not opened at a very slow rate, the hesitation either stalled the engine or caused it to surge to a high speed before decreasing to the proper throttle speed. Again, better carburetion or a better mixture heating system such as intake air preheating could reduce the amount of hesitation experienced at warm-engine operation.

The second type of problem encountered was the mechanical problems associated with the 12:1 compression ratio piston installation. The first



problem originated from the poor initial condition of the tractor engine. Each cylinder was either badly tapered or out-of-round. To optimize the performance with ethanol and to obtain an accurate base to compare future measurements of engine wear, the decision was made to rebore the engine cylinders and fit the new pistons to new cylinder sleeves. After the resleeved cylinder block was assembled and the engine was operated for a short period of time the dark color of the engine oil indicted that the block had been improperly cleaned after the reboring job. Dirt and metal flakes were left in the oil passages and consequently quickly became embedded in the bearings and ruined them. This required the total disassembly of the engine to properly clean all the engine components and replace the bearings.

The second major mechanical problem was discovered during the short period of engine operation. A heavy knocking noise was noticed which turned out to be the pistons hitting the exhaust valves during the exhaust stroke. The conclusion was drawn that the manufacturing tolerances of the different engine components provided for too little piston-valve clearance. By milling .020 inch from the top of each piston, clearance was increased.

The final mechanical problem encountered required the most time and effort to solve. The 12:1 compression ratio pistons should provide a compression pressure in the 1850-2060 kPa range. Measurements obtained were roughly half the anticipated values. Poor valve seating and mixture blowby past the piston rings were considered as the most probable causes. After the valves were reseated and the piston-cylinder measurements were rechecked and confirmed by four different sources as giving a proper piston fit, the problem was finally narrowed down to improper valve timing. This timing problem was caused by the original engine design for the Ford 2000



model, in which a lower power rated model was developed from a higher rated power design by simply changing the camshaft. The stock camshaft of the Ford 2000 caused the valves to close much later than most gasoline engine designs. When the new pistons, which were stock Ford 3000 diesel pistons with the combustion chamber milled out to lower the compression to 12:1, were installed, the later valve closing caused some of the fuel-air mixture to be blown past the intake valve guides. This was the primary reason for low compressions readings and the main factor causing the oil dilution. The late valve closings were also the apparent reason for the valve-piston interference. A stock, Ford 3000 diesel camshaft was installed which increased the compression pressures to the anticipated range and cut down the amount of oil dilution considerably.

VI SUMMARY AND CONCLUSIONS

The results of this research reveal that a spark ignition engine can be adapted to operate on straight ethanol fuel with very few engine modifications. However, to achieve the year-round gasoline engine performance level with ethanol fuel requires more detailed and expensive engine modifications. Achieving adequate engine power is not a problem with ethanol fuel. Ethanol power output was consistently equal to or greater than gasoline fuel power output. The higher compression pistons produced a substantial maximum power increase over gasoline. Fuel consumption will always be greater for ethanol fuels due to the lower energy content of ethanol.

Ethanol water content is not a limiting factor for ethanol fuel use. Since 90% ethanol produced greater power, better thermal efficiency and only slightly less fuel efficiency than 100% ethanol, the best ethanol fuel for engine performance as well as economical value contains 10% water. Ethanol fuels containing less water are simply too costly to produce and the slight improvement in fuel efficiency does not offset the higher production costs. Engine deterioration problems do not seem to be a major obstacle for using ethanol as a fuel. Long run internal engine examination tests were not completed during this research, but many vehicles have been tested for long term ethanol fuel engine wear and have produced very positive results.

Indeed, the major problems in using ethanol fuel in a spark ignition engine converted from gasoline operation appear to be in the areas of materials compatibility and driveability. Materials compatibility problems may lead to costly engine modifications, especially in more modern farm

tractors. Many late model engine components contain complex designs utilizing materials which may be adversely affected by ethanol fuel. A fuel injection system is one area where ethanol may create severe problems. The simple engine design of the Ford 2000 provided few material compatibility problems.

The driveability of the Ford 2000 using 90 or 100% ethanol fuel was under many conditions unacceptable. Cold weather created serious problems which most farmers would not accept. High load, constant speed engine operation was adequate, but no load, multi-speed operation caused acceleration hesitation and surging which needed to be alleviated. More efficient and expensive carburetion systems as well as a controlled air preheating system may be essential for tractor performance that is acceptable to the operator at any temperature.



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