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Energy in Agriculture: The Use of Ethanol as an Unmixed Fuel for Internal Combustion Engines

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ENERGY IN AGRICULTURE

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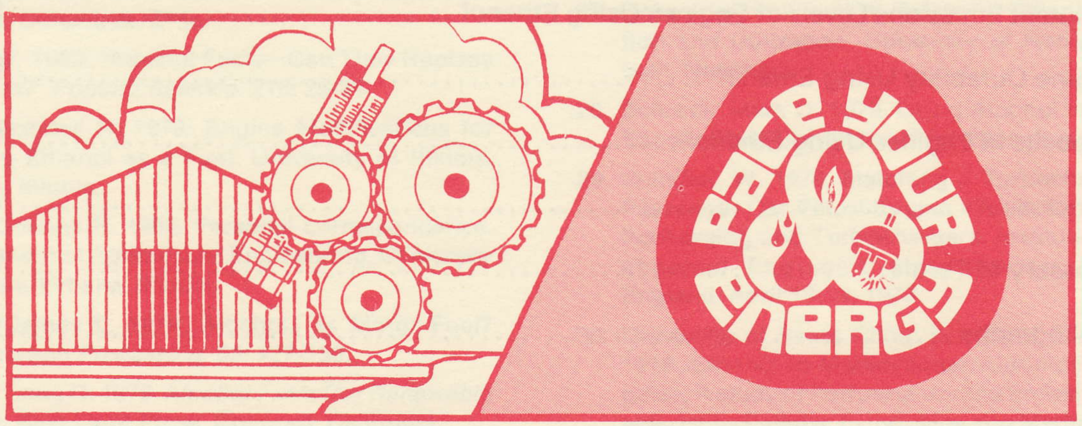

UNIVERSITY of KENTUCKY
COLLEGE of AGRICULTURE
DEPT. of AGRIC. ENGINEERING
COOPERATIVE EXTENSION SERVICE

in cooperation with

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Preface

A committee of the Agricultural Engineering Department, University of Kentucky, of which the authors are members, is investigating the feasibility of certain farmers becoming energy independent by producing their own engine fuel.

A part of this investigation concerns just how low a proof of ethanol can be tolerated by internal combustion engines from several aspects. Naturally, the lower the proof the easier the production will be.

This paper describes the results of a literature search on the effect of water dilution in ethanol on the combustion process in internal combustion engines.

CONTENTS

Introduction

The use of ethanol (ethyl alcohol) as a fuel for spark ignited (SI)* internal combustion engines has been evaluated and considered satisfactory since the early 1900s. Today due to the increasing cost of petroleum and the current world oil uncertainty, which may greatly affect the future availability of petroleum, some alternative fuels for internal combustion engines are needed. Ethanol is one of the fuels that has shown promise as a petroleum substitute. Today the country of Brazil has chosen a path of less dependence on petroleum by developing an ethanol fuel technology. In the spring of 1980, cars designed to run exclusively on ethanol were offered for sale to the Brazilian public. Brazil has also encouraged its citizens to use ethanol by making it available to the consumer at half the cost of gasoline.

This paper reviews the use of ethanol as an unmixed fuel for internal combustion engines. Anhydrous ethanol (no water present) is required when fuel mixtures are made with gasoline or diesel fuel. Presence of greater than 1.5% water in ethanol will cause separation of the ethanol from the petroleum fuel. On-farm production of ethanol will yield ethanol fuel with at least 5% water present or up to 50% water present. Thus, on-farm ethanol fuel production would necessitate adapting internal combustion engines for use of unmixed ethanol fuel.

Several basic fuel properties of ethanol in comparison to other conventional fuels need to be noted because of their effects on the use of ethanol as a fuel for internal combustion engines. Some of the fuel property comparisons are shown in Table 1.

Conventional hydrocarbon fuels (gasoline and diesel oil) contain 18,900 and 18,250 Btu/lb in comparison to ethanol, which contains 11,500 Btu/lb. In order to achieve equivalent engine power output for different fuels there must be similar energy input, as fuel. For example, pure ethanol contains 61% of the energy of gasoline per unit weight, therefore more pounds of ethanol are required than gasoline for equivalent engine power output. If an ethanol fuel contains water, which has no combustion energy, there must be an increased fuel rate to the engine to supply sufficient input energy.

Another important difference between conventional fuels and ethanol is the heat of vaporization. Ethanol requires 361 Btu/lb to volatilize, which is approximately 2.5 times the heat required per pound of gasoline or diesel fuel. Water has a heat of vaporization 2.7 times that of alcohol.

The auto-ignition property of a fuel becomes important for the type engine in which the fuel is used. The octane number measures the resistance to self-ignition while the cetane number measures the ease of self-ignition. Low auto-ignition properties (high octane number and low cetane number) are desirable for spark ignition engines. Ethanol and gasoline both indicate high octane and low cetane numbers. But diesel engines require a high auto-ignition value fuel (high cetane number, low octane number), which diesel fuel does possess.

Finally the air-fuel ratio to achieve the complete burning of the fuel (stoichiometric A/F ratio) is 14.7:1 for gasoline but only 9:1 for ethanol. This fuel property requires carburetor fuel-rate adjustments to achieve maximum engine efficiency.

Proof of Ethanol Tolerable by Internal Combustion Engines

The proof of alcohol tolerable by an internal combustion engine is one of the most important

Table 1.—Fuel Properties.

	Heat of Combustion Btu/lb	Density lb/gal	Heat of Vaporization Btu/lb	Octane Number	Cetane Number	Stoichiometric Air/Fuel Ratio
Gasoline	18,900	6.2	142	77-86	10-20	14.7
Diesel Fuel	18,250	7.3	115	10-30	45	15.0
Ethanol	11,500	6.6	361	89	20-10	9.0
Water	—	8.3	970	—	—	—

*Abbreviations are defined at the end of the publication.

factors that must be considered in the use of ethanol. Ethanol is concentrated during the distillation of a mixture of ethanol and water. Each time the mixture is distilled, its proof (two times the percentage content of the alcohol in the alcohol water solution) increases. Therefore, the lower proof (higher the water content) ethanol is cheaper to produce and economically more attractive as a petroleum substitute.

The use of ethanol in an internal combustion engine with a proof as low as 70 has been reported (Schrock, 1979). But in a test done on a 1947 Plymouth engine at wide open throttle (WOT) with the ignition, spark timing and air-fuel ratio carburetor adjusted for maximum power, and using hotter spark plugs than for normal gasoline operation, *it was found that as the proof of alcohol decreases, the horsepower and thermal efficiency decrease while the fuel consumption increases.* The results of this test are shown in Table 2 (Schrock, 1979).

Another test performed on an Oliver in-line six-cylinder engine with a heater for the air-fuel mixture showed slightly different results for the thermal efficiency. The results indicated that as water was added to 200 proof alcohol the thermal efficiency increased until the mixture was 180 proof, then decreased as increasing amounts of water were added. However, the power output of the engine was maximum at 200 proof (Deardorff, 1979).

These tests indicate that the higher proof ethanol is a more desirable fuel. But as before, the economics must consider more than just the cost of the fuel.

Lower proof ethanol also has caused some engine problems. Pure ethanol requires more heat per gallon for vaporization than gasoline or diesel fuel. Further, the lower the proof of the ethanol the more Btu of heat per gallon for vaporization are required because of the high heat of vaporization of water. Therefore, more heat is needed for the intake manifold (Hunt, 1979). In the two tests mentioned previously, the fact that the Oliver engine had a heater for the air-fuel mixture and the Plymouth engine did not, may have caused the discrepancy in the thermal efficiency results. Further, lower proof ethanol fuels (168 proof) have also produced starting problems (Hunt, 1980).

Oil dilution has also been reported during use of lower proof ethanol. In a test performed on the 1947 Plymouth engine, oil dilution was encountered when using 70 proof ethanol. At WOT the engine ran smoothly on 70 proof ethanol but was inconsistent in its operation. But under these same conditions running the engine for one hour resulted in the crankcase oil volume increasing from 6 to 8 quarts, due to the dilution of the oil by the alcohol and water (Schrock, 1979). Oil dilution can be overcome or greatly reduced by raising the cooling water temperature by changing thermostats (Deardorff, 1979).

Without heat addition to the fuel-air mixture, the temperature of the charge entering the engine cylinder is lower for ethanol or ethanol-water fuel than gasoline. This results in a denser fuel-air charge to the cylinder and a higher volumetric efficiency for an engine fueled with ethanol over gasoline.

Table 2.—Engine Performance on Various Proof Alcohol.

Proof	Brake Horsepower	Blend Consumption Gal/hr	Ethanol Consumption lb/bhp-hr	Thermal Efficiency[a]	Optimum Spark Advance
200	47.67	6.85	.944	21.2	17.5
190	46.18	7.53	1.029	19.4	20.4
180	46.67	7.94	1.042	19.2	21.3
160	45.07	9.52	1.127	17.8	27.0
140	45.58	11.33	1.162	17.2	29.0
120	43.60	12.90	1.207	16.6	33.0
110	42.00	14.53	1.278	15.6	35.0
100	42.94	19.00	1.490	13.4	36.0
90	42.35	17.90	1.277	15.6	41.5
80	41.40	20.87	1.341	14.9	47.0
70	34.10	26.70	1.853	10.8	50.0

[a]Higher heating value used by this study (Duck et al., 1945) to calculate thermal efficiency.

One interesting fact about the lower proof ethanol is that it *may* be able to withstand greater increases in the compression ratio than the higher proof (Hunt, 1980). If this is true the power output and the engine efficiency would be increased for the lower proof ethanol.

Ethanol is more suitable for use in spark ignition engines than in diesel engines because of ethanol's high octane number (the octane number and the cetane number are inversely related). The cetane number of ethanol can be raised by the use of additives. Amyl nitrate is an additive that is popular in the United States. A 1.5% mixture of amyl nitrate in ethanol increases the cetane number of ethanol by 15 points. However, no reports on the performance of a diesel engine using ethanol and amyl nitrate have been found (Schrock, 1979).

Cyclohexanol is an additive that is popular in Europe. When it makes up 10% of a mixture with ethanol, the cetane number of ethanol is comparable to that of diesel fuel. A diesel engine can be run on this mixture with no major changes to the engine (Schrock, 1979).

Mechanical Modifications Required for Use of Ethanol as a Fuel in a SI Engine

When gasoline that contains more than 25% ethanol is used in a SI engine, some modification must be made to the engine (Flowers et al., 1979). This of course includes ethanol-water blends that contain no gasoline. The modifications depend on the engine and what is required of the engine.

But before mechanical modifications are undertaken on an engine, a choice must be made as to the ease of reversibility of the engine changes. This choice must be based on the availability of alcohol fuel for all anticipated vehicle uses, the cost of the engine modifications, and the expertise required to make the engine changes.

Reversible Modifications

The first types of engine modification that will be discussed are reversible. The cost is a few hundred dollars or less depending on the modification undertaken. As implied, these modifications can be undone with relative ease to permit operation on conventional fuels. These modifications include:

1. changing the spark timing,
2. changing the vacuum advance,
3. modifying the carburetion for increased fuel flow,
4. heating the air-fuel mixture to ensure the vaporization of the alcohol, and
5. using various methods to enhance the cold-starting ability of the engine.

Spark Timing

As a general rule the spark timing of an engine must be advanced to run on ethanol. This is done to provide the ethanol with enough time to complete combustion, since ethanol burns slower than gasoline. One study recommended advancing the timing approximately 20° (Flowers et al., 1979).

In another study, done recently in the United States, a 1979 Ford Fiesta was modified to run on ethanol (ADM Corp., 1980). In this test the ignition timing was changed from 12° to 6° BTC. The ignition also was reduced on a four-cylinder, 1.6 liter engine used in a test on ethanol in Brazil (Paul, 1979). The ignition time, before BTC, was reduced in the latter two tests because of the differences in the modifications done to the different engines.

The spark timing of an engine operating on ethanol can be set two different ways. A tachometer can be hooked up to the engine and the timing adjusted until the maximum RPM reading is found with the engine on fast idle. Another way to set the timing is to start with an advance in the ignition timing of 4° BTC (Mingle, 1979). Then use a stop watch to determine the time it takes for the vehicle to accelerate from 30 to 55 mph in high gear at full throttle. This procedure is repeated in 4° of advance increments until the minimum acceleration time is reached.

From the different changes made in the spark timing in the tests reviewed and the procedures used to set the timing, *it can be seen that there is no general rule about setting the spark timing for all engines using ethanol as a fuel. The correct setting of the timing depends on the engine and the other modifications done to the engine. It must be determined by experiment.*

Vacuum Advance

Changing the setting of the vacuum advance is another reversible modification. The vacuum advance affects the fuel economy of the engine operating on ethanol. From Figure 1, (Chui et al., 1979) it is shown that the best fuel economy on the engine tested occurs when the vacuum advance is set to give an additional 10° of advance over the idle ignition time.

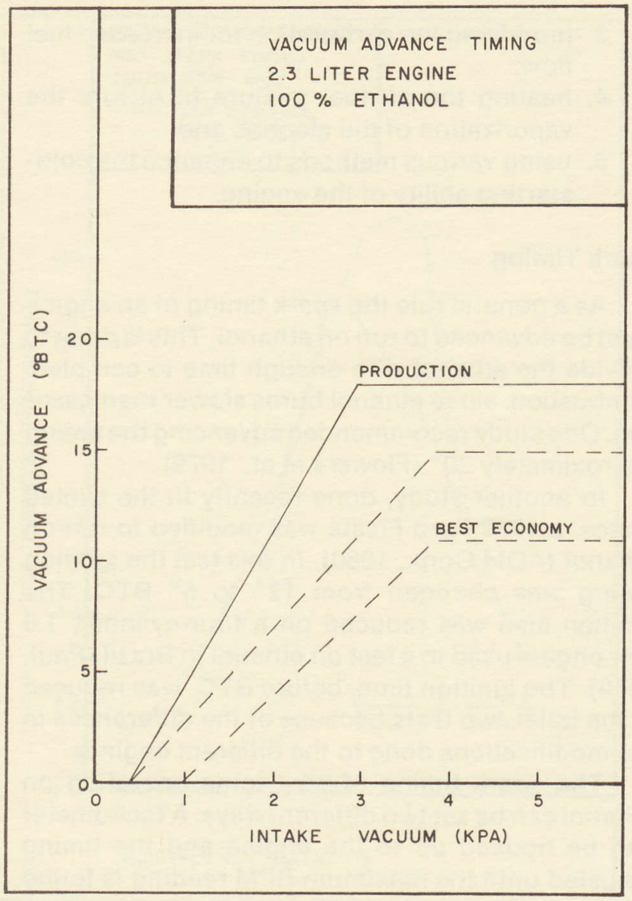

Fig. 1.—For the SI engine using ethanol as fuel, the optimum spark advance for economy is found to be below the production vacuum advance over the full range of engine in the vacuum that is related to engine RPM.

Carburetor Modifications

In all of the tests reviewed *the engines required more volume of fuel when operated on ethanol as compared to operation on gasoline.* The correct stoichiometric air-fuel mixture for ethanol is 9:1, while the correct mixture for gasoline is 14.7:1 (Hunt, 1979). The reason for the differences in the ratios is that ethanol has a lower energy content per volume than gasoline.

The fuel-flow increase is achieved by modifying the carburetor. The general procedure for the fuel-flow increase is to enlarge the carburetor fuel jet diameter 1 1/2 times. This can be done by drilling out the original jet or replacing the jet. However, one recent study (Engleman, 1980) showed different results. In using a single-cylinder engine, adjustment of the carburetor float will increase the flow of ethanol. Increased flow was achieved because of increased liquid head as well as the differences in vapor pressure, surface tension and viscosity of ethanol as compared to gasoline.

Table 3 shows these results using an arbitrary scale for the float level at different RPMs and proofs of ethanol. In this test an increase in jet size of 10 to 15% was sufficient, but *the conclusion reached was that the actual jet size needed in the carburetor must be found by experiment.*

Adjusting the carburetor also adjusts the equivalence ratio, that is,

$$\frac{\text{actual air/fuel ratio}}{\text{stoichiometric air/fuel ratio.}}$$

The equivalence ratio affects the fuel economy, thermal efficiency and power output of the engine. Figure 2 (University of Santa Clara, 1978) shows that the fuel economy of an engine operating on 200 proof ethanol is best when the equivalence ratio is approximately .8, which is in the lean region. Figure 3 (University of Santa Clara, 1978) shows that this is approximately the same equivalence ratio for maximum thermal efficiency. The power output of an engine is also greater when the equivalence ratio is the lean region (<1.0). However, *it should be noted that running an engine on too lean a mixture*

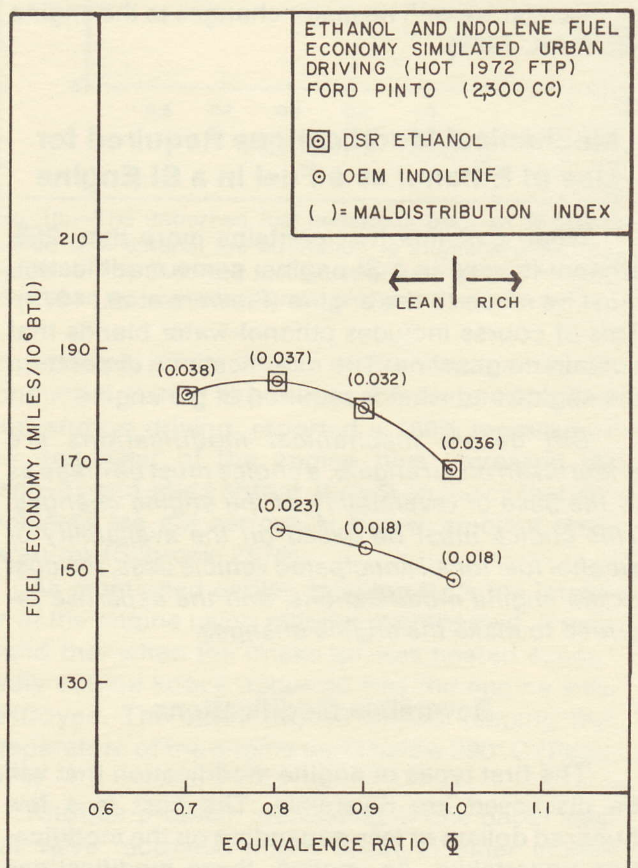

Fig. 2.—The fuel economy for an SI engine utilizing ethanol is higher than one using indolene (a standard gasoline mix) over all tested equivalence ratios under simulated urban driving conditions.

Table 3.—Effect of Carburetor Float Adjustment on Fuel Flow.

Carb Float		Indolene	190 Proof	180 Proof
		900 RPM		
	Fuel lb/hr	2.601	3.404	4.291
1.0	A/F	11.79	8.93	9.18
	IHP	3.47	4.51	4.20
	Fuel lb/hr	2.484	2.984	2.874
2.0	A/F	12.44	10.27	10.60
	IHP	4.93	3.91	3.45
	Fuel lb/hr	2.270	2.678	(Rough running and misfiring)
2.6	A/F	13.50	11.54	
	IHP	3.55	2.30	
		1,200 RPM		
	Fuel lb/hr	2.829	4.513	4.155
1.0	A/F	12.72	8.09	8.50
	IHP	6.41	5.93	5.45
	Fuel lb/hr	2.516	4.105	3.863
2.0	A/F	14.30	9.10	8.90
	IHP	6.43	5.58	7.17
	Fuel lb/hr	2.410	3.862	3.749
2.6	A/F	14.75	9.67	9.29
	IHP	6.43	5.79	4.78
		1,500 RPM		
	Fuel lb/hr	2.996	4.947	4.884
1.0	A/F	13.12	8.18	8.45
	IHP	6.39	6.55	6.01
	Fuel lb/hr	2.811	4.728	4.622
2.0	A/F	14.05	8.71	9.23
	IHP	6.50	6.33	5.67
	Fuel lb/hr	2.411	5.547	4.476
2.6	A/F	16.47	8.97	9.53
	IHP	6.23	6.08	5.57

can result in burnt valves. A lot of practical experience attests to this conclusion. Running an engine on a rich mixture still does not eliminate the advantage of ethanol over gasoline for thermal efficiency and economy as seen in Figures 2 and 3.

Preheating Air-Fuel Mixture

As mentioned previously, heating the air-ethanol fuel mixture requires 2.5 times more heat for vaporization than does gasoline. For this reason some additional heat may be desirable for the air-fuel mixture before it enters the cylinder. Two of the tests reviewed used some additional heat and two did not.

In a test performed in 1948, a gasoline tractor was modified to run on 95% ethanol (Meyer, 1948). In this test the exhaust gases were recycled to provide the extra heat in two different ways. In one part of the test the recycled exhaust gases were mixed directly with the intake air. The other method used was to heat the intake air with the exhaust through a heat exchanger. This second method seemed to be more satisfactory.

In another test from Brazil the exhaust gases were also recycled to provide more heat for the intake air on a four-cylinder, 1.6 liter engine (Paul, 1979). However, in this test it was shown that

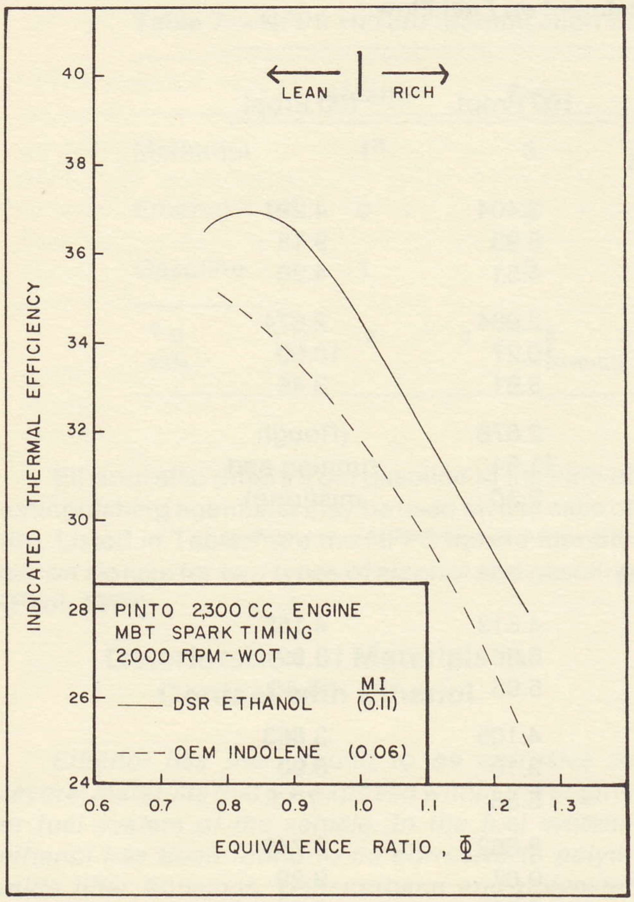

Fig. 3.—The indicated thermal efficiency of an SI engine using ethanol is higher than one using indolene (a standard gasoline mix) over all tested equivalence ratios at WOT of 2,000 RPM.

problems can result from excessively preheating the intake air. In the early tests the intake air was excessively preheated, causing severe engine knock, resulting in the destruction of the engine.

Cold Start Modification

One of the main problems in using ethanol in an engine is low temperature. This problem arises from the fact that ethanol requires more heat for vaporization than gasoline. *Saturated ethanol vapors are too lean to ignite below 50°F and starting problems become significant below 40°F (Keller, 1979).*

The cold-start problem with ethanol can be overcome in several different ways. First is the use of additives. In one test it was found that the addition of 10% gasoline to 200 proof ethanol extended the cold-start ability from the original 40°F down to 32°F (Chui, 1979). Another additive that reportedly has good results in overcoming cold starts is ether (Keller, 1979). There is commercially available an ether injection system for diesel engines (Hill, 1980).

Another simple cold-start system has been used. This system is shown in Figure 4. It consists of a secondary gas tank for gasoline (the starting fuel), a secondary electric fuel pump, and a toggle switch to engage the cold-start system and needle valves to completely shut off the cold-start system. Volkswagen has come up with a similar cold-start system.

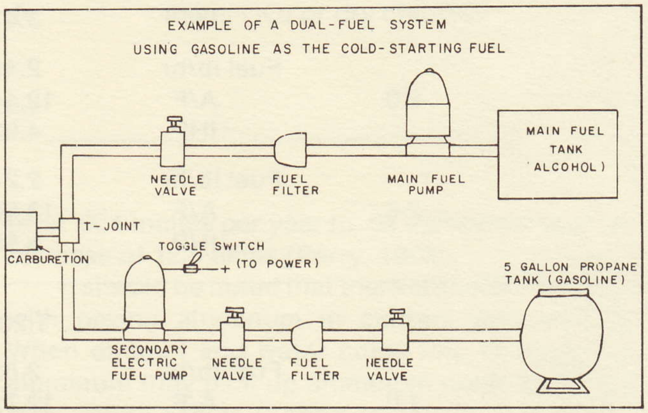

Fig. 4.—This is a diagram of a dual-fuel system using gasoline as a cold-starting fuel. The system requires a separate storage tank, fuel pump and fuel filter.

Other methods that have been used to overcome the cold-start problem include using a 350 watt resistance heater in the intake manifold (Schrock, 1979); using electric glow plugs in the manifold (Hunt, 1979); or using an electric screen grid between the carburetor and intake manifold to heat the air-fuel mixture (Hill, 1980). This last system is shown in Figure 5. Whenever cold-start problems are encountered, the driver turns on the key for 30 seconds to let the grid warm up. Then the car is started as usual.

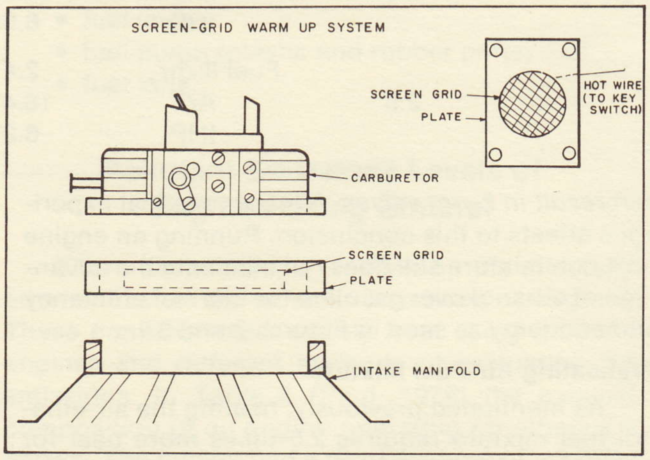

Fig. 5.—This is a diagram of a cold-start system that uses a grid of heater wire to heat the air-fuel mixture after it leaves the carburetor and before entering the intake manifold.

Another problem encountered with ethanol at very high temperatures was vapor lock. In one study it was found that vapor lock in the fuel pump became a problem at temperatures above 173°F (Keller, 1979).

Irreversible Modifications

Modifications that are irreversible are ones that are hard to remove. *They also are usually more expensive, require more expertise, and can be very hazardous when the engine fails.* Modifications in this category include:

1. camshaft change,
2. increasing the engine compression ratio, and
3. using turbochargers or superchargers.

Camshaft Change

In the study on the 1979 Ford Fiesta (ADM Corp., 1980) the camshaft was changed. According to the study this was done to provide more low RPM torque, easier starting and better fuel economy. The details of this change and the other modifications made are shown in Table 4.

Table 4.—1979 Ford Fiesta Specifications.

	Original	Modified
Primary Fuel	Unleaded Gasoline	Ethyl Alcohol*
Bore	3.188	3.000
Stroke	3.056	3.056
Total Cubic Inch	97.6 (1,600cc)	86.4 (1,416cc)
Compression Ratio	8.6:1	12.5:1
Cam Timing		
Intake:		
Open	29° (Before TDC)	16°
Close	63° (After BDC)	54°
Exhaust		
Open	71° (Before BDC)	54°
Close	21° (After TDC)	16°
Ignition Timing (static)	12° (Before TDC)	6°

*180 proof (90% ethyl alcohol: 10% water) or 200 proof ethyl alcohol. Other ratios may also be tried.

It is interesting to note that even though the ignition timing was retarded in this test, there is still more time for combustion to take place with the ethanol. This extra time is needed because ethanol burns slower than gasoline. The original engine cylinder has 121° for combustion and expansion to take place, while the engine modified to run on ethanol had 132° for combustion and expansion to take place.

Change in Compression Ratio

In all of the tests reviewed, the compression ratio was increased to take advantage of the high octane rating of ethanol to produce more power. One study suggested increasing the compression ratio to somewhere between 10 to 15:1 (Flowers et al., 1979). Two of the studies reviewed followed this recommendation. The study on the Ford Fiesta (ADM Corp., 1980) increased the compression ratio from 8.6:1 to 12.5:1. The Brazilian study (Paul, 1979) increased compression ratio from 7.2:1 to 11.1.

The study performed on the tractor in 1948 (Meyer et al., 1948) did not follow this recommendation. Rather, the compression ratio was increased from 6.4:1 to 7.35:1. The reason for this relatively lower compression ratio was that all engine compression ratios at that time were much lower than those of today.

The compression ratio can be increased several different ways. They include installing different pistons, shaving the head or using a thinner head gasket. Even though some of these modifications are easy and inexpensive to do, one thing must be emphasized. *The increase in compression ratio can damage or even destroy an engine if the other parts of the engine are not strong enough to handle the increased power or cylinder pressures.*

All of the tests mentioned previously increased the compression ratio to take advantage of ethanol's high octane rating to increase the power output of the engine. Another way to take advantage of the high octane rating of ethanol to increase the power output of the engine is to raise the compression pressure of the engine by turbocharging. Table 5 shows the theoretical equivalent compression ratios for different increases in the air pressure (Goering, 1979).

Table 5.—Equivalent Compression Ratios of Turbocharged Engine.

Actual compression ratio	Equivalent compression ratio at boost pressure of: 5 psi	10 psi	15 psi
7	8.8	10.4	12.0
8	10.0	11.9	13.7
9	11.3	13.4	15.5
10	12.5	14.9	17.2
11	13.8	16.4	18.9
12	15.0	17.9	20.6

A turbocharger uses exhaust gases to drive a turbine connected to another turbine that forces outside air through the carburetor. The air that is forced through the carburetor causes an increase in the combustion pressure. One drawback of the turbocharger is that the exhaust does not have enough power to effectively run the system until a relatively high engine RPM is reached, usually 2,500 to 3,000 RPM (Lynch, 1979).

Supercharging overcomes the turbocharger drawback. A supercharger operates on the same principle as a turbocharger but instead of being driven by the exhaust gases, it runs off the engine using a belt-drive mechanism. Therefore, the supercharger operates at all RPM levels.

There are drawbacks in using a turbocharger or supercharger to increase the compression pressure in order to increase power. One is the cost. The kits currently available commercially range in price from $600 to $1,200 (Lynch, 1979). This makes the turbocharger or supercharger a major investment.

The other drawbacks of these units are mechanical. The increase in cylinder pressure during combustion may cause increased wear on many engine parts. However, in one test performed on a four-cylinder engine, it was found that as long as the pressure increase was kept moderate (overall pressure of 55 to 60 bars) no harm was done to the bearings, push rods or crankshaft (Spindler, 1978).

In addition to the increased pressure there is an increase in the heat needed to be dissipated from the engine. The test mentioned previously (Spindler, 1978) used a special, steel cylinder head gasket, increased the valve stem clearance to avoid burnt or sticking valves, and modified the cooling system to avoid problems with the cylinder head cracking. It has also been found that using bronze valve guides overcame the valve problems (Lynch, 1979).

The high amount of heat dissipated from the exhaust manifold also caused problems (Spindler, 1978). Initially the increase in heat caused both the exhaust manifold and the tubing used to recycle the exhaust to crack. This problem was overcome by modifying the exhaust manifold and tubing. Even though there are several mechanical problems with using turbochargers or superchargers, they all can be overcome as they were in this test.

One fact worth mentioning is that the fuel used in the previously mentioned test was gasoline. Figure 6 (Pyre, 1937) shows that alcohol (195 proof) as compared to gasoline, gives more heat to the exhaust and less heat to the cylinder walls (cooling water) when run in an engine without turbocharging or supercharging. From this it might be concluded that operation on alcohol might decrease the problems caused by the increased heat entering the engine, while increasing the problems caused by the increased heat leaving the engine.

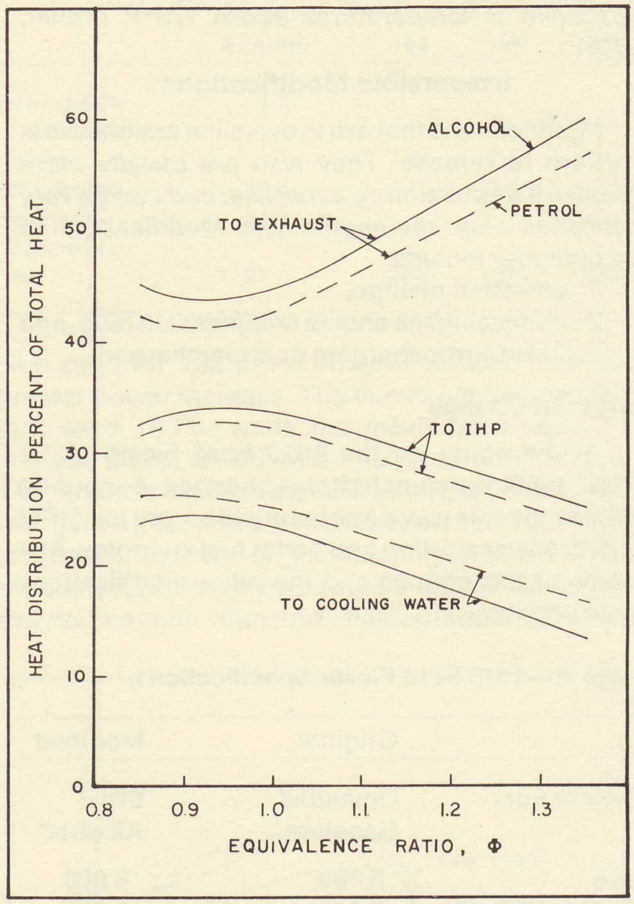

Fig. 6.—Heat distribution in an SI engine using ethanol or gasoline. A higher percentage of heat is found in the exhaust and in engine horsepower, but a lower percentage of heat is found in cooling water when fueled with ethanol over all equivalence ratios.

Again, as with the compression ratio increase, if the parts of the engine are not strong enough to handle the increased power, the engine may be damaged or destroyed.

Mechanical Modifications Required for Use of Ethanol as Fuel in a Diesel Engine

As mentioned before, the diesel engine is not well-suited to the use of ethanol. But, four basic approaches to using ethanol in a diesel engine have been found:

1. convert diesel engine to a high compression, spark ignition engine,
2. modify the diesel to tolerate straight ethanol injection,
3. carburet the ethanol, and
4. use dual injection of ethanol and diesel fuel.

One engine that lends itself to this conversion to spark ignition is the 855 Cummins Diesel Engine (Schrock, 1979). The areas that require modification include the pistons, head assembly, intake manifold ignition system, carburetor and governor. Parts are available for the conversion, but the estimated minimum cost for the modifications is $3,000.

A multifuel engine, developed for the military, is designed to function using fuels ranging from diesel oil to low octane combat gasoline. The MAN Diesel (also known as the Meurer or Whisper diesel) has a unique combustion chamber design to function smoothly using low cetane fuels and low octane gasoline (Schrock, 1979). This diesel engine design could be the most tolerant of manufactured engines to use ethanol without modification. This engine was offered for limited agriculture use by International Harvester and White in the last 10 years, but it is not presently available.

Another way to use ethanol in diesel engines is to carburet ethanol into the air intake in front of the turbocharger (Schrock, 1979). A kit to do this will soon be commercially available by M & W Gear Company, Gibson City, Illinois. This system uses the turbocharger boost to pressurize the alcohol fuel tank in order to meter the fuel as a function of engine load. The alcohol fuel is not added at low load. Research has indicated reduced engine efficiency at light load, but increased thermal efficiency over diesel fuel may occur only at heavy loading. In general though, it should be assumed that carburetion of alcohol into a diesel engine replaces diesel fuel on an equal heat content basis with no change in efficiency (Schrock, 1979).

There was a development of an alternative diesel engine with dual injection during WW II in which the main fuel, a low cetane rated fuel, is injected with the air into a diesel and a pilot fuel, a high cetane fuel, is injected near the end of the compression cycle that ignites, from compression heat, the total fuel mixture (Bro et al., 1977). See Figure 7. The low cetane main fuel makes up approximately 70 percent of the total fuel energy. Research efforts have utilized only 200 proof ethanol as a main fuel, but there seems to be no limitation of using an ethanol fuel that has a lower proof.

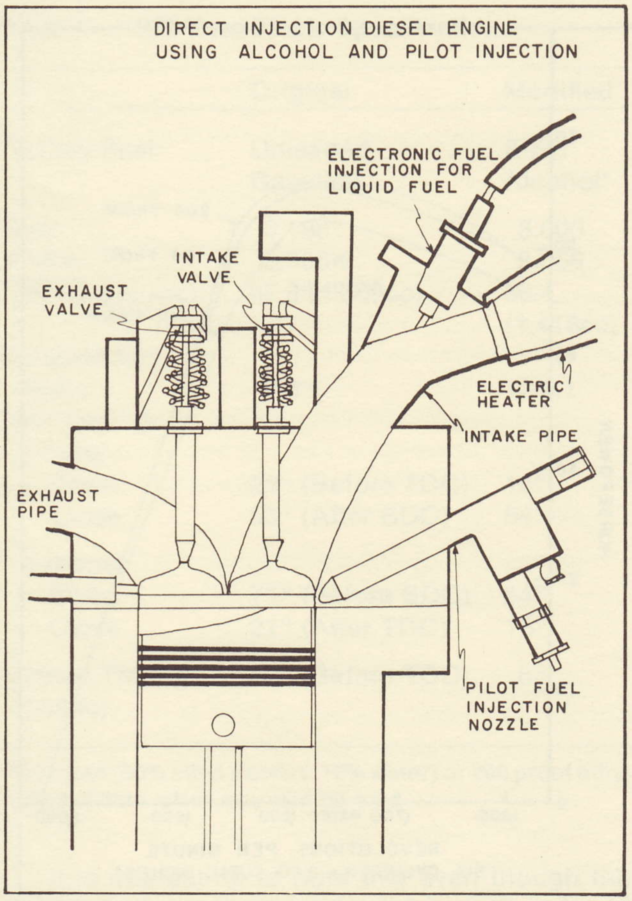

Fig. 7.—Dual injectors fuel a diesel engine. One injector puts in 30% of fuel energy as a high cetane fuel that ignites due to heat of compression, and then a second injector puts in the remainder of fuel energy as low cetane fuel.

Comparison of Engine Performance on Ethanol and Conventional Fuels

Fuel Economy

The volumetric fuel economy of SI engines using ethanol as a fuel is not as good as that of the same engines operating on gasoline. The major reason for this is that ethanol does not contain as much energy per unit volume or per unit weight as gasoline. Pure ethanol (200 proof) contains 65% of the energy per unit volume and 61% of the energy per unit weight when compared to gasoline (Schrock, 1979). Therefore, when compared to gasoline, more ethanol is required to do the same work in an engine.

The above is confirmed in all of the studies reviewed. But different tests give different results depending on the engine and the modifications of the engine. In a test performed in Brazil, it was found that volumetric fuel consumption was 5 to 10 % higher for 200 proof ethanol as compared to gasoline (Mueller, 1978). Another test, of which the results are shown in Figure 8 (Mueller, 1978), shows that the specific energy consumption in terms of Btu per gallon is about 12% lower in a low compression engine and 15% lower in a high compression engine for ethanol as compared to gasoline. This implies that higher compression ratio engines are more efficient in using the higher octane value of 190 proof ethanol.

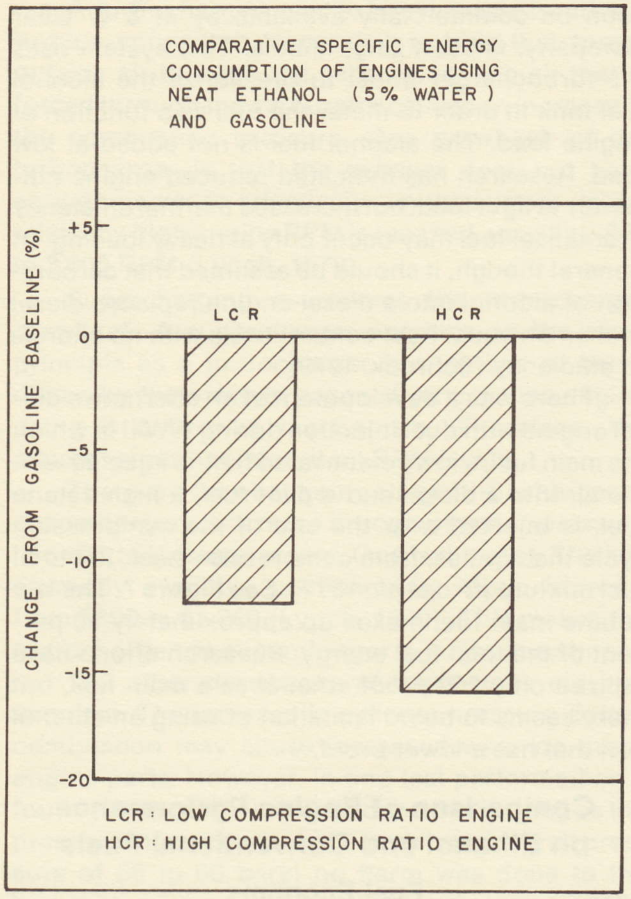

Fig. 8.—The comparison of the specific energy consumption of high compression and low compression SI engines show that the ethanol-fueled engines require less energy than gasoline-fueled engines. The high-compression engine requires less energy than the low-compression gasoline engine.

As the proof of ethanol increases the volumetric fuel economy improves. As expected, this is due to the fact that increasing the proof increases the volumetric energy content of the ethanol. Table 6 (Hunt, 1980) indicates this in terms of the range of a vehicle operating on ethanol as compared to gasoline. A fuel tank that would carry a vehicle 200 miles on gasoline would go 135 miles on 200 proof ethanol, 95 miles on 160 proof ethanol and 60 miles on 120 proof ethanol (Schrock, 1979).

Power Output

The power output of ethanol was greater in all of the tests reviewed when compared to gasoline. One study, which compared 190 proof ethanol and gasoline, showed a 3% increase in power output for ethanol at the same compression ratio (Schrock, 1979).

Another study that used 7.2:1 compression ratio for gasoline operation and an 11:1 compression ratio for 192 proof ethanol showed an even greater power increase. The maximum horsepower increased 18.7%, while the maximum torque increased 20.5% on ethanol operation (Paul, 1979). The increase in power gained from ethanol is shown in Figure 9 (Hunt, 1980) as a function of RPM. In this test the six-cylinder engine running on ethanol had the compression ratio increased from 7.5:1 to 8.45:1, a reworked carburetor and a heated intake manifold.

Table 6.—Fuel Efficiency of a Six-Cylinder Engine.

	Gasoline (Original Engine)	Ethanol Proof 164	186	200
Fuel, gal/hr (at maximum power)	4.3	7.44	7.4	6.3
HP—hr/gal	11.7	7.13	7.6	8.82
Thermal Efficiency, %	27	26%	25%	27%

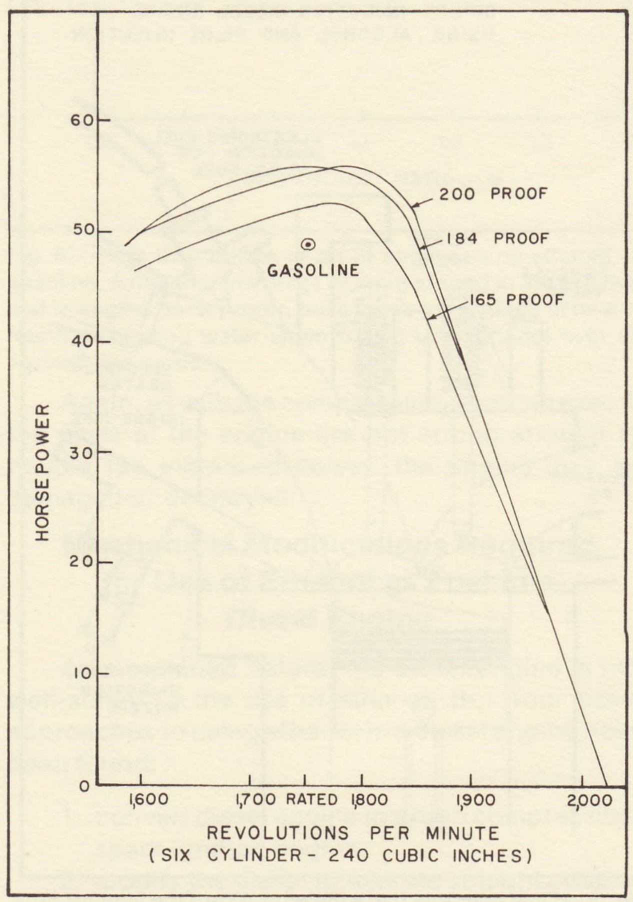

Fig. 9.—The indicated horsepower of an SI engine indicates that the ethanol fueled engine at all proofs was higher than the gasoline engine at the rated RPM.

Figure 10 (University of Santa Clara, 1978) shows the horsepower as a function of equivalence ratio for both gasoline and commercial grade ethanol. The engine operated on ethanol used the Deresserator Induction System. Ethanol fuel gave greater brake horsepower in comparison to indolene (a standard gasoline).

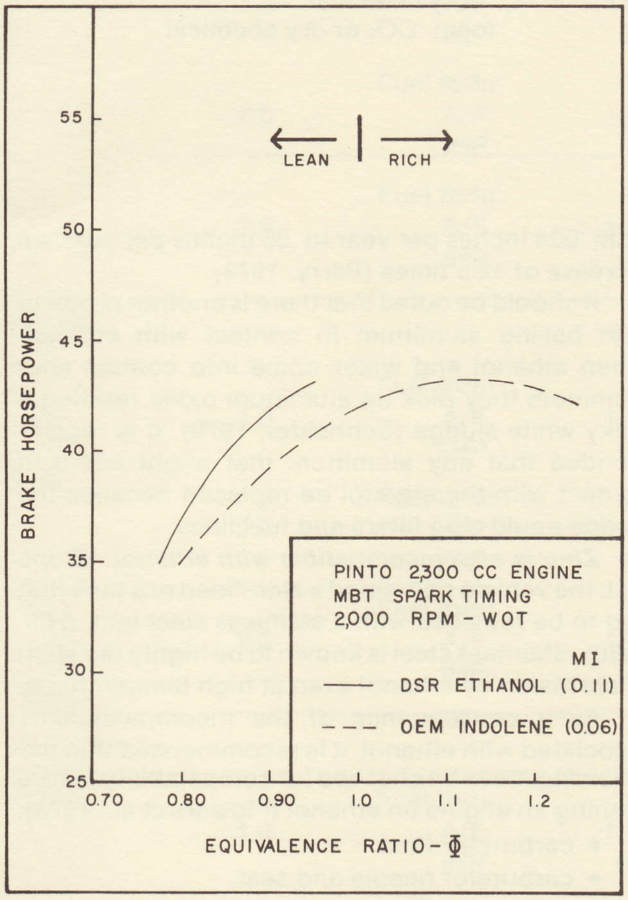

Fig. 10.—The brake horsepower of an SI engine fueled with ethanol is higher than engines fueled with indolene over the tested equivalence ratios at 2,000 RPM.

In Figure 11 (Mueller, 1978) the percentage power increases are shown for both a high compression ratio engine and a low compression ratio engine operating on 190 proof ethanol as compared to gasoline. The engine operating on ethanol had modifications on the carburetor and ignition system.

Safety in Handling Ethanol

Ethanol is not highly toxic but some discomforts have been known to occur if the fumes are inhaled for a long period of time in a poorly ventilated area (Mueller, 1978). The discomforts associated with prolonged inhalation include coughing, eye irritation and headaches.

The storage of ethanol must be handled differently from that of gasoline. For maximum safety and to reduce losses during storage, ethanol should be stored in white tanks in a shaded area. The tanks should be equipped with pressure-vacuum relief filler cups. No rubber hoses or seals should be used within the system in order to avoid leaks caused by the deterioration of rubber when in contact with ethanol (Rider et al., 1979).

Ethanol is totally different from gasoline in that it does mix with water. For this reason ethanol should never be stored in a tank where there is any water or there exists a possibility of water coming into contact with the ethanol. This also includes prolonged exposure to high humidity air.

Ethanol burns with a nearly invisible blue flame, while gasoline or diesel burns with a highly visible yellow or orange flame. Sometimes the only detectable feature of burning ethanol is the heat waves.

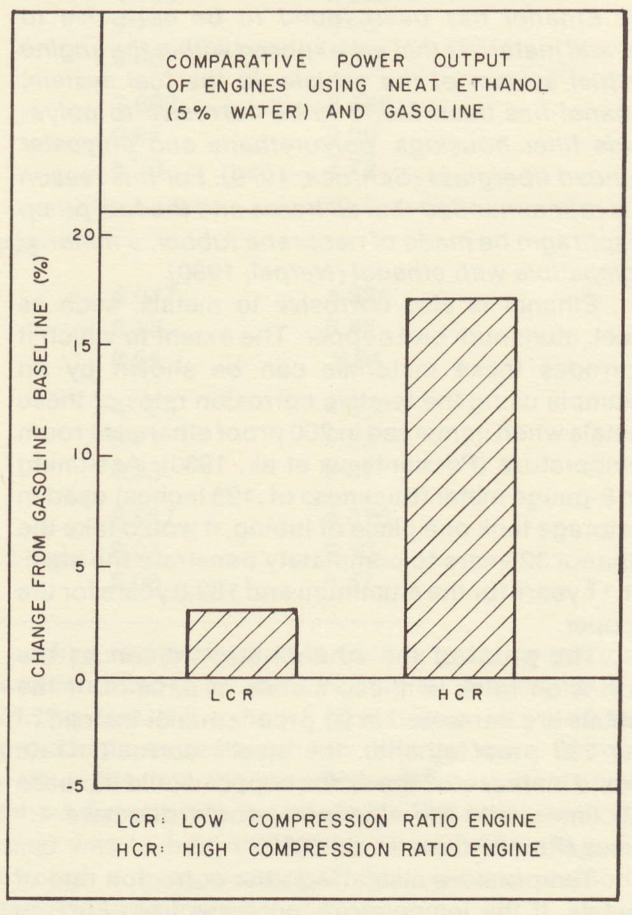

Fig. 11.—The comparative power output of a high and a low compression engine fueled with ethanol is higher than when fueled with gasoline.

Table 7.—NFPS Hazard Identification Signals.

	Health	Fire	Reactivity	Extinguish Agent
Methanol	1[a]	3	0	alcohol foam, CO_2 or dry chemical
Ethanol	0	3	0	water, alcohol foam, CO_2 or dry chemical
Gasoline	1	3	0	foam, CO_2 or dry chemical

[a] 0 safe 1 2 3 4 severely hazardous

Ethanol also differs from gasoline in the kind of extinguishing agent that may be used on it in case of fire. Listed in Table 7 are the NFPS hazard identification signals for two types of alcohol and gasoline (Paul, 1979).

Deterioration of Materials in Contact with Ethanol

Ethanol has been found to be corrosive to several materials that are exposed within the engine or fuel system of the vehicle. In the fuel system, ethanol has been found to be corrosive to polyamide filter housings, polyurethane and polyester bonded fiberglass (Schrock, 1979). For this reason it is recommended that all hoses and the fuel pump diaphragm be made of neoprene rubber, a material compatible with ethanol (Nerpel, 1980).

Ethanol is also corrosive to metals, such as steel, aluminum and copper. The extent to which it corrodes these materials can be shown by an example using the relative corrosion rates of these metals when immersed in 200 proof ethanol at room temperature (Persiantseva et al., 1980). Assuming an 8-gauge metal (thickness of .128 inches) used in a storage tank or a piece of tubing, it would take the ethanol 32 years to completely penetrate the steel, 31.17 years for the aluminum and 182.9 years for the copper.

The proof of the ethanol also influences the corrosion rates of these metals in ethanol. If the metals are immersed in 90 proof ethanol instead of the 200 proof ethanol, the steel's corrosion rate would increase 2.3 times, the copper would increase 1.6 times, and the aluminum would decrease 4.1 times (Persiantseva et al., 1980).

Temperature also affects the corrosion rate of metals. If the temperature increases from 80°F to 280°F the corrosion rate for steel in ethanol goes up from .004 inches per year to .05 inches per year, an increase of 12.5 times (Perry, 1973).

It should be noted that there is another problem with having aluminum in contact with ethanol. When ethanol and water come into contact with aluminum they pick up aluminum oxide forming a milky white sludge (Schneider, 1979). It is recommended that any aluminum that might come in contact with the ethanol be replaced because the sludge could clog filters and fuel lines.

Zinc is also incompatible with ethanol. In one test, the vehicle contained a zinc-lined gas tank that had to be replaced with a stainless steel tank (Hill, 1980). Stainless steel is known to be highly resistant to corrosion by ethanol even at high temperatures.

As a consequence of the incompatabilities associated with ethanol, it is recommended that the following areas be checked for compatability before running an engine on ethanol (Flowers et al., 1979):

- carburetor float,
- carburetor needle and seat,
- carburetor filter (plastic gasket),
- fuel filter (plastic),
- fuel lines,
- fuel pump (plastic and rubber parts) and
- fuel tank.

Pollutant Emissions Levels of Engines Using Ethanol

There are conflicting reports on the effects of ethanol use on the exhaust emissions of engines. These conflicts result mainly from using different engines and different methods of evaluating the emissions. In Table 8 (Paul, 1979) the exhaust composition of an engine operating on ethanol is shown. The engine had a displacement of 2.3 liters and a modified carburetor.

Table 8.—Exhaust Composition from Neat Ethanol by FTIRS and Other Methods.

Compound	FTIRS Amount at 4 Hours (ppm)	Error	Amount at 26 Hours
Water	1.10*	0.2	0.52
Carbon dioxide	1.08*	0.2	1.07
Carbon monoxide	488.	18.4	490.
Heavy hydrocarbons (C_6+)	0.3**	14.7	0.
Nitric oxide	14.4	0.6	4.0
Nitrogen dioxide	46.9	0.6	31.5
Nitrous oxide	0.4	0.2	0.4
Nitrous acid	2.4	0.2	2.2
Hydrogen cyanide	0.1	0.4	0
Ammonia	0	0.2	0.1
Sulfur dioxide	0.3	0.4	0
Methane	8.7**	0.2	8.8
Acetylene	4.6**	0.4	4.5
Ethylene	26.0	0.9	26.0
Ethane	1.8**	0.4	1.7
Propylene	0.5**	1.8	0.6
Isobutane	3.0**	1.8	3.5
Formaldehyde	8.8**	0.2	7.8
Acetaldehyde	57.4**	1.6	55.6
Formic acid	0.6**	0.2	0.2
Methanol	7.6**	0.2	6.4
Ethanol	194.**	0.2	168.
Total NO_X	63.7	—	37.6
Total HC	313.3**	—	280.0

* %

** ppm carbon

NO_X Emissions

It was found that NO_X emissions were generally less for ethanol as compared to gasoline. This held true except in the very lean and very rich regions. Figure 12 (University of Santa Clara, 1978) points this out in graphical form.

The amount by which the NO_X emissions decrease varies between tests. One test reported reduction of 55 to 60 % using ethanol at the same equivalence ratio (Paul, 1979). Another test found that reduction to be 8 to 12 % at the same equivalence ratio (University of Santa Clara, 1978).

CO Emissions

The CO emissions were found to be lower when operating on ethanol than with gasoline. One test reported that CO emissions were reduced 30 to 60 % when operating on ethanol at the same equivalence ratio (University of Santa Clara, 1978).

Unburned Fuel Emissions

The unburned fuel emissions were found to be higher for ethanol than for gasoline. One test with the same engines operating at the same equivalence ratio, reported increases of 6 to 25 % (University of Santa Clara, 1978). In Figure 13 (Mueller, 1978) this increase is also shown except in the rich region.

Aldehyde Emissions

It should be noted that at the present time aldehyde emissions are not federally regulated. But the aldehyde emissions from ethanol operation are much higher when compared to operation on gasoline. In one test, with the carburetor and distributor modified, a 50% increase was found (Chui, 1979). In Figure 14 (University of Santa Clara, 1978) a larger increase is shown. The increase shown from this graph ranges from three to six times the gasoline

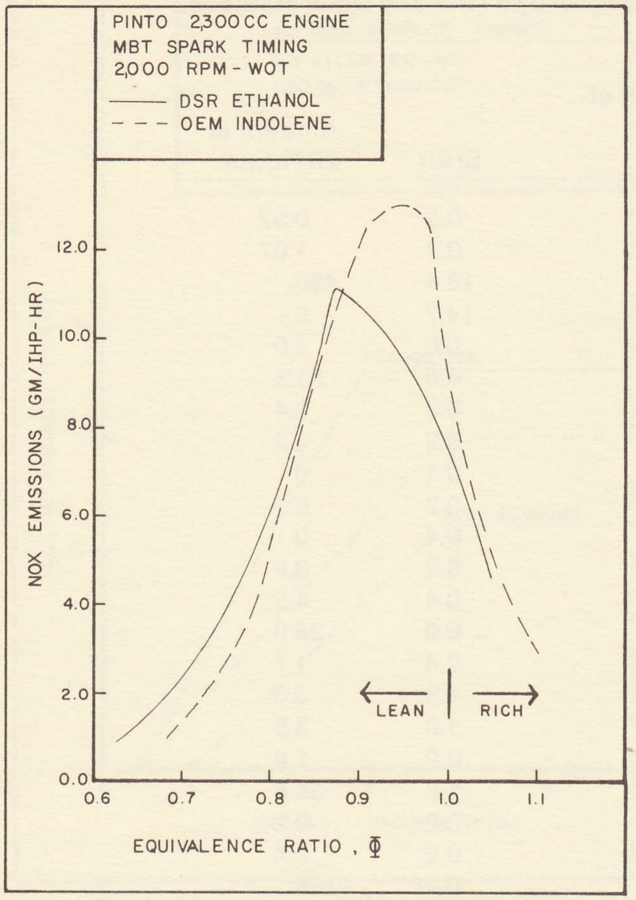

Fig. 12.—The nitrogen oxides emitted from an SI engine fueled with ethanol and indolene are nearly equal for all equivalence ratios except in the 0.9 to 1.0 range where the ethanol fueled engines emit considerably less NO_X.

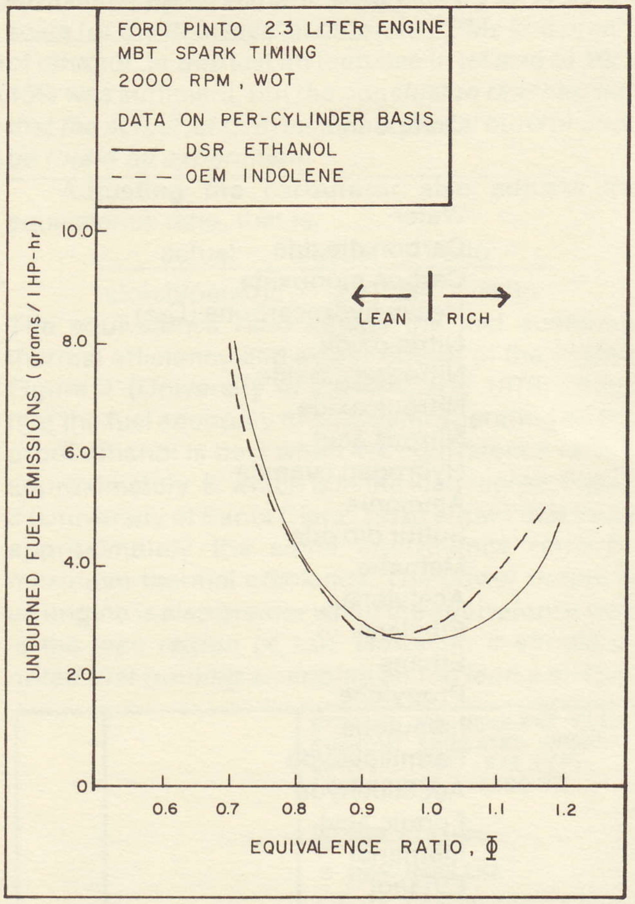

Fig. 13.—The unburned fuel emissions from an SI engine fueled with ethanol are equivalent to engines fueled with indolene. The unburned fuel emissions are greater for indolene when the equivalence ratio is higher than 1.0.

operation values. One test reported that a standard catalytic converter can eliminate the problems of aldehyde emissions (Hill, 1980).

One problem pointed out in the emissions tests was the maldistribution between cylinders (failure of fuel to distribute evenly among cylinders) resulting from the use of ethanol. It was found that this problem increased with increasing vehicle speed (Chui, 1979). The maldistribution varied the emissions from one cylinder to the next, but it is not known what effect this problem has on other areas of engine operation on ethanol.

Engine Durability Using Ethanol

There seems to be some conflict between reports on the effect of ethanol on engine durability. One study reported no documented incidences of engine corrosion due to ethanol use. It stated that the engine corrosion attributed to ethanol was really a result of the denaturant or other additives used in the ethanol (Rider et al., 1979). Another study conducted during the winter, on short trips and stop-and-go driving, reported a 180% increase in the iron wear of the engine plus increased oil viscosity and acid content. It went on to say that the problems are not serious at higher ambient temperatures (Schrock, 1979).

As mentioned earlier, in some tests the intake air of the engine using ethanol is preheated. It was found that when the intake air was heated excessively engine knock occurred and the engine was destroyed. The study recommended keeping the temperature of the engine parts below 290°C (Paul, 1979).

Another problem mentioned in one paper was that valve recession might occur in older model engines operating on ethanol (Schrock, 1979). This problem can also occur in older model engines operating on unleaded gasoline. The problem occurs because of the absence of tetraethyl lead. New model cars are equipped with valve seat inserts to eliminate this problem. If this problem occurs it is recommended that valve seat inserts be placed in the heads or that the heads be replaced with a newer model.

Friction and wear characteristics of various fuels were tested by Baily et al. (1979) in accordance with ASTM standards. The lubrication performance of ethanol was poorer than diesel fuel, but it was superior to gasoline.

In dual injection diesel engines (one injecting both ethanol and diesel fuel) the problem of heavy knock occurred when the intake air was heated excessively. It was found that at air temperatures above 200°C the ethanol self-ignited during the compression stroke (Bro et al., 1977).

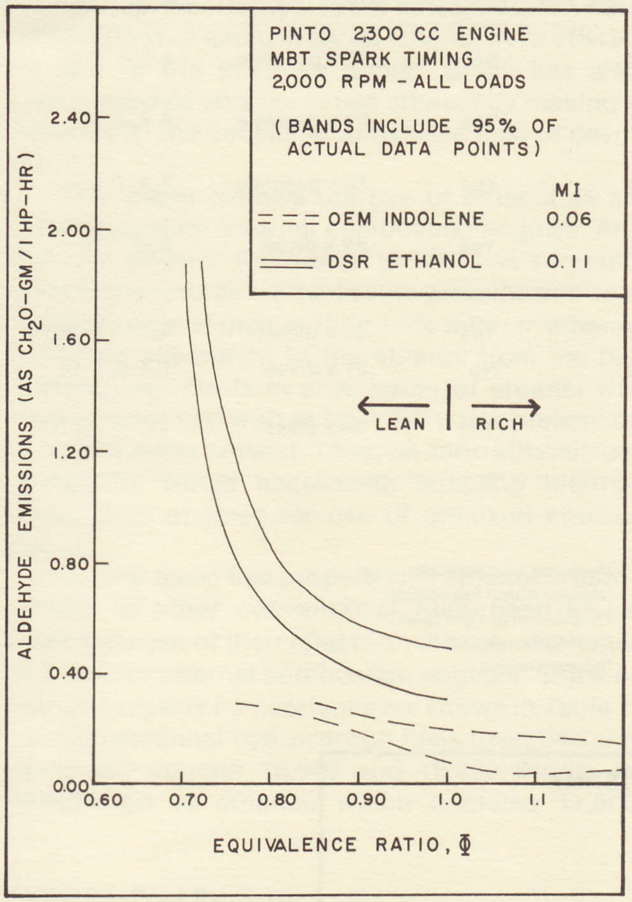

Fig. 14.—The aldehyde emissions of an SI engine fueled with ethanol show very significant increases at low equivalence ratios. When the equivalence ratio is greater than 0.9 the ethanol fueled engine approaches the indolene fueled engine but still is significantly greater.

Deposits in Engines Using Ethanol

In the studies reviewed ethanol has not been found to leave any unfavorable engine deposits. In one study practically no combustion chamber deposits were found in an engine after 500 hours of operation on ethanol (Meyer et al., 1948). In fact ethanol does just the opposite. It cleans deposits out of the engine. It has been found that ethanol, being an excellent solvent, will loosen up gums and deposits already formed in the engine. One problem with this is that when ethanol is first used in an engine, one should expect that some filters may clog up due to the gums and deposits being cleansed from the engine. However, after the engine is initially cleansed there should not be any more problems with clogged filters, unless the ethanol comes into contact with some of the incompatible materials mentioned earlier (Rider et al., 1979).

Conclusion

Ethanol seems to be an attractive substitute for petroleum fuels in the SI internal combustion engine. Its two most positive qualities are that it can be used in today's engines and can be made from renewable resources, such as grain. However, there are problem areas in ethanol use, some of which are listed in Table 9 (Schrock, 1979). Other problems with its widescale use are its cost, production and distribution to the public.

In summary, the following generalizations can be made based on the literature reviewed in this paper:

1) The higher proof ethanol (>180) is a more suitable fuel for today's engines due to its increased power output, increased volumetric fuel economy, and the absence of some of the problems associated with lower proof ethanol.
2) Ethanol is more adaptable to use in spark ignition engines than in diesel engines.
3) When ethanol is used in a SI engine, modifications should be made to the carburetor, compression ratio and ignition timing, and some additional form of heat may be needed for the intake air.
4) When compared to gasoline, ethanol delivers more power, better fuel economy, higher thermal efficiency, but less volumetric fuel economy.
5) Some additional form of heat or a separate starting fuel is needed to start engines operating on ethanol at low temperatures.
6) Ethanol is less toxic than gasoline, but more precautions must be taken in its storage to insure its initial quality.
7) Ethanol is corrosive to several materials used in vehicles currently operating on gasoline. The compatability of materials in a vehicle should be checked before using ethanol.
8) The NO_X and CO emissions are less, and the unburned fuel and aldehyde emissions

are greater for ethanol as compared to gasoline.

9) There seem to be no major problems in engine durability using ethanol that cannot be overcome with minor modifications.

10) There are no unfavorable engine deposits left in engines using ethanol. In fact, there are fewer engine deposits than found from the use of gasoline.

Even though there are some problems associated with its use, ethanol has been used as a gasoline substitute before, and there are no insurmountable problems to keep it from being used again. A great number of barriers exist in the use of unmixed ethanol in diesel engines because of the low cetane number for ethanol. To make its use practical today, there are active research programs around the world investigating these problems.

Table 9.—Summary of Ethanol Applications in Engines.

Application	Engine	Approximate % Fuel Replaced by Ethanol[a]	Utilize Low Proof?	200 Proof Ethanol Value	Potential[c] Problems
1) Ethanol-gasoline mixtures	Vehicles and older SI tractors	10	No	.75 x gasoline	1, 2, 5, 7
2a) Ethanol in SI Std. CR	Vehicles, natural gas engines, old SI tractors	100	Yes	.67 x gasoline	3, 4, 7, 9
2b) Ethanol in SI High CR	Natural gas Irr engines, old SI tractors	100	Yes	.76 x gasoline	3, 4, 7, 9
3) Ethanol in SI converted diesels high CR	CI tractors, combines	100	Yes	.52 x diesel	4, 6, 7, 9
4) Ethanol in diesels	CI tractors, combines	100	Yes[b]	.55 x diesel	4, 5, 7, 8, 10
5) Ethanol-diesel mixtures	CI tractors, combines	10	No	.51 x diesel	1, 4, 6, 7, 10
6) Carbureted ethanol CI	CI tractors, combines	30	Yes	.55 x diesel	11

[a]Assuming 100% adoption
[b]Speculative
[c]Potential Problems

1 = Phase separation
2 = Driveability
3 = Valve recession
4 = Starting (below 40°F)
5 = Vapor lock
6 = Unavailability of retrofit conversion hardware
7 = Materials compatibility
8 = Injector pump lubrication
9 = Oil dilution at light loads
10 = Combustion knock
11 = Inconvenience

GLOSSARY OF TERMS

A/F	Air to fuel ratio
BTC	Before top dead center
CI	Compression ignition
DSR	Dresserator induction system—sonic flow fuel/air induction
Φ	Equivalence ratio—$\frac{\text{actual air/fuel ratio}}{\text{stoichiometric air/fuel ratio}}$
FTIRS	Fuorier transform infrared spectroscopy
FTP	Federal test procedure
IHP	Indicated horsepower
MBT	Minimum spark advance for best torque
MI	Maldistribution index
MI	$\frac{\Phi \text{ richest cylinder - leanest cylinder}}{2 \times \Phi \text{ average}}$
NFPS	National Fire Protection Society
NO_x	Nitrous oxides
OEM	Original equipment manufacturer
SI	Spark ignition
WOT	Wide open throttle

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