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DIESEL ENGINE EXPERIMENTS WITH OXYGEN ENRICHMENT, WATER ADDITION AND LOWER-GRADE FUEL

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ABSTRACT

The concept of oxygen enriched air applied to reciprocating engines is getting renewed attention in the context of the progress made in the enrichment methods and the tougher emissions regulations imposed on diesel and gasoline engines. An experimental project was completed in which a direct injection diesel engine was tested with intake oxygen levels of 21% - 35%. Since an earlier study indicated that it is necessary to use a cheaper fuel to make the concept economically attractive, a less refined fuel was included in the test series. Since a major objection to the use of oxygen enriched combustion air had been the increase in NO_x emissions, a method must be found to reduce NO_x. Introduction of water into the engine combustion process was included in the tests for this purpose. Fuel emulsification with water was the means used here even though other methods could also be used. The test data indicated a large increase in engine power density, slight improvement in thermal efficiency, significant reductions in smoke and particulate emissions and NO_x emissions controllable with the addition of water.

INTRODUCTION

The concept of using oxygen enriched air for diesel engine combustion has been studied by several researchers over the last two decades. The main motivation for oxygen enrichment is to lower the smoke and other exhaust emission as well as to improve the thermal efficiency. Wartinbee[1] considered and rejected the concept for spark-ignition engines due to the difficulties involved in controlling NO_x emissions caused by oxygen enrichment. Quader[2] studied the combustion mechanisms of oxygen enrichment and the concept was again rejected due to the NO_x and the fuel consumption penalties that were encountered. Ghojel[3] and Lida[4] published their work on indirect-injected and direct-injected diesel engines respectively. They were more encouraged by the use of this concept and later Lida and Sato[5] found that the increased NO_x could be controlled by retarding the injection timing, which is made possible by the reduced ignition delay.

The oxygen enrichment concept as applied to diesel engines deserves a more comprehensive review in the context of the particulate emissions standards proposed by the United States Environmental Protection Agency (EPA) which will go into effect in 1994. Since oxygen enrichment can potentially reduce smoke and particulate emissions significantly, this technology may be the solution to the diesel engine emission problems.

Recent work[6,7] by engine developers indicate a renewed interest in the concept. In parallel developments, funded primarily by the U.S. Department of Energy (DOE), significant advances were reported in practical oxygen enrichment devices such as "asymmetric hollow fiber" membranes which could be used for various end-use applications[8,9,10]. Argonne National Laboratory (ANL) undertook a systematic research project of the application of oxygen enrichment to stationary diesel engines. Although the concept offered several advantages in performance and emissions, it is obvious that without a definite means of controlling the NO_x emissions, oxygen enriched diesel engines could not be commercialized in stationary or transportation applications in the U.S. Hence the use of water injection, in the form of emulsified fuel, was included as part of the ANL research. Water injection has been previously studied and reported to reduce NO_x[11,12]. Analytical studies[13,14] of the performance, emissions and economic aspects of the diesel engine with oxygen enrichment and emulsified fuels revealed that significant decreases in smoke, particulates and other emissions parameters, except NO_x, and ignition delays are possible while, at the same time, excellent increases in power density and slight increase in efficiency could be achieved. In the second phase of the project, ANL conducted tests on a single cylinder diesel engine to obtain performance, emissions and cylinder pressure data. The results of the test series are being published in three reports for clarity. This paper concentrates on the comparisons of performance and emissions of #2 and #4 diesel fuels with various degrees of emulsions.

OBJECTIVES

The main objective of the tests is to experimentally quantify the operation of the engine with the standard #2 and with the less refined #4 diesel fuels. Emulsions of these two fuels with up to 10% water were planned in the test matrix. However, due to the difficulty in preparing stable emulsions, the water content in the fuel varied widely from one to another. In some tests water content of the fuel was over 20%. The major parameters of interest are the maximum limit on power density increase when enriched oxygen is used, the effects of O_2 and water on thermal efficiency, NO_x, smoke and particulate levels.

EXPERIMENTAL SETUP

Engine and Fuels Used

A single cylinder, four stroke, direct injection diesel engine was used in this series of experiments. This is a one cylinder version of a heavy-duty diesel engine commonly used in on-highway trucks and other applications. The major specifications of the base engine are given in Table 1. No hardware changes were made to the basic engine and the manufacturer's recommendations were used in the setup and operating procedures.

Table 1. Test Engine Specifications

Number of Cylinder	1
Bore x Stroke	137 mm x 165 mm
Displacement	2.44 liters
Engine Speed	1800 rpm.
Injection Timing	32° btdc
Compression Ratio	14.5
Peak Cylinder Pressure	110 Bar

The engine was designed to run on #2 diesel fuel. The objective of this project was to test the engine on a less refined fuel, such as #6 diesel. It was felt, however, that the engine might not run smoothly on # 6 diesel fuel without extensive modifications. Hence it was decided to compromise and test the engine on # 4 fuel, which is generally used in marine applications. Water introduction into the combustion process was accomplished by emulsifying the two base fuels with distilled water and a small percentage of stabilizing chemical additive. Three levels of water content were tested with each base fuel. The fuel specifications are illustrated in Table 2.

Table 2. Test Engine Specifications

	#2 diesel	#4 diesel
Kinematic Viscosity (C. Stokes @ 80°C)	1.8	5.2
Lower Heating Value (k.J./kg)	42,668	40,909
Water Used for emulsion (% of fuel weight)	0,5,10	0,5,10
Chemical Additive (%)	0.333	1.0

The Oxygen Supply System

Compressed oxygen from a bank of cylinders was mixed with air in a large tank before the intake manifold of the engine. A micro-fuel cell type (Teledyne model 326A) oxygen sensor located in the engine intake manifold was used to measure and control the intake oxygen content of the air entering the engine. Elaborate safety systems were provided to handle oxygen. The engine crank case was purged with nitrogen for added safety while running the engine. The amount of oxygen supplied from the cylinders was measured separately.

Fuel Supply System

A separate fuel preparation system was installed and the test fuel was supplied to the engine fuel pump from this system. Fuel preparation consisted of making fuel emulsion in a tank, keeping it circulated to prevent water from settling, measuring the mass flow rate of the fuel and a heater to maintain the fuel temperature. Many problems were encountered in maintaining consistent fuel emulsion, which indicated a need for additional research into the means of introducing water into the engine combustion process. Fuel samples were taken immediately before and after the test. These samples were analyzed in the chemistry laboratory for water content. The average value of the two samples was used in the data analysis of each test.

Instrumentation

Most of the instrumentation used in these tests were standard engine test cell instrumentation. The only special instrumentation, to be described in a future report, was to measure cylinder pressure traces. NO_x and oxygen level were the only gaseous emissions measured in the exhaust gas stream. A conventional filter method was used to measure the emissions of particulate matter down to 0.5 micron. Smoke was measured by the degree of filter darkening due to reflected light, which was read on a scale of 0-100%. More detailed emissions measurements will be made when a scaled up multi-cylinder engine is tested in the future.

Test Matrix

Two engine operating conditions were tested in this series. "50% Load" is defined as the engine operating conditions (intake maniflod pressure, exhaust manifold pressure and ass flow rate of air plus oxygen) corresponding to 50% brake power level of the base engine, which is 18.65 KW (25 h.p.). "100% Load" is defined as the engine operating conditions corresponding to the rated power level of the base engine, which is 37.3 KW (50 hp). The intake manifold pressures were maintained at 112 cm Hg. abs. at "50% load" and 140 cm Hg. abs. at "100% load" points respectively. The exhaust manifold pressure was maintained at 81 cm. Hg. abs. throughout. Three types of data were obtained at each oxygen level:

i. Constant power output
ii. Constant exhaust to intake oxygen ratio
iii. Constant exhaust oxygen level

Intake oxygen level was varied from 21% to 35%. Water content of the fuel emulsion showed wide variation ranging from 0% to 22%. A total of 112 test runs were made and a large number of graphs were plotted. Only a portion of the most significant trend curves are presented in this report. Baseline data were repeated, and checked frequently during the test program. Some data had to be disregarded due to instrumentation failures. Overall the test series was completed without any major engine problems.

DISCUSSION OF THE RESULTS

Engine Performance

Diesel engine power output is usually limited by the exhaust smoke level. Smoke increases due to incomplete combustion of fuel which is caused by, among several other reasons, lack of adequate amount of oxygen for combustion. The tests showed that even a slight enrichment of the O_2 level reduces smoke to a point where the output is no longer limited by smoke but by exhaust temperature limits imposed on the engine by the materials. In this regard oxygen enrichment is similar to turbocharging in increasing the smoke-limited output of the engine. Figures 1 and 2 show the maximum power potential at various oxygen levels. High temperature materials, such as silicon nitride valves and seats in the exhaust gas stream would enable the engine to produce even higher power levels until the engine's mechanical limits, as indicated by peak cylinder pressures, are reached. It is clear that both #2 and #4 fuels are capable of producing 140% higher power at 50% load setting and 50% higher power at 100% load setting, when the same exhaust O_2 level is maintained. Since the concept being tested includes water injection for NO_x control, the question arises whether such remarkable increases in power density are possible when fuels emulsified with water are used in conjunction with O_2 enrichment. The test data indicates that water content in the fuel does not affect the gains in power density when #2 diesel fuel is used or when #4 diesel fuel is used at 50% load setting. However, at 100% load setting with emulsified #4 fuel, the exhaust-temperature-limited-maximum-power showed only 40% gain. This fact must be carefully taken into account when this system is scaled up for large installations.

Thermal Efficiency

Another major indicator of engine performance is brake specific fuel consumption (bsfc), which is expressed as gms/(kw-hr) or lbs/(bhp-hr). In this test series the fuel characteristics varied considerably due to the water content. Hence comparisons on the basis of bsfc could lead to erroneous conclusions. The comparisons on the basis of thermal efficiency based on the energy content of the test "fuel" eliminates any confusion. The thermal efficiency is defined as:

$$\eta = \frac{p}{(\dot{m} * q)}$$

where

η = thermal efficiency
p = power output
$\dot{m}$ = mass flow rate
q = energy per unit mass of fuel

A consistent set of units was used in calculating the thermal efficiency.

The test data shows that the thermal efficiencies are higher with #2 diesel fuel compared to #4 diesel fuel. This could be due to the fact that the engine was designed and fine-tuned to operate on #2 diesel fuel. Addition of moderate amount of water consistently showed an increase in thermal efficiency. This could be due to micro-explosion phenomenon reported by other investigators[15]. However, as more water is added the efficiency starts to decrease, as shown in Figure 3. Figure 4 shows similar results for the effects of oxygen enrichment. Thermal efficiency increases slightly at first, then decreases as more oxygen is added.

Emissions of Oxides of Nitrogen (NO_x)

The NO_x emissions are known to go up when combustion temperatures increase. The effect of oxygen enrichment is higher combustion and adiabatic flame temperatures and, therefore, higher NO_x emissions. The presence of water is to reduce the temperatures and, as a result, reduce NO_x emissions. The data presented in Figure 5 confirm this. This is very encouraging since the major objection to this application of the oxygen enrichment technology has been the high NO_x emissions. It is clear from Figure 5 that the NO_x emissions at 25% oxygen could be brought back to the base level when the fuel contains about 20% water. This technique, combined with other established NO_x reduction methods such as retarded injection timing, appears promising in controlling the overall NO_x emissions from a diesel engine with oxygen enriched combustion air. The same trend was not observed when #4 diesel fuel emulsions were used and the engine was run at a constant power, as shown in Figure 6. However, as illustrated in Figure 7, the effect of power output increase is to lower the specific NO_x level with either base fuel. This again confirms the earlier conclusion that these two technologies work well with diesel engine only if the engine output is increased to the maximum level, the limiting factor being the exhaust temperature.

Particulate Emissions and Smoke

The test engine appears to have low particulate emissions even in the baseline reference test runs. Hence the measured mass particulate emissions did not go down as much as expected when oxygen levels were increased. In fact, the particulate emissions could go up with higher O_2

enrichment, if the power output level is kept the same. An example is shown in Figure 8. The particulate emissions with #4 diesel fuel were consistently higher than with #2 diesel fuel. This data, illustrated in Figure 9, shows the importance of increasing the engine output at higher O_2 level. The general tendency of particulate emissions is to go up with water content level in the fuel. The data indicated considerable scatter depending on the base fuel, O_2 level, engine load conditions and water content. A typical data comparison is shown in Figure 10. This figure also indicates the importance of higher power output level when emulsified fuels are used. Exhaust smoke level went down as soon as oxygen level in the intake is increased. Amount of oxygen concentration did not make any measurable difference in smoke level, which was already low at 25% O_2. This trend was observed with both base fuels and their emulsions included in the test matrix. This fact discussed earlier, results in a major departure in the way in which diesel engines are generally rated. The rated power would not be smoke-limited when oxygen enriched air is used. Rather, limiting factor is the gas temperatures that the materials could withstand. If high- temperature materials could be employed cost effectively, the next limiting parameter would be the cylinder pressures.

CONCLUSIONS AND RECOMMENDATIONS

Oxygen enrichment is a viable technology for diesel engine applications. The increase in power density potential is important in industrial cogeneration and electricity generation plants which are capital intensive and consume large amounts of fuel. Engines that operate on #2 diesel fuel could be converted to oxygen enriched air and cheaper fuel such as #4 diesel. The engine runs with no adverse effect with water emulsified fuel. Thermal efficiency, and hence fuel consumption, is slightly improved in the presence of moderate amount of water. Visible smoke is reduced with oxygen enrichment. NO_x emissions go up with O_2 level but go down with the water content in the fuel. Thus the combination of oxygen enrichment and water addition to the fuel makes it a workable system with cheaper fuel such as #4 diesel fuel. It is concluded that when these technologies are employed in a diesel engine it is important to increase the power output of the engine. Otherwise the excess oxygen that is inducted into the engine will simply go out in the exhaust. Effects of O_2 on particulates is mixed: particulates tend to go down for #2 fuel, but go up for #4 fuel.

One important variable that was not included in this test matrix is the fuel injection timing. Since retarding the injection timing is a well known means of controlling NO_x emissions, it is recommended that injection timing optimization be done in conjunction with oxygen enrichment and emulsified fuels. Another important experiment is the test of the diesel engine with an oxygen enriching membrane as an integral part of the system. Such a test is being carried out and is expected to shed light on the parasitic losses involved in the system. It is also recommended that other alternative fuels such as methanol, ethanol and compressed natural gas be studied in the context of O_2 enrichment and water induction in the combustion chamber. If oxygen enriching device could be miniaturized, transportation applications are also possible for these technologies. The test project reported here revealed the problems involved in fuel emulsification. A separate effort is needed to develop emulsified fuels.

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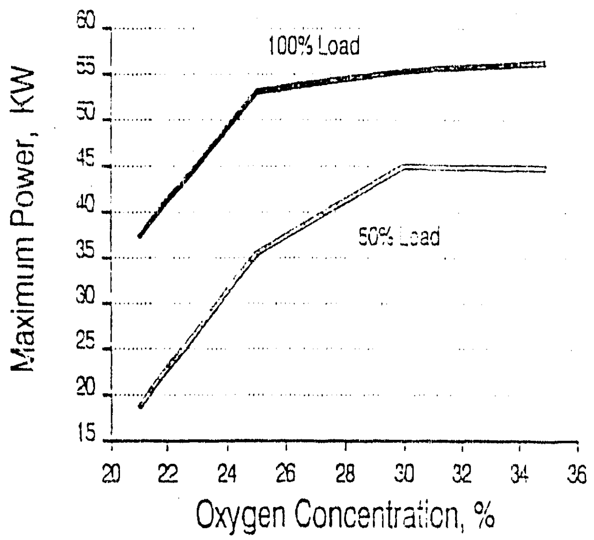

Figure 1. Maximum Attainable Power with No. 2 Diesel Fuel

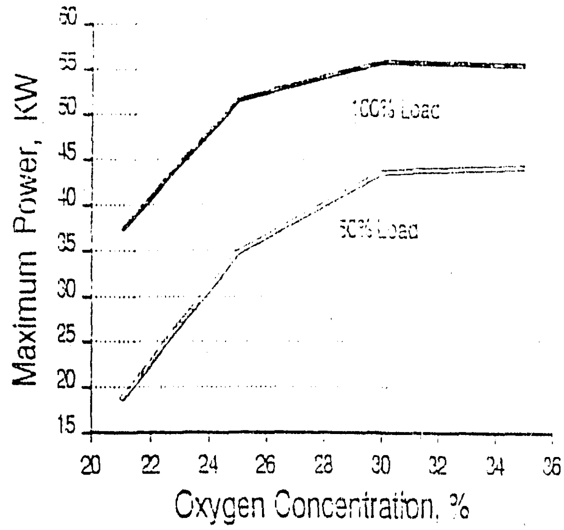

Figure 2. Maximum Attainable Power with No. 4 Diesel Fuel

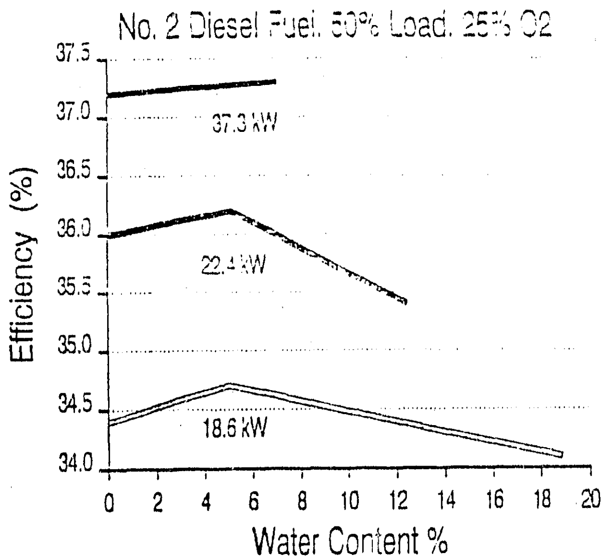

Figure 3. Effect of Water Content on Thermal Efficiency

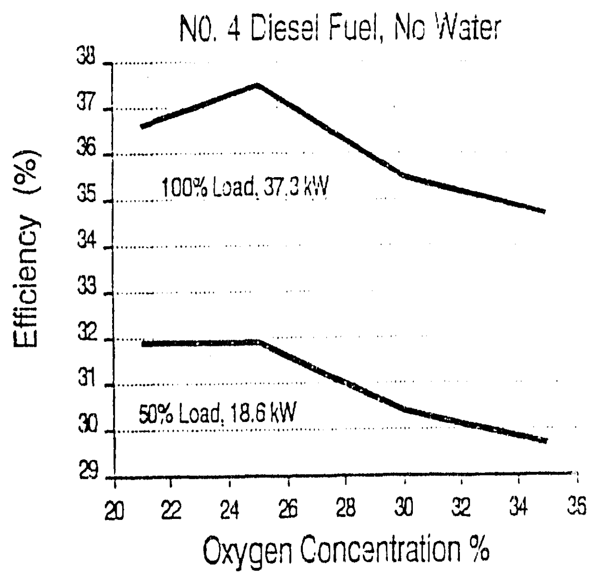

Figure 4. Effect of Oxygen on Thermal Efficiency

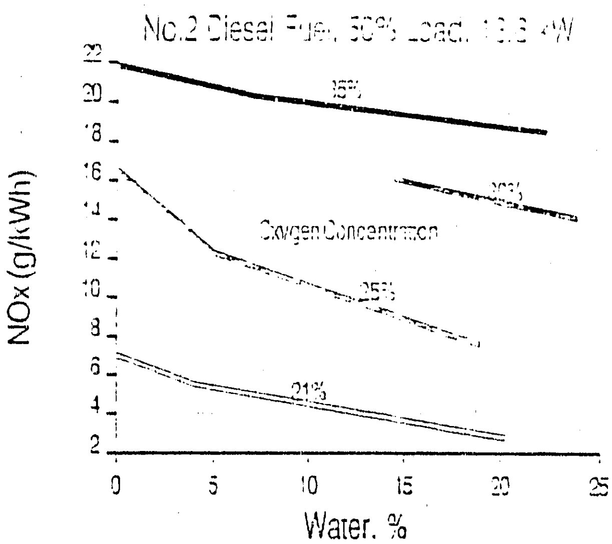

Figure 5. Effect of Water and Oxygen on NOx Emissions (No.2 Diesel Fuel)

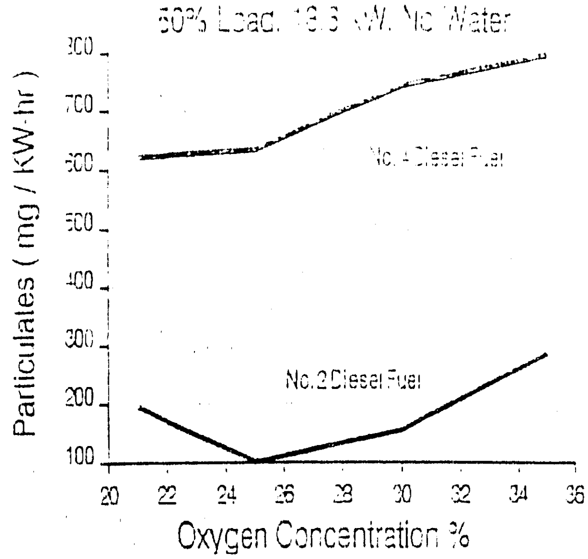

Figure 8. Effect of Oxygen on Particulate Emissions

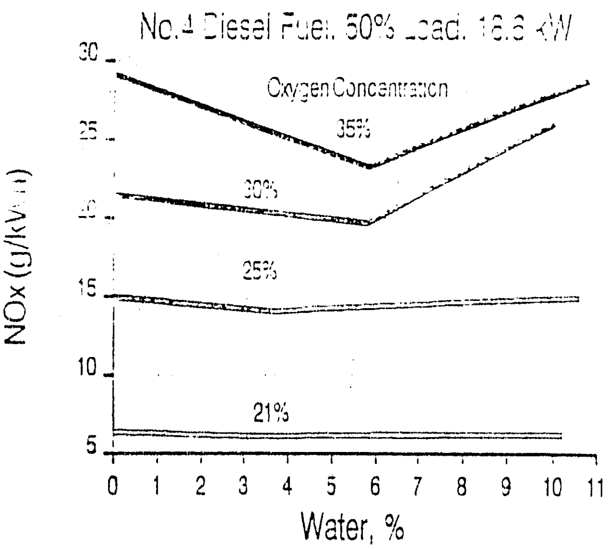

Figure 6. Effect of Water on NOx Emissions (No. 4 Fuel)

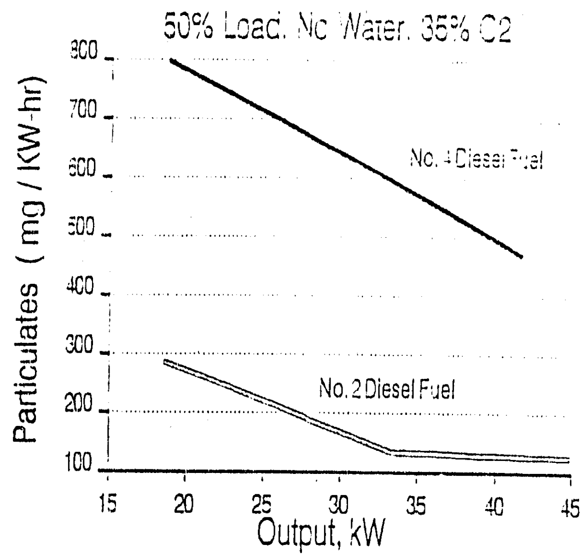

Figure 9. Effect of Power on Particulate Emissions

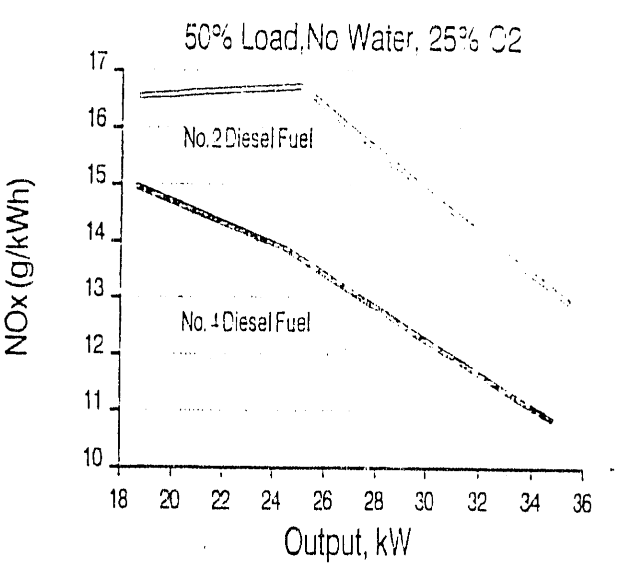

Figure 7. Effect of Power on NOx Emissions

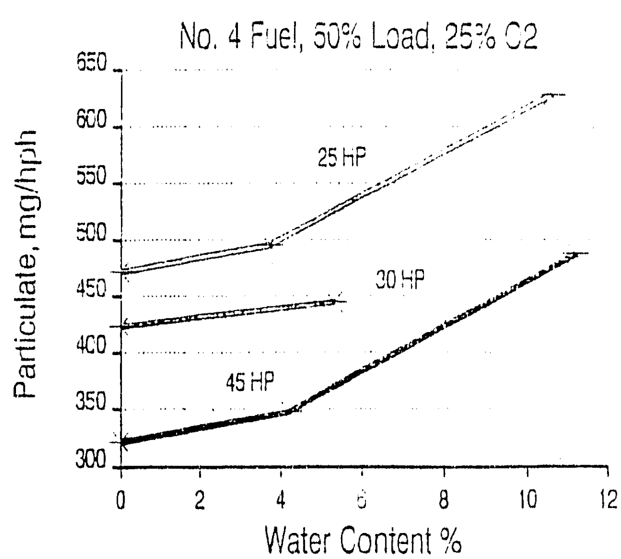

Figure 10. Effect of Water Content on Particulate Emissions

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