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Experimental Evaluation of Oxygen-Enriched Air and Emulsified Fuels in a Six-Cylinder Diesel Engine

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Abstract

The objectives of this investigation are to (1) determine the technical feasibility of using oxygen-enriched air to increase the efficiency of and reduce emissions from diesel engines, (2) examine the effects of water-emulsified fuel on the formation of nitrogen oxides in oxygen-enriched combustion, and (3) investigate the use of lower-grade fuels in high-speed diesel engines by emulsifying the fuel with water. These tests, completed on a Caterpillar model 3406B, six-cylinder engine at the facilities of AutoResearch Laboratories, Inc., are a scale-up from previous, single-cylinder-engine tests. The engine was tested with (1) intake-air oxygen levels up to 30%, (2) water content up to 20% of the fuel, (3) three fuel-injection timings, and (4) three fuel-flow rates (power levels). The Taguchi technique for experimental design was used to minimize the number of experimental points in the test matrix. Four separate test matrices were run to cover two different fuel-flow-rate strategies and two different fuels (#2 diesel and #6 diesel). A liquid-oxygen tank located outside the test cell supplied the oxygen for the tests. The only modification of the engine was installation of a pressure transducer in one cylinder. All tests were run at 1800 rpm, which corresponds to the synchronous speed of a 60-Hz generator. Test results show that oxygen enrichment results in power increases of 50% or more while significantly decreasing the levels of smoke and particulates emitted. The increase in power was accompanied by a small increase in thermal efficiency. Maximum engine power was limited by the test-cell dynamometer capacity and the capacity of the fuel-injection pump. Oxygen enrichment increases nitrogen-oxide emissions significantly. No adverse effects of oxygen enrichment on the turbocharger were observed. However, if oxygen enrichment is used to increase power, the turbocharger size should be rematched to the engine. The engine operated successfully with #6 fuel, but it operated at a lower thermal efficiency and emitted more smoke and particulates than with #2 fuel. Oxygen enrichment increased thermal efficiency and significantly reduced smoke and particulate emissions when the engine operated with #6 fuel.

* Longman is affiliated with AutoResearch Laboratories, Inc.

1 Introduction

1.1 Background

Initial investigations showed that it is economically desirable to use low-grade diesel fuel to operate diesel engines for cogeneration.[1,2] However, the high viscosity and poor ignition characteristics of low-grade fuel have limited its use in medium- and high-speed diesel engines. Those investigations suggested that oxygen-enriched air and water emulsified with the fuel would improve the ignition and combustion characteristics of low-grade fuel while significantly increasing the power output of the engine.

A series of experiments was designed with the objectives of (1) determining the technical feasibility of using oxygen-enriched air to increase the efficiency of and reduce emissions from diesel engines, (2) examining the effects of water-emulsified fuel on the formation of nitrogen oxides (NO_x) in oxygen-enriched combustion, and (3) investigating the use of lower-grade fuels in high-speed diesel engines by emulsifying the fuel with water. Although neither oxygen enrichment nor water-emulsified fuel use in diesels is new, the experimental program was the first in which both concepts had been used together.

Results of single-cylinder-engine tests indicated that (1) power output from the engine could be increased by at least 50% with only a 20% increase in peak cylinder pressure; (2) smoke and particulate emissions could be dramatically decreased with oxygen enrichment; (3) oxygen enrichment improved engine operation with lower-grade (#4 diesel) fuel; (4) NO_x emissions increased significantly with oxygen enrichment; and (5) primarily through fuel-injection retard, the NO_x emissions (measured in grams per kilowatt-hour) with oxygen-enriched air could be decreased to about the normal-air level.[3–7]

The current test project used a six-cylinder diesel engine. The objectives were to (1) investigate whether the trends observed in the single-cylinder engine would scale up to a commercial engine; (2) study the effect of oxygen-enriched air on turbocharger performance and matching requirements; (3) study the effects of water-emulsified fuels, using a commercially available emulsifier, on engine performance and emissions; and (4) use a low-grade (#6) diesel fuel in a high-speed engine in conjunction with oxygen enrichment and water emulsification.

The earlier, single-cylinder-engine tests required a larger number of experimental data points. The current series of tests was limited to a few test points because of budgetary constraints. To obtain as much information as possible with a few test points, it was decided to use the Taguchi technique of experimental design. This statistical method identifies the most significant variables and provides an error band in the measurements.

A Caterpillar model 3406B engine (a popular, mass-produced six-cylinder engine) was used in this test. Tests were conducted at the AutoResearch Laboratories, Inc. (ALI), facility in

Harvey, Illinois. The test facility and instrumentation details are discussed in Section 2 of this report.

1.2 Report Structure

Section 2 of this report contains a description of the test setup, including (1) the engine, (2) the fuels, (3) the oxygen-supply system, (4) the instrumentation, and (5) the test matrix. The Taguchi technique for experimental design is briefly described; more detailed descriptions can be found in Appendix A and in the references.

Section 3 presents the pertinent results of the experiments and a description of the problems encountered during testing. Section 4 draws upon the results of Section 3 to present the conclusions and to make recommendations.

The appendixes contain information about the Taguchi technique (Appendix A) and detailed test results (Appendixes B and C).

2 Experimental Setup

2.1 Engine

The experiments were performed with a six-cylinder, four-stroke-cycle, turbocharged and aftercooled diesel engine (Caterpillar model 3406B) that is commonly found in heavy-duty on-highway trucks. The engine specifications are listed in Table 2.1. The only engine modification was installation of a combustion-pressure transducer in cylinder number 1. A photograph of the engine in the test cell is shown in Figure 2.1. The control panel is shown in Figure 2.2.

2.2 Fuels

Fuels of grades 2 and 6 (ASTM D-396) were used for the experiment. The tightly controlled parameters for #2 fuel are shown in Table 2.2. The parameters for #6 fuel are loosely controlled. The sample of #6 fuel that was used in these experiments was derived from a blend of #2 fuel with residual fuel to obtain better control of the viscosity. Measured properties of the #6 fuel are shown in Table 2.3.

2.3 Oxygen-Supply System

Oxygen was supplied from a liquid-oxygen storage tank located outside the test cell. The oxygen level of the engine's intake air was enriched by injecting a controlled flow of vaporized oxygen into the intake air-filter housing, where it was diluted with ambient air. The turbocharger mixed the oxygen with the air. The volume-percent (% vol.) oxygen level of the intake air was measured at the aftercooler housing by using a microfuel-cell-type (Teledyne model 326A) oxygen analyzer. The safety systems installed were similar to those used in the previous tests done on the single-cylinder engine.[7] An "oxygen enable" safety valve, activated by engine boost pressure, was added to provide early detection of possible turbocharger problems. A schematic diagram of the oxygen-supply system is shown in Figure 2.3.

2.4 Fuel-Supply System

2.4.1 #2 Diesel Fuel

The engine's fuel-supply system was modified to accommodate an emulsification system. The emulsifier, made by Harrier, Inc., was installed according to the schematic diagram shown in

TABLE 2.1 Engine Specifications

Item	Value
Number of cylinders	6
Bore (mm) x stroke (mm)	137 x 165
Displacement (L)	14.6
Engine speed (rpm)	1800
Injection timing (°btdc,[a] static)	24
Compression ratio	14.5 : 1

[a] °btdc = degrees before top dead center.

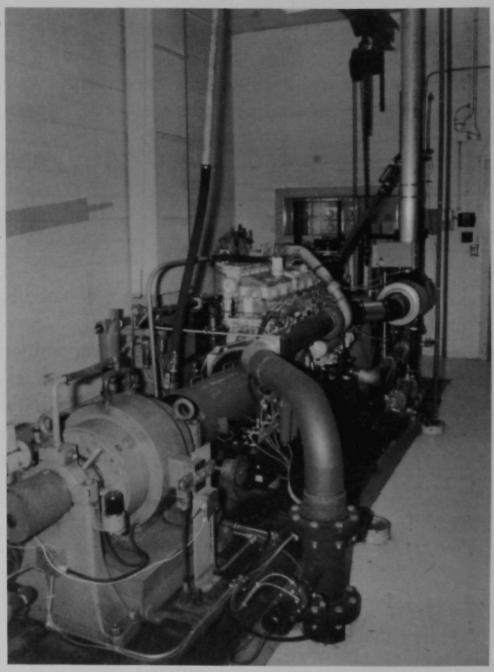

FIGURE 2.1 Photograph of Engine in Test Cell

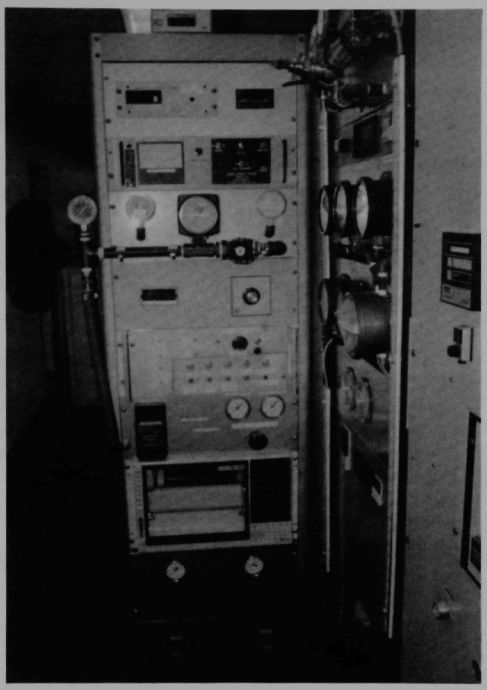

FIGURE 2.2 Photograph of Control Panel

Figure 2.4. The device mechanically created a "micro-emulsion" of fuel and water.[8] The amount of water emulsified with the fuel was controlled by adjusting the calibration factor of the device's electronic feedback system. The engine's fuel-injection system was not modified.

2.4.2 #6 Diesel Fuel

A special supply system was designed to handle the #6 fuel. A schematic diagram is shown in Figure 2.5. Because of the high viscosity of this fuel, the system included primary and secondary heating systems to bring the viscosity down to 20 centistokes (20 cSt), the maximum fuel viscosity recommended by the engine manufacturer for marine fuels.[9] The fuel was derived from a blend of residual fuel and #2 diesel fuel to achieve a viscosity that could be handled by the engine's fuel-injection system without modifications.

The fuel-supply pressure to the engine's fuel-injection pump was also increased to ensure proper injection-pump filling with the high-viscosity fuel. No modifications were made to the engine's fuel-injection pump, lines, or nozzles.

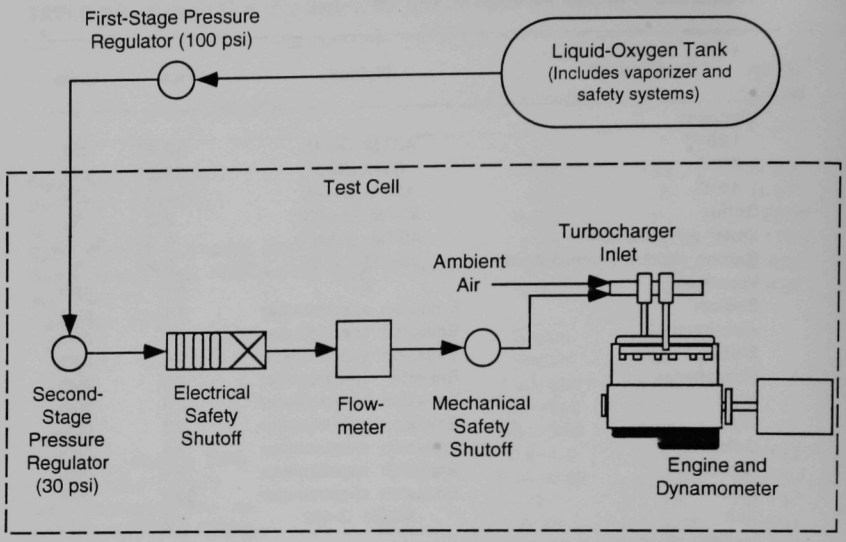

FIGURE 2.3 Schematic Diagram of Oxygen-Supply System

2.5.2 Combustion Pressure

The engine's cylinder head was modified to accept an AVL 8ZP30 combustion-pressure-transducer adapter. An AVL 8QP500ca water-cooled, piezoelectric, pressure transducer was attached to the adapter. A newer model QC32-E transducer was installed at the beginning of the #6-fuel series of tests, but it quickly corroded because of the high sulfur content of the fuel. Combustion pressures and crank angle (CA) were recorded by means of the computer-based data-acquisition system developed during single-cylinder-engine testing.[7]

2.5.3 Fuel Flow

A positive-displacement, four-piston, Fluidyne flowmeter was used for the #2-fuel series. However, the Fluidyne flowmeter was unable to operate without the pistons sticking in their bores with the #6 fuel. The unit was replaced by a Flo-Tron mass-flowmeter system, and no further problems were experienced.

1. Diesel Fuel Tank *
2. Fuel Pump *
3. Diesel Fuel Filter *

5. Harrier Diesel Cleaner ***
6. Fuel Injector *
7. Injection Pump *
8. Water Tank **
9. Water Pump ***
10. Water Pressure Control Valve ***
11. Water Filter ***
12. Water Injector ***
13. Fuel Flow Sensor ***

15. Electronic Control Unit ***

* Existing on Vehicle
** Optional
*** Diesel Cleaner System

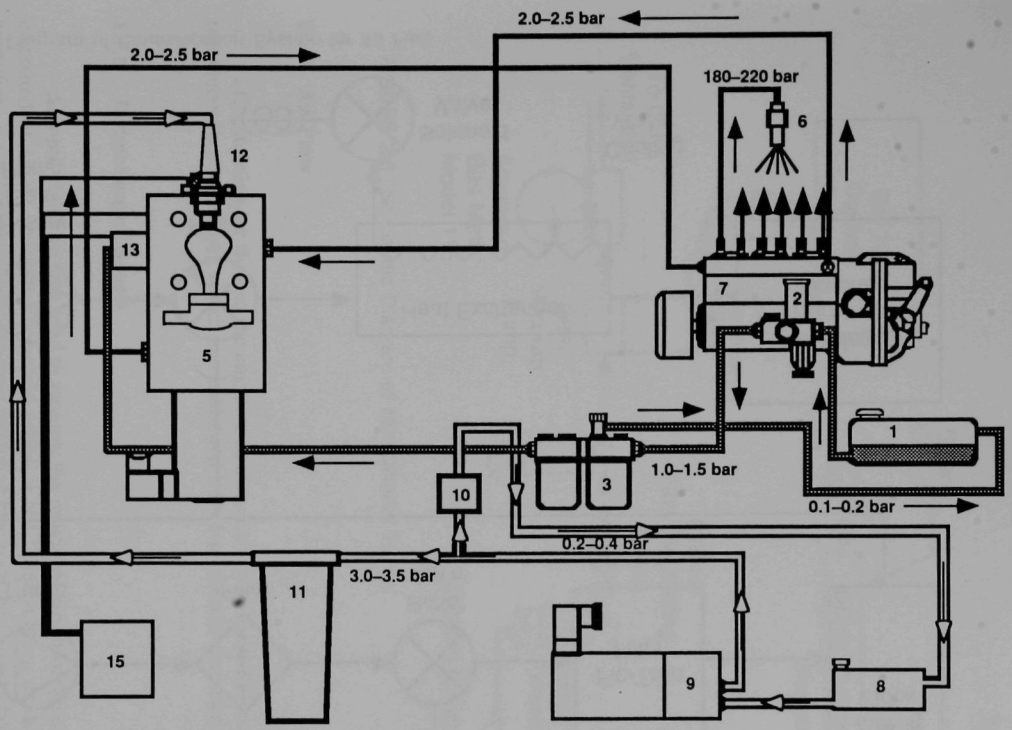

FIGURE 2.4 Schematic Diagram of Emulsification System for #2 Fuel

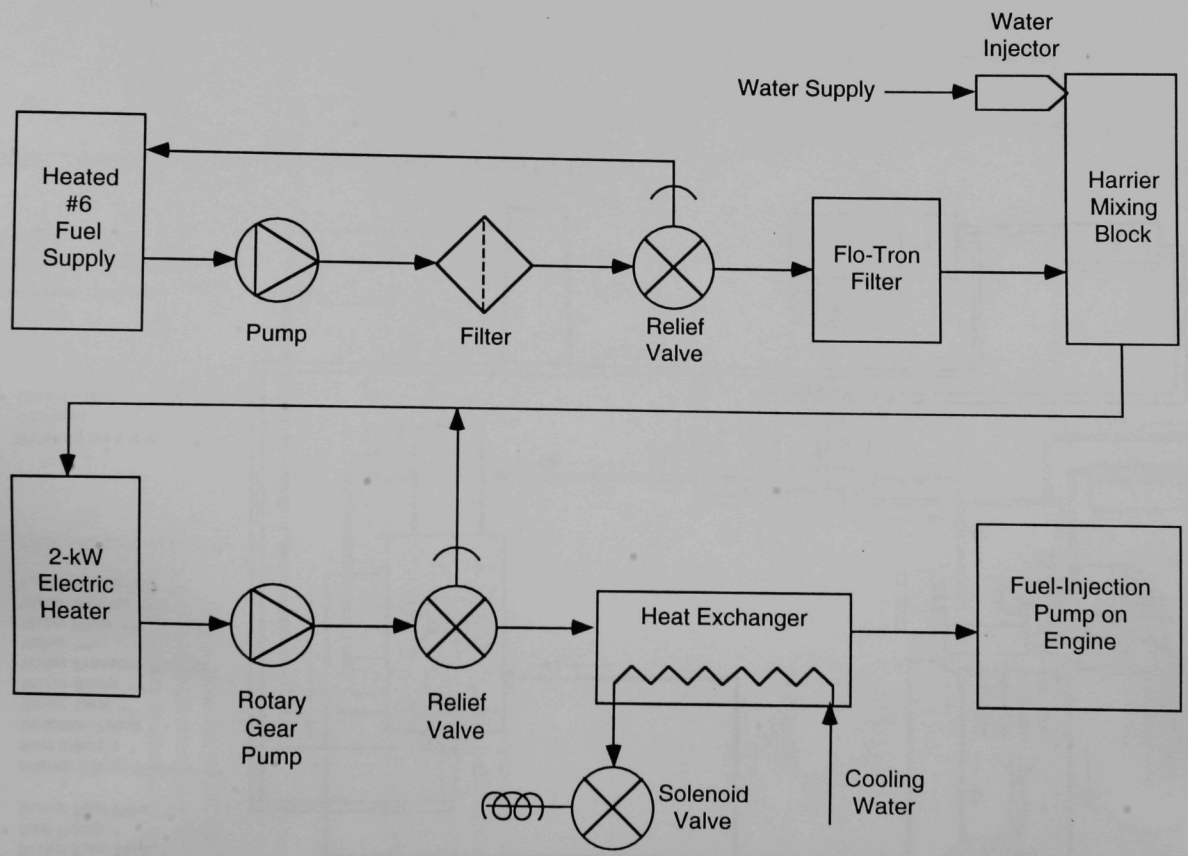

FIGURE 2.5 Schematic Diagram of Emulsification System for #6 Fuel

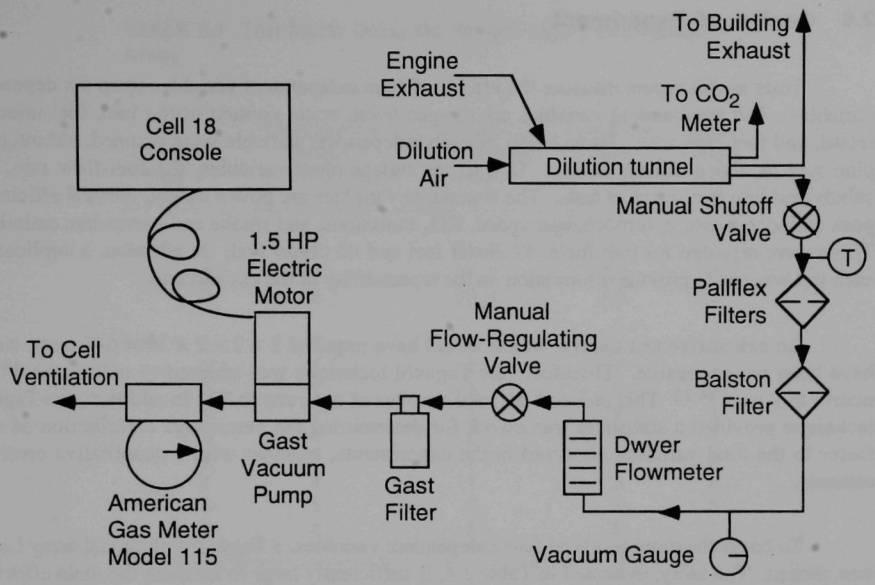

FIGURE 2.6 Schematic Diagram of Mini-Dilution Tunnel

2.5.4 Air Flow

Combustion air flow to the engine was measured by using a TSI model 8450 air-velocity transducer (hot-wire type), which was calibrated for a 6-in. (inside-diameter) air duct.

2.5.5 Turbocharger Speed

An optical device was used to monitor the rotational speed of the turbocharger. The unit consisted of a heat-resistant fiber-optic probe, a red light-emitting diode, a photocell, and an amplifier. A small piece of heat-resistant reflective tape epoxied to the turbocharger shaft reflected one pulse of red light onto the photocell for each revolution of the shaft.

2.5.6 Engine Coolant Flow

An Aeroquip (Barco) venturi-type flowmeter was used to measure the coolant flow.

2.6 Design of Experiment

Tests in this report measure the effects of four independent variables upon six dependent variables. The independent variables are oxygen level, water content of the fuel, fuel-injection retard, and fuel-flow rate. Three levels of each independent variable were planned, although the plan was modified during testing. One of the independent variables, the fuel-flow rate, was subdivided into two series of tests. The dependent variables are power output, thermal efficiency, peak cylinder pressure, turbocharger speed, NO_x emissions, and smoke and particulate emissions. These were repeated for two fuels, #2 diesel fuel and #6 diesel fuel. In addition, a duplicate of each test was run to provide information on the repeatability of the experiments.

An exhaustive test matrix, which would have required $2 \times 2 \times 2 \times 3^4 = 648$ tests, would have been too expensive. Therefore, the Taguchi technique was adopted to reduce the 3^4 test matrix to 9 runs.[14,15] This reduced the total number of test runs to 72. In addition, the Taguchi technique provided a statistical framework for determining the percentage contribution of each factor to the total variation observed in the experiments, together with a quantitative error-bar estimate.

To cover the three levels of four independent variables, a Taguchi orthogonal array $L_9(3^4)$ was chosen. The array, indicated in Table 2.4, is sufficiently large to measure the main effects of each independent variable, but it does not provide information on interactions between the independent variables.

Some departures from the ideal Taguchi technique were necessary. The Taguchi technique specifies that the trials should be run in random order, to the extent that it is possible. This minimizes the effect of unknown or uncontrolled factors, such as engine wear. Because of the difficulty of changing the fuel-injection timing, randomization was done only within each block of timing settings.

The two different fuels, #2 diesel and #6 diesel, were treated as separate orthogonal arrays because the fuel type is a discreet, rather than a continuous, variable and because only two levels of fuel type were tested.

The fuel-flow rate was also divided into two series having separate L_9 orthogonal arrays. The first series, designated as matrix A, is based on fuel-flow rates measured with the engine drawing 100%, 75%, and 50% of full power at 0° injection retard, 21.0%-oxygen air, and no water added to the fuel. These fuel-flow rates were measured in baseline tests separate from the orthogonal test array. In the matrix A tests, adding oxygen to the air did not result in significantly more power being produced by the engine, because the fuel flows were held constant for each fuel-rate level.

TABLE 2.4 Test Matrix Using the Taguchi $L_9(3^4)$ Orthogonal Array

Level, Trial #		Fuel-Injection Retard (°)	Oxygen Concentration (%)	Fuel-Flow Rate (%)	Water Content (%)
Level	1	0	21.0	100	0
	2	4	25.5	75	10
	3	8	30.0	50	20
Trial #	1	1	1	1	1
	2	1	2	2	2
	3	1	3	3	3
	4	2	1	2	3
	5	2	2	3	1
	6	2	3	1	2
	7	3	1	3	2
	8	3	2	1	3
	9	3	3	2	1

The second series of fuel-flow rate tests, designated as matrix B, was based on the fuel flows required to achieve specified equivalence ratios. The equivalence ratio is defined as the measured combustible-to-oxygen ratio divided by the stoichiometric combustible-to-oxygen ratio. The equivalence ratios were measured from tests with the engine drawing 100%, 75%, and 50% of full power at 0° injection retard, 21.0%-oxygen air, and no water added to the fuel. These equivalence ratios were measured in baseline tests separate from the orthogonal test array. In contrast to the matrix A series, the fuel-flow rates in matrix B vary in direct proportion to the amount of oxygen flowing into the engine. Thus, as oxygen is added to the air, the fuel-flow rate increases and the engine produces more power.

The increased power of the second fuel-flow-rate series (matrix B) required another modification of the L_9 matrix. Maximum engine power was limited by (1) the dynamometer capacity; (2) the test-cell heat-removal capacity; and (3) the maximum flow rate of the fuel injectors, particularly when water was added to the fuel. Because of these limitations, neither 30.0% oxygen nor 100% fuel-flow rate could be run. For the tests using #2 fuel, those points on the orthogonal array were treated as dummy conditions, as shown in Table 2.5, and the analysis of variance (ANOVA) was modified accordingly. Dummy treatment of conditions and modification of ANOVA are described in detail in the Taguchi technique references.

To minimize the need for dummy treatment when #6 fuel was used, the oxygen concentrations, fuel-flow rates, and water contents for matrix B were modified (see Table 2.5).

TABLE 2.5 Levels of Independent Variables for Matrix B

Fuel and Level	Fuel-Injection Retard (°)	Oxygen Concentration (%)	Fuel Rate (%)	Water Content (%)
#2 Diesel				
1	0	21.0	75	0
2	4	25.5	75	10
3	8	21.0	50	20
#6 Diesel				
1	0	21.0	75	0
2	4	23.0	62.5	5
3	8	25.0	50	10

The main advantages of the Taguchi technique are (1) a nine-fold reduction in the number of test runs; (2) straightforward determination of the percentage contribution of each independent variable to the observed variation of the dependent variables; and (3) determination of error bands, which can be plotted.[16] Details of the Taguchi technique are given in Appendix A and in the references.

3 Experimental Results

As discussed in Section 2, the Taguchi technique was used to design the test matrix. All the tests were conducted at a single engine speed — 1,800 revolutions per minute (rpm). The independent variables and the test sequence are presented in Tables 3.1 and 3.2. Because of dynamometer capacity limitations, constant-equivalence-ratio tests at higher oxygen levels could not be run at the 100% load point. This would have required the engine to operate at over 500 brake horsepower (bhp), which exceeds the dynamometer limit of about 400 bhp. Hence, matrix B (Table 3.2) was modified so that the maximum load point is only 75% of the base engine rating. The nine-point matrix was analyzed to study the main effects and the confidence interval due to each independent variable. The dependent variables of interest — NO_x and particulate emissions, thermal efficiency, brake specific fuel consumption (BSFC), exhaust temperature, turbocharger speed, cylinder pressure, and ignition delay — are discussed below. Selected graphs are shown to support the discussion.

3.1 Test Series I: #2 Diesel Fuel

Tests with #2 diesel fuel were fairly standard, except that some test points were run with water-emulsified fuel. Two sequences of tests were conducted, the first at constant fuel rate and the second at constant equivalence ratio. Although the first sequence was completed as planned, the constant-equivalence-ratio test matrix had to be modified because of the facility's limitations (noted above). Test results were similar to those from the single-cylinder-engine tests, except that the six-cylinder engine produced slightly higher levels of NO_x emissions. Differences in the way the two engines were supercharged probably account for the differences in NO_x emissions.

TABLE 3.1 Percent Contribution by Independent Variables and Error, #2 Fuel, Matrix A

	Dependent Variables							
Independent Variable	NO_x	Particulates	Smoke	Thermal Efficiency	Exhaust Temperature	Turbocharger Speed	Peak Cylinder Pressure	Ignition Delay
Timing	4.48	13.90	1.68	7.92	0.91	0.55	28.26	0.00
Oxygen	95.10	38.74	37.46	1.18	0.78	0.90	1.23	52.03
Fuel rate	0.05	22.96	8.23	88.88	95.63	98.16	68.44	33.16
Water	0.29	19.70	12.44	0.07	2.19	0.29	1.34	7.68
Error	0.08	4.70	40.19	1.94	0.48	0.09	0.73	7.12

TABLE 3.2 Percent Contribution by Independent Variables and Error, #2 Fuel, Matrix B

	Dependent Variables							
Independent Variable	NO_x	Particulates	Smoke	Thermal Efficiency	Exhaust Temperature	Turbocharger Speed	Peak Cylinder Pressure	Ignition Delay
Timing	4.44	19.31	5.77	11.83	4.39	5.19	12.17	5.05
Oxygen	93.91	58.13	25.55	46.76	42.66	49.05	57.50	20.81
Fuel rate	0.00	1.00	20.61	35.82	48.43	42.23	26.25	16.19
Water	1.08	2.66	17.23	0.57	0.58	0.19	1.83	53.97
Error	0.57	18.89	30.83	5.01	3.95	0.09	2.25	3.98

3.1.1 Percent Contributions by Independent Variables

One of the benefits of applying the Taguchi technique to experimental design is the ability to estimate the contributions of independent variables to a given effect and of random error to the variation measured in the dependent variables. These estimates are tabulated for #2 fuel and shown in Tables 3.1 (matrix A) and 3.2 (matrix B). Taking the NO_x column in Table 3.1 as an example, the interpretation is as follows: Random error accounts for only 0.08% of the variation in the NO_x measurement, so the measurements are a good representation of the physical results. Oxygen enrichment accounts for 95.10% of the variation in NO_x measurement, so it is the most important independent variable with respect to NO_x emissions. Fuel-injection timing accounts for 4.48% of the variation in NO_x measurement, so it is a minor independent variable. The fuel rate and water content of the fuel have negligible effects on NO_x emissions.

Under the smoke column, the random error accounts for 40.19% of the variation in the smoke measurement, which is the largest percentage contribution. Therefore, the smoke measurement is probably an unreliable indicator of actual smoke. The smoke results indicate the difficulty of making accurate measurements near the detection threshold of the instrument. The particulates measurement, which used a different instrument, produced a more reliable result, as indicated by its 4.7% error contribution.

3.1.2 Emissions of Nitrogen Oxides

As observed in the earlier, single-cylinder-engine tests,[3] combustion-air oxygen level has the largest effect on NO_x emissions. Tables 3.1 and 3.2 show that it accounts for over 93% of the measured variation. Higher oxygen levels increased NO_x substantially (Figure 3.1), which could pose a major challenge in commercializing this concept. Injection-timing retard reduced NO_x

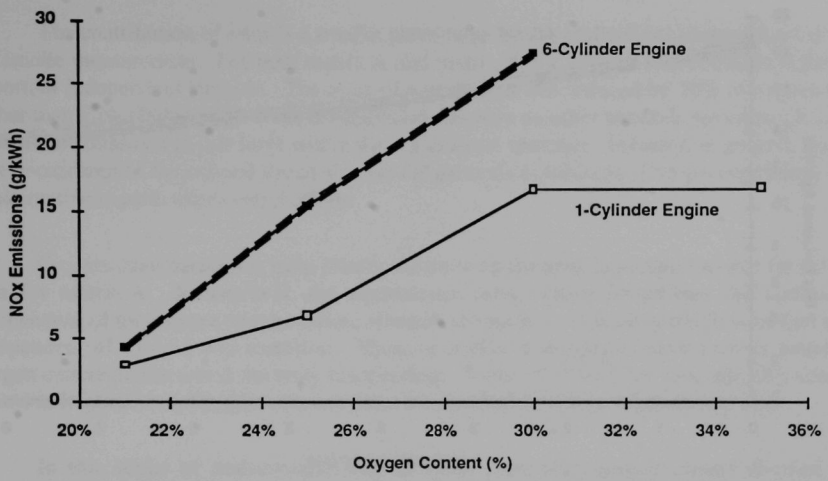

FIGURE 3.1 Effect of Oxygen Content on NO_X Emissions, #2 Fuel, Sequences 1 and 2, Matrix A

significantly (Figure 3.2), but since it accounted for only 4.4% of the measured variation, it was not sufficient to offset the effect of the increased oxygen level. The insignificantly small effect of water-emulsified fuel on NO_X emissions (Figure 3.3) for this multicylinder-engine test series is similar to that observed in the single-cylinder-engine tests. It is possible that a larger quantity of water may be required to produce a significant reduction in NO_X emissions. Both the single-cylinder-engine tests and the six-cylinder-engine tests used as much as 20% water.

The level of NO_X emissions from oxygen-enriched diesel engine operation continues to be a major challenge. However, as the only component of the exhaust emissions that is still a problem, the NO_X emissions may be easier to solve by using a catalyst or some other means of after-treatment. Fuel-flow rate has a negligible effect on NO_X emissions.

3.1.3 Smoke and Particulate Emissions

As noted above, the contribution of random error to the variation in smoke measurement was larger than the contributions of any of the independent variables. This is because the amount of smoke emitted by the engine is close to the lower detection threshold of the instrument. Visual observations showed that smoke, which was very low to start with, virtually disappeared with increased oxygen.

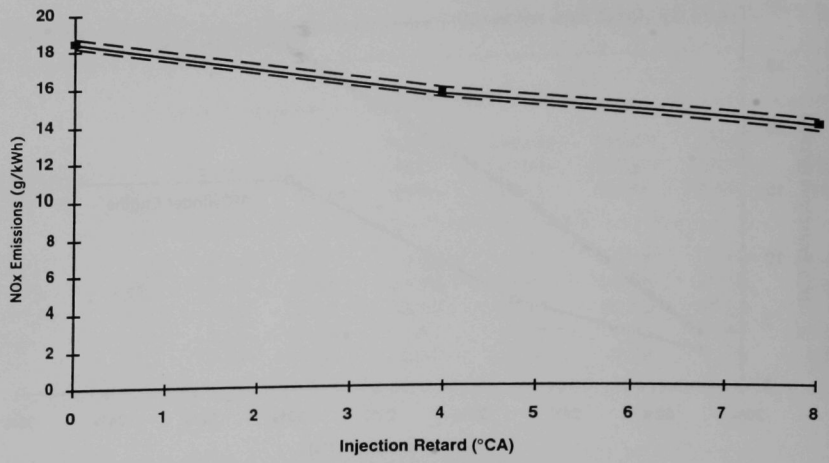

FIGURE 3.2 Effect of Injection Timing on NO_X Emissions, #2 Fuel, Sequences 1 and 2, Matrix A

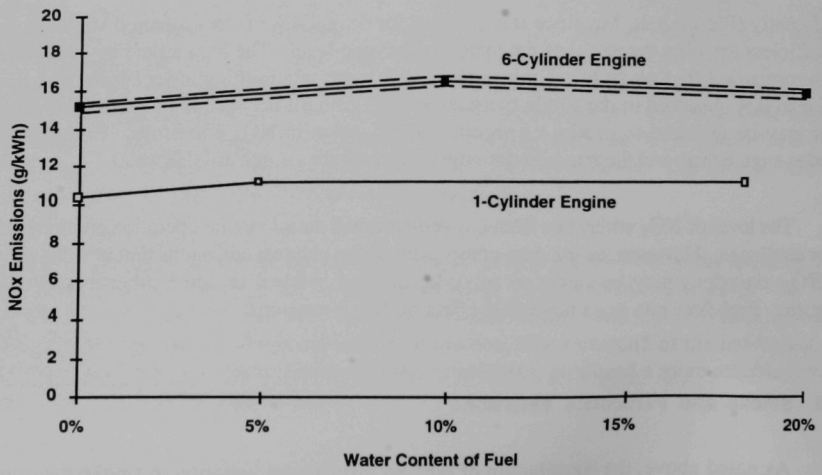

FIGURE 3.3 Effect of Water Content on NO_X Emissions, #2 Fuel, Sequences 1 and 2, Matrix A

The contribution of error is a smaller percentage for the particulates measurement than for the smoke measurement. For both matrix A and matrix B, the oxygen concentration is the most important independent variable. The mass of particulates was reduced by 50% at oxygen levels higher than 25% (Figure 3.4). This is significant, because no other methods are known to reduce particulate emissions to this level within the combustion chamber. Industry, in general, depends on trap oxidizers in the exhaust stream to meet the particulate standards. Oxygen enrichment offers an alternative in particulate control efforts.

Oxygen concentration is more clearly shown to be the most important variable for matrix B than for matrix A. In matrix B, the equivalence ratio, which determines the fuel rate, is independent of the oxygen concentration, whereas in matrix A, it is the mass flow of fuel that is independent of oxygen concentration. Thus, in matrix A the equivalence ratio is coupled to oxygen concentration and is not truly independent. Table 3.2 shows that fuel-injection timing is second in importance to oxygen concentration, but its effect is obscured by random error.

In this series of multicylinder-engine tests, particulate measurements showed more consistency than they did in the previous, single-cylinder-engine tests. Use of the mini-dilution tunnel is responsible for the improvement.

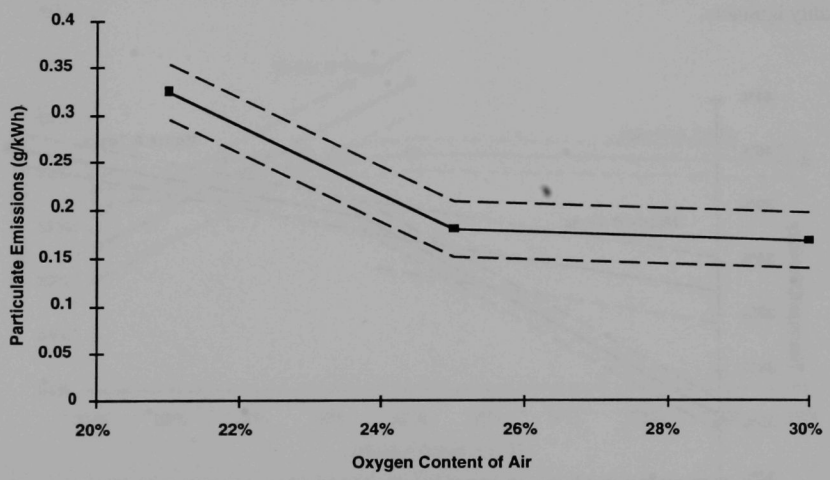

FIGURE 3.4 Effect of Oxygen Content on Particulate Emissions, #2 Fuel, Sequences 1 and 2, Matrix A

3.1.4 Thermal Efficiency

Table 3.1 shows that the fuel-flow rate accounts for over 88% of the variation in thermal efficiency in the matrix A tests. When the fuel-flow rate is increased, friction and other losses do not increase as rapidly as power output increases. Injection timing accounts for about 8% of the variation in thermal efficiency. Retarding the timing reduces thermal efficiency slightly. Oxygen, by itself, has a negligible effect on thermal efficiency. However, if the fuel-flow rate is increased as oxygen is added, as in the matrix B tests, there is a gain in thermal efficiency from 36.7% to 39.7% as oxygen increases from 21% to 25%. These trends were also observed in the single-cylinder-engine tests. Figures 3.5, 3.6, and 3.7 show the effects of fuel-flow rate, injection timing, and oxygen content of air, respectively, on thermal efficiency for both matrix A and matrix B tests.

3.1.5 Ignition Delay

Although Tables 3.1 and 3.2 suggest that ignition-delay results differ between matrix A and matrix B, the measured results are similar. Oxygen, as shown in Figure 3.8, significantly reduces ignition delay. This is to be expected, because a higher oxygen concentration makes the fuel more readily ignitable.

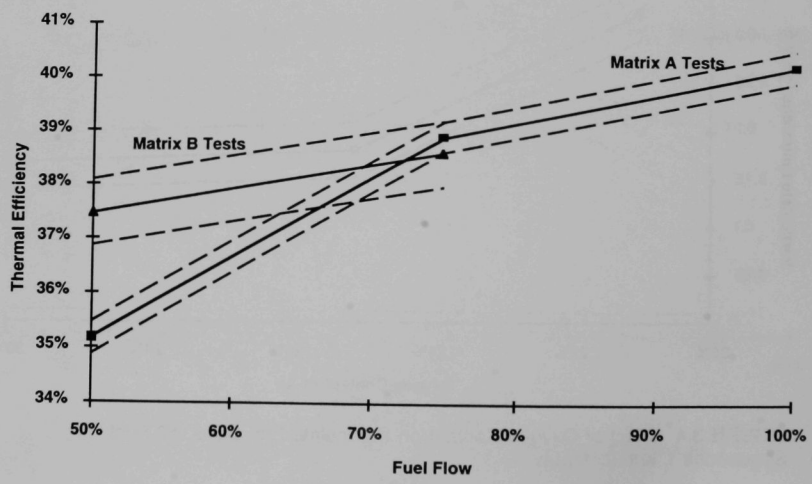

FIGURE 3.5 Effect of Fuel-Flow Rate on Thermal Efficiency, #2 Fuel

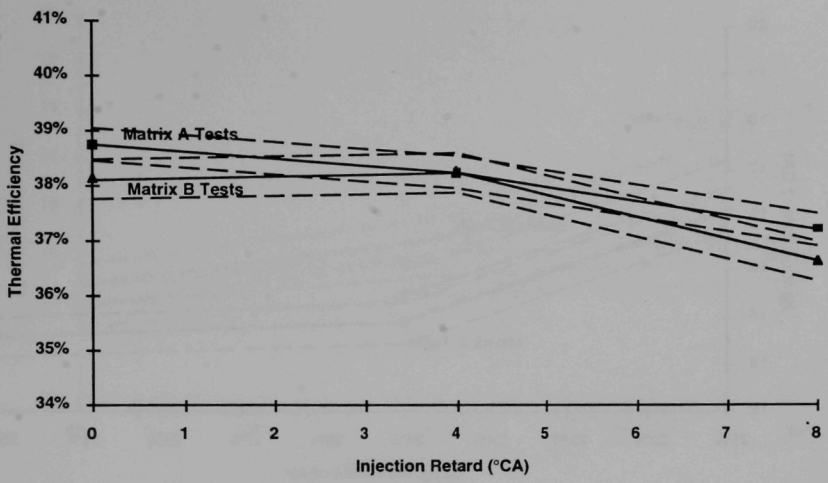

FIGURE 3.6 Effect of Injection Timing on Thermal Efficiency, #2 Fuel

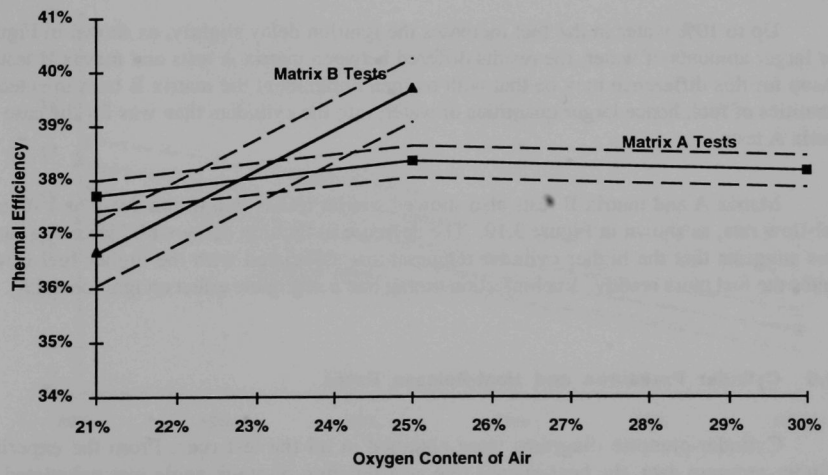

FIGURE 3.7 Effect of Oxygen Content on Thermal Efficiency, #2 Fuel

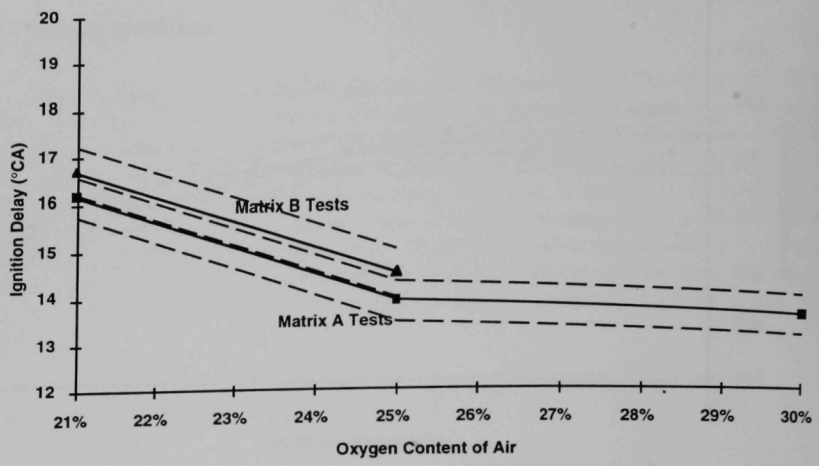

FIGURE 3.8 Effect of Oxygen Content on Ignition Delay, #2 Fuel

Up to 10% water in the fuel increases the ignition delay slightly, as shown in Figure 3.9. For larger amounts of water, the results differed between matrix A tests and matrix B tests. The reason for this difference may be that with oxygen enrichment the matrix B tests injected larger quantities of fuel, hence larger quantities of water, into the cylinders than was for the case for the matrix A tests.

Matrix A and matrix B tests also showed similar trends in ignition delay as a function of fuel-flow rate, as shown in Figure 3.10. The decrease in ignition delay with increasing fuel-flow rates suggests that the higher cylinder temperatures associated with the higher fuel-flow rates ignites the fuel more readily. Fuel-injection timing had a negligible effect on ignition delay.

3.1.6 Cylinder Pressures and Heat-Release Rates

Cylinder-pressure diagrams were obtained in all the test runs. From the experimental cylinder-pressure data, the heat-release rate as a function of crank angle was calculated with a computer code developed for this project. All the cylinder pressures, heat-release rates, rates of change of cylinder pressure, and cumulative heat-release rates are presented in Appendixes B and C. As expected, the heat-release diagrams show a faster combustion rate and reduced ignition delay at high oxygen levels. These are desirable attributes in diesel engines.

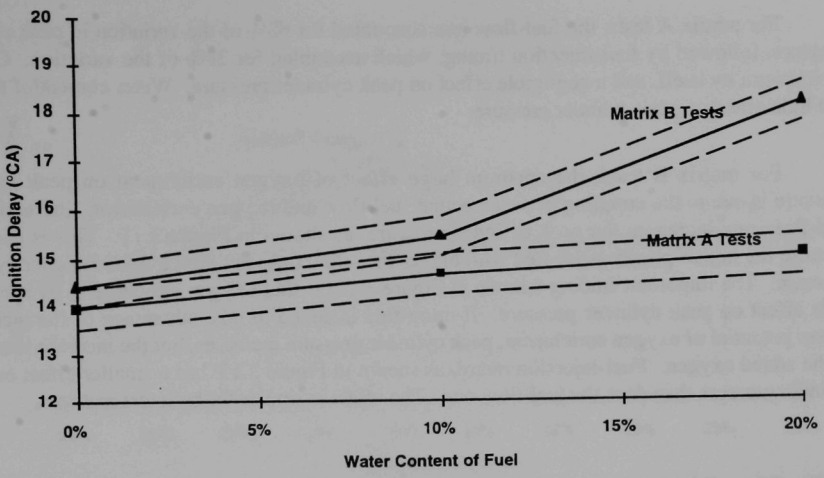

FIGURE 3.9 Effect of Water on Ignition Delay, #2 Fuel

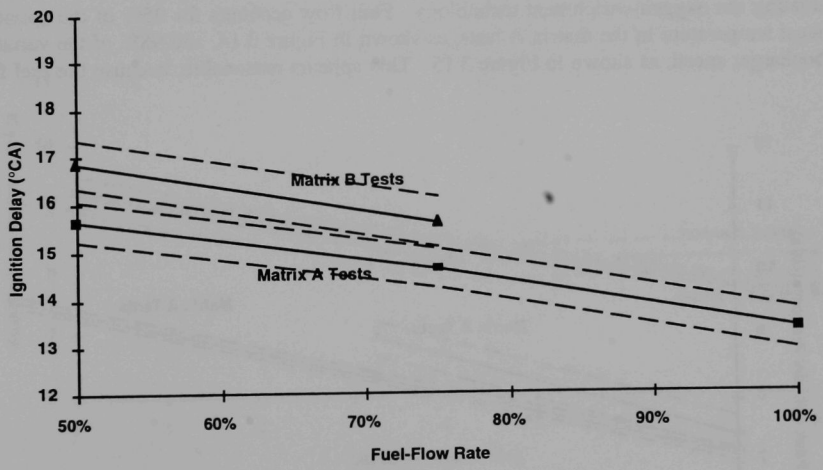

FIGURE 3.10 Effect of Fuel-Flow Rate on Ignition Delay, #2 Fuel

For matrix A tests, the fuel-flow rate accounted for 68% of the variation in peak cylinder pressure, followed by fuel-injection timing, which accounted for 28% of the variation. Oxygen enrichment, by itself, had a negligible effect on peak cylinder pressure. Water content of the fuel had little effect on peak cylinder pressure.

For matrix B tests, the apparent large effect of oxygen enrichment on peak cylinder pressure is due to the coupling between actual fuel flow and oxygen enrichment. Increasing the fuel-flow rate increases the peak cylinder pressure, as shown in Figure 3.11. This is expected because the higher power associated with higher fuel-flow rates is derived from a higher cylinder pressure. The important finding (shown in Figure 3.12) is that oxygen enrichment, by itself, has little effect on peak cylinder pressure. If more fuel is added to take advantage of the increased power potential of oxygen enrichment, peak cylinder pressure increases, but the increase is not due to the added oxygen. Fuel-injection retard, as shown in Figure 3.13, has a smaller effect on peak cylinder pressure than does the fuel-flow rate. The effect is similar for both test matrices.

3.1.7 Other Parameters

Exhaust temperature and turbocharger speed are the other parameters of interest in evaluating the oxygen-enrichment technology. Fuel flow accounts for 95% of the variation in exhaust temperature in the matrix A tests, as shown in Figure 3.14, and 98% of the variation in turbocharger speed, as shown in Figure 3.15. This appears reasonable, because the fuel flow is

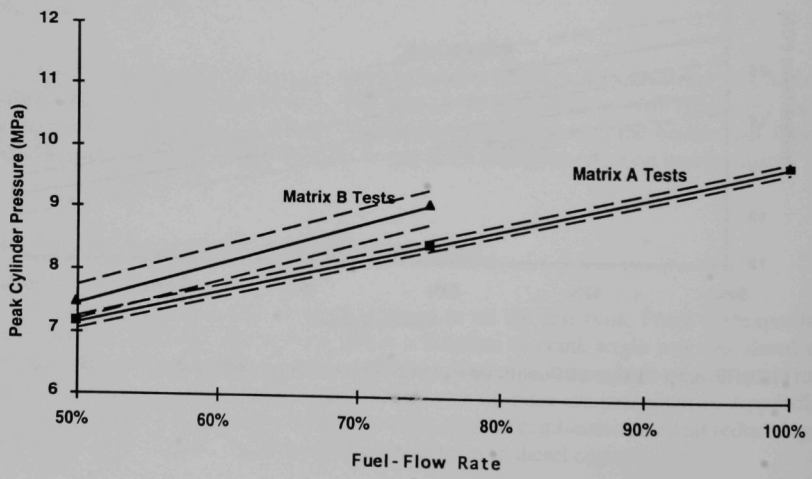

FIGURE 3.11 Effect of Fuel-Flow Rate on Peak Cylinder Pressure, #2 Fuel

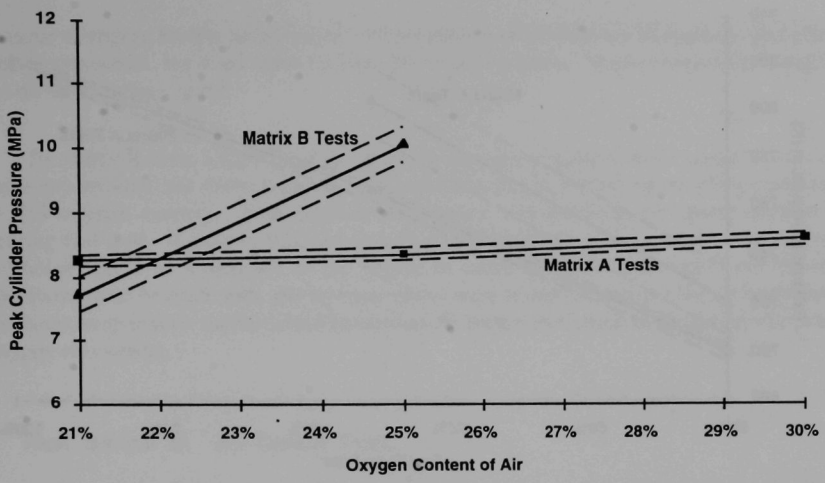

FIGURE 3.12 Effect of Oxygen Enrichment on Peak Cylinder Pressure, #2 Fuel

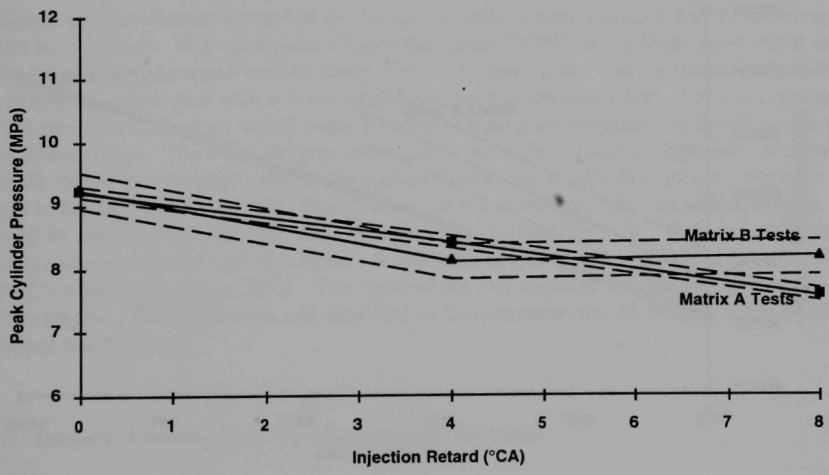

FIGURE 3.13 Effect of Fuel-Injection Retard on Peak Cylinder Pressure, #2 fuel

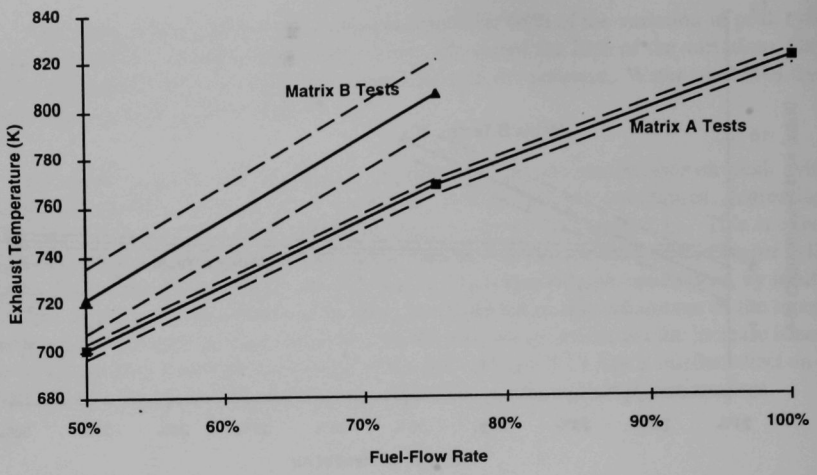

FIGURE 3.14 Effect of Fuel-Flow Rate on Exhaust Temperature, #2 Fuel

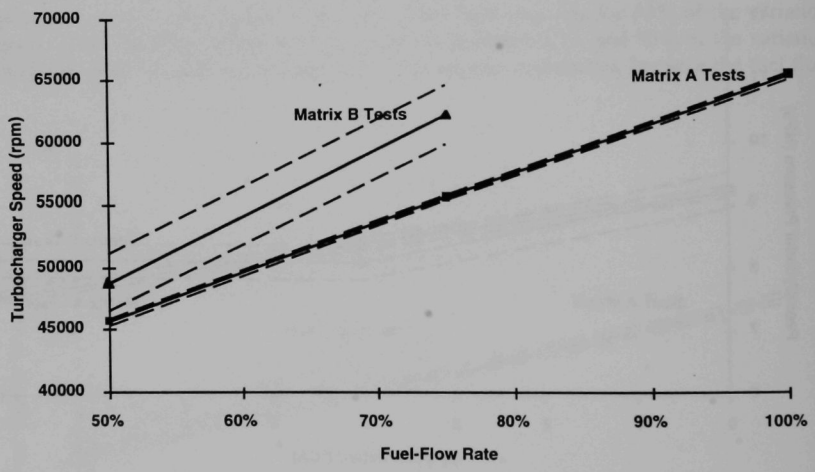

FIGURE 3.15 Effect of Fuel-Flow Rate on Turbocharger Speed, #2 Fuel

the source of energy for the turbocharger. Water content of the fuel has the next-largest effect on exhaust temperature, but it accounts for only 2% of the variation. Water content has a negligible effect on turbocharger speed.

In matrix B tests, oxygen content of the air appears to make a major contribution to both exhaust temperature and turbocharger speed, but this is due to the strong coupling between fuel flow and oxygen content. Both exhaust temperature and turbocharger speed increase with increasing fuel flow. If oxygen enrichment is used to increase the power output of the engine, the turbocharger must be rematched to the engine to avoid excessive pressures, and the higher temperatures must be dealt with. No adverse effects were observed from the higher boost pressure and exhaust temperature, but test-stand limitations prevented realization of the full power potential of oxygen enrichment.

3.2 Test Series II: #6 Diesel Fuel

Test matrix A, characterized by constant fuel-flow rate, for #6 fuel was identical to the one used for #2 fuel. However, test matrix B (constant equivalence-ratio case) had to be modified when #6 fuel was used. The limitations of the dynamometer, malfunctioning of the water-fuel emulsifier, and the inability of the fuel system to efficiently handle the heavy fuel forced the engine load to be redefined. The test engine, Caterpillar model 3406B, was a high-speed diesel engine that had never been operated with #6 diesel fuel before these tests. One of the project objectives was to operate this engine with a lower-grade fuel, such as #6 diesel fuel. The expectation was that the oxygen-enriched air would make it easier to burn a lower-grade, cheaper fuel in a high-speed diesel engine. The main problem with a heavy fuel is its viscosity. Typically, commercial-grade #2 diesel fuel (widely used in the United States) has a 3.0-cSt viscosity, which is very closely controlled and monitored. Heavy fuels, on the other hand, are not well-specified. The batch of #6 fuel used in this test series had a viscosity of about 22.0 cSt. Thus, the problem was to pump and inject the fuel into the engine. A fuel-heating system was installed in the test cell, and the fuel was heated to about 200°F. This reduced the fuel viscosity sufficiently to inject the fuel into the engine. The engine was not modified to accommodate the #6 fuel, so some penalty in efficiency was expected.

3.2.1 Percent Contributions by Independent Variables

The percent contributions of the independent variables and of random error to the measured variation in dependent variables are shown in Tables 3.3 (matrix A tests) and 3.4 (matrix B tests). The contribution of random error to the smoke measurement is a smaller percentage of the variation than was the case for #2 fuel. The engine produced considerably more smoke when running on #6 fuel than when running on #2 fuel. Thus, the measuring instrument was able to operate in a more accurate range.

TABLE 3.3 Percent Contribution by Independent Variables and Error, #6 Fuel, Matrix A

Independent Variable	Dependent Variables							
	NO_x	Particulates	Smoke	Thermal Efficiency	Exhaust Temperature	Turbocharger Speed	Peak Cylinder Pressure	Ignition Delay
Timing	4.29	13.14	2.40	15.14	7.95	1.98	18.26	0.00
Oxygen	93.75	31.43	72.29	15.08	0.28	0.21	0.60	14.56
Fuel rate	0.14	35.82	8.24	58.75	83.97	95.37	75.01	45.23
Water	1.44	13.86	5.95	0.00	1.05	0.48	0.00	0.00
Error	0.36	5.74	11.13	10.77	6.74	1.95	6.13	40.21

TABLE 3.4 Percent Contribution by Independent Variables and Error, #6 Fuel, Matrix B

Independent Variable	Dependent Variables							
	NO_x	Particulates	Smoke	Thermal Efficiency	Exhaust Temperature	Turbocharger Speed	Peak Cylinder Pressure	Ignition Delay
Timing	7.98	6.88	0.94	11.91	26.57	22.70	1.65	12.81
Oxygen	90.39	65.63	70.06	48.08	34.21	42.59	59.87	0.99
Fuel rate	0.00	15.72	14.79	19.98	23.69	22.64	16.68	1.72
Water	1.66	5.94	5.14	0.00	1.56	1.28	1.11	11.16
Error	0.98	5.83	9.06	20.03	14.97	10.78	20.69	73.31

The ignition delay shows a large percent contribution due to error for the tests with #6 fuel. During these tests, the shaft encoder slipped, with the result that the ignition-delay measurements are inaccurate. However, other measurements are not affected.

3.2.2 Emissions of Nitrogen Oxides

The NO_x emissions were slightly lower with #6 fuel than with #2 fuel. The trends were similar to those of the earlier data. Oxygen enrichment was the dominant variable (as shown in Figure 3.16); NO_x emissions increased by a factor of five when the oxygen level was increased from 21 to 30%. Water-emulsified fuel had no measurable effect in reducing NO_x emissions.

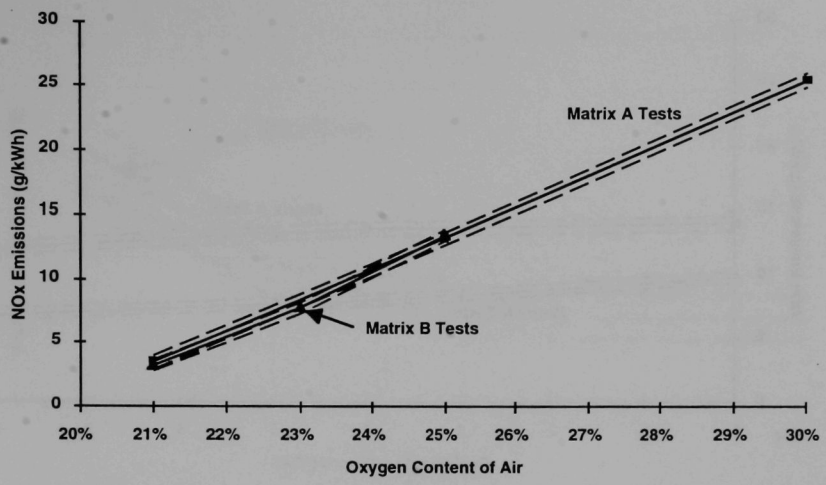

FIGURE 3.16 Effect of Oxygen Enrichment on NO_x Emissions, #6 Fuel

Retarding the injection timing reduced NO_x (as shown in Figure 3.17), but not enough to compensate for the effects of higher oxygen levels. The data indicate that, if the objective is to have the lowest NO_x emissions with #6 fuel, then zero oxygen enrichment and the maximum timing retardation should be employed. The data reinforce the conclusion that one of the two major challenges to implementing oxygen enrichment in engines is NO_x control.

3.2.3 Smoke and Particulate Emissions

The engine produced more smoke with #6 fuel than with #2 fuel. With oxygen enrichment, the visible smoke virtually disappeared. The smoke meter was not working properly and could not provide quantitative data. The mass particulate measurements were repeatable and showed predictable trends. Oxygen-enriched air (Figure 3.18) and fuel-flow rate (Figure 3.19) markedly decreased particulates. Retarding the injection timing increased the particulate emissions (as shown in Figure 3.20). Figure 3.21 shows that water emulsification of the fuel had a mixed effect on particulates, which increase with small amounts of water but decrease with larger amounts of water.

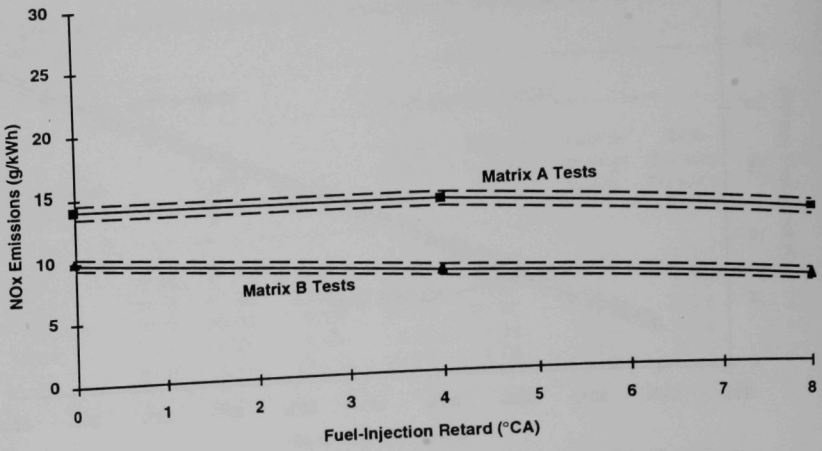

FIGURE 3.17 Effect of Fuel-Injection Timing on NO_X Emissions, #6 Fuel

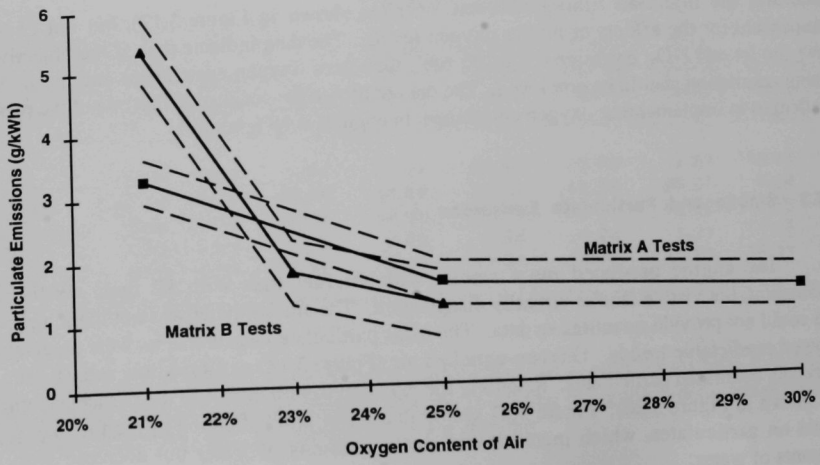

FIGURE 3.18 Effect of Oxygen Enrichment on Particulate Emissions, #6 Fuel

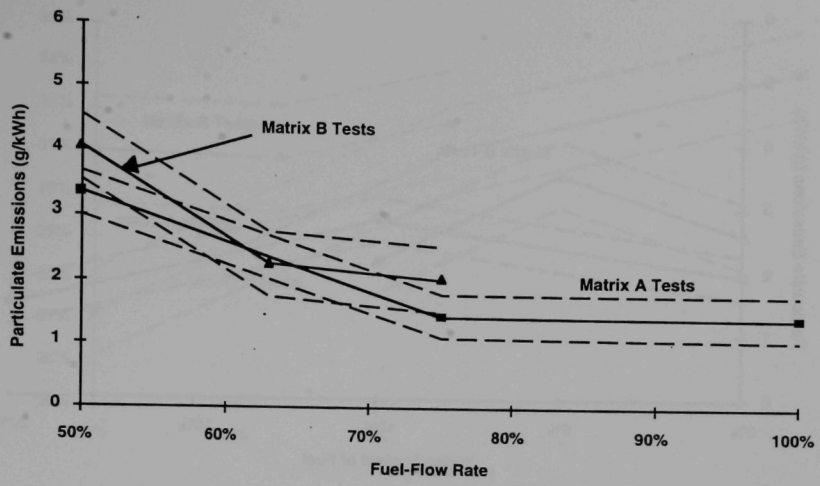

FIGURE 3.19 Effect of Fuel-Flow Rate on Particulate Emissions, #6 Fuel

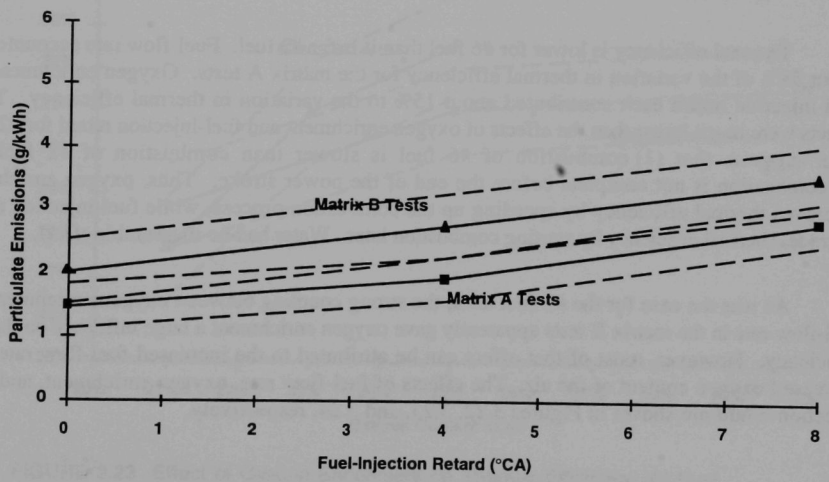

FIGURE 3.20 Effect of Fuel-Injection Retard on Particulate Emissions, #6 Fuel

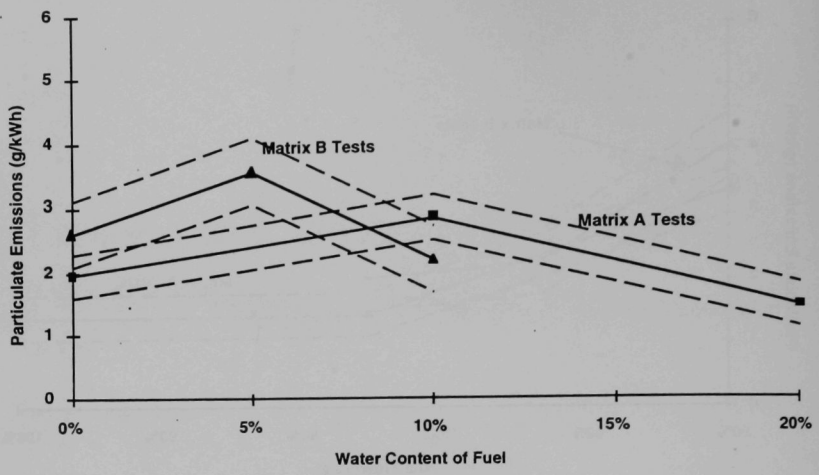

FIGURE 3.21 Effect of Water Content of Fuel on Particulate Emissions, #6 Fuel

3.2.4 Thermal Efficiency

Thermal efficiency is lower for #6 fuel than it is for #2 fuel. Fuel-flow rate accounted for about 58% of the variation in thermal efficiency for the matrix A tests. Oxygen enrichment and fuel-injection retard each contributed about 15% to the variation in thermal efficiency. These effects were much larger than the effects of oxygen enrichment and fuel-injection retard for #2 fuel. This suggests that (1) combustion of #6 fuel is slower than combustion of #2 fuel and (2) combustion is not complete before the end of the power stroke. Thus, oxygen enrichment improves thermal efficiency by speeding up the combustion process, while fuel-injection retard degrades thermal efficiency by starting combustion later. Water had no measurable effect.

As was the case for the #2 fuel tests, the strong coupling between oxygen enrichment and fuel-flow rate in the matrix B tests apparently gave oxygen enrichment a large influence on thermal efficiency. However, most of that effect can be attributed to the increased fuel-flow rate with increased oxygen content of the air. The effects of fuel-flow rate, oxygen enrichment, and fuel-injection retard are shown in Figures 3.22, 3.23, and 3.24, respectively.

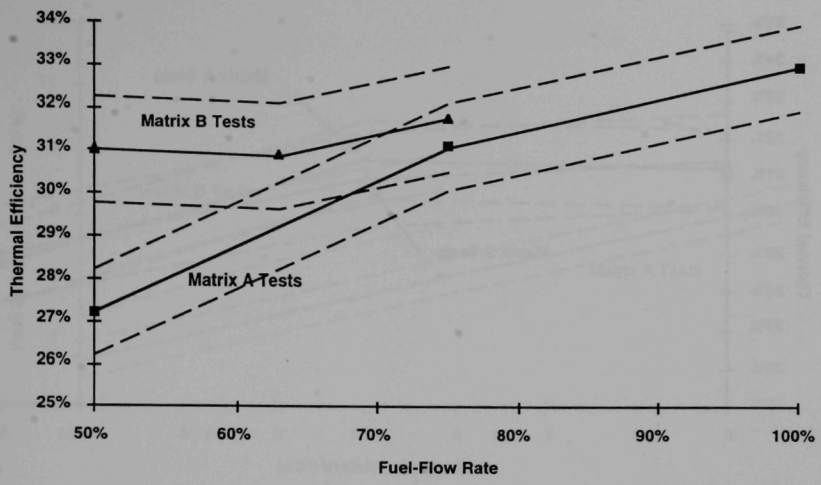

FIGURE 3.22 Effect of Fuel-Flow Rate on Thermal Efficiency, #6 Fuel

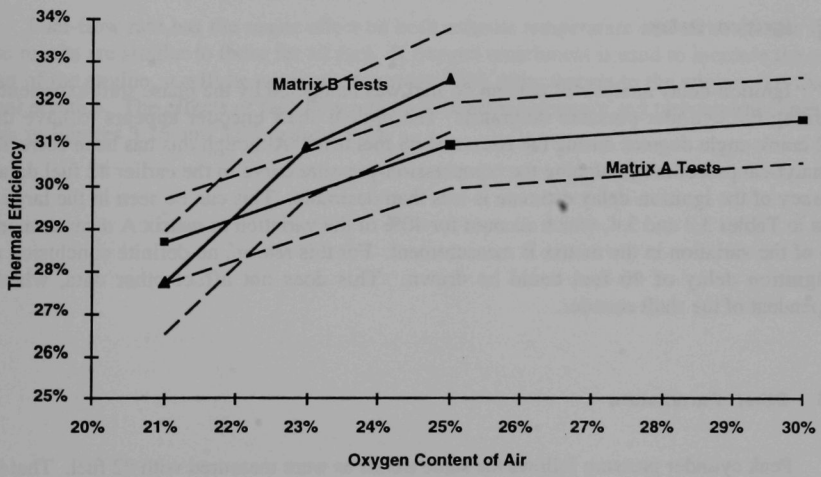

FIGURE 3.23 Effect of Oxygen Enrichment on Thermal Efficiency, #6 Fuel

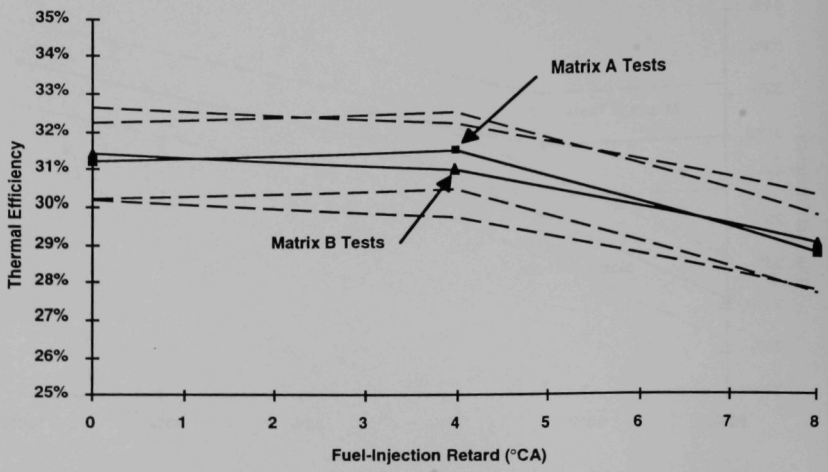

FIGURE 3.24 Effect of Fuel-Injection Retard on Thermal Efficiency, #6 Fuel

3.2.5 Ignition Delay

Ignition-delay analysis of data on #6 fuel was hampered by the phase shift experienced in obtaining the cylinder-pressure diagrams. The optical shaft encoder appears to have drifted 7–12 crank-angle degrees during the course of #6 fuel tests. Although this has been corrected by an analytical procedure (matching the compression-pressure curve to the earlier #2 fuel data), the accuracy of the ignition-delay estimate is less than desirable. This can be seen in the large error terms in Tables 3.3 and 3.4, which account for 40% of the variation in matrix A measurement and 73% of the variation in the matrix B measurement. For this reason, no definite conclusion about the ignition delay of #6 fuel could be drawn. This does not affect other data, which are independent of the shaft encoder.

3.2.6 Other Parameters

Peak cylinder pressure follows the same trends as were measured with #2 fuel. That is, the fuel-flow rate makes the main contribution to the variation in peak cylinder pressure, with fuel-injection retard having a smaller effect. Oxygen enrichment and water content of the fuel have negligible effects. The coupling between fuel-flow rate and oxygen enrichment in the matrix B tests accounts for the apparent large effect of oxygen enrichment in those tests. The effect of fuel-flow rate on peak cylinder pressure is shown in Figure 3.25.

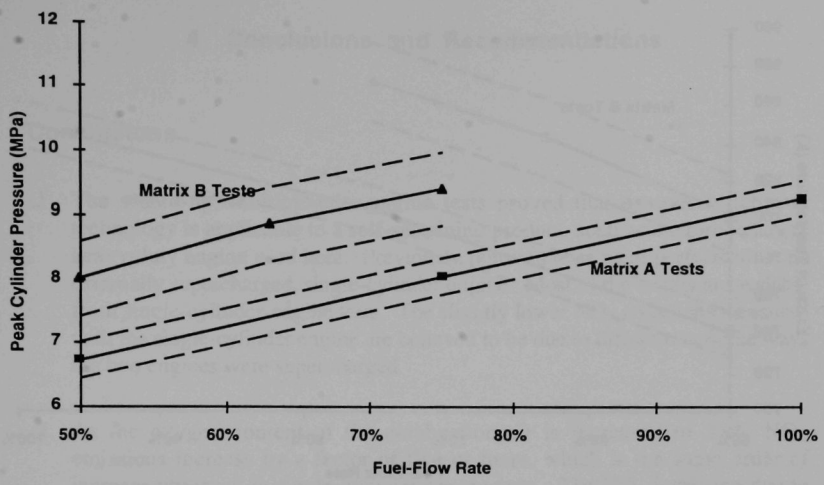

FIGURE 3.25 Effect of Fuel-Flow Rate on Ignition Delay, #6 Fuel

Fuel-flow rate has the major effect on both exhaust temperature and turbocharger speed. These results are similar to those for #2 fuel. If oxygen enrichment is used to increase the power output of the engine, it will be necessary to rematch the turbocharger to the engine, but this is a normal practice. The effects of fuel-flow rate on exhaust temperature and turbocharger speed are shown in Figures 3.26 and 3.27, respectively.

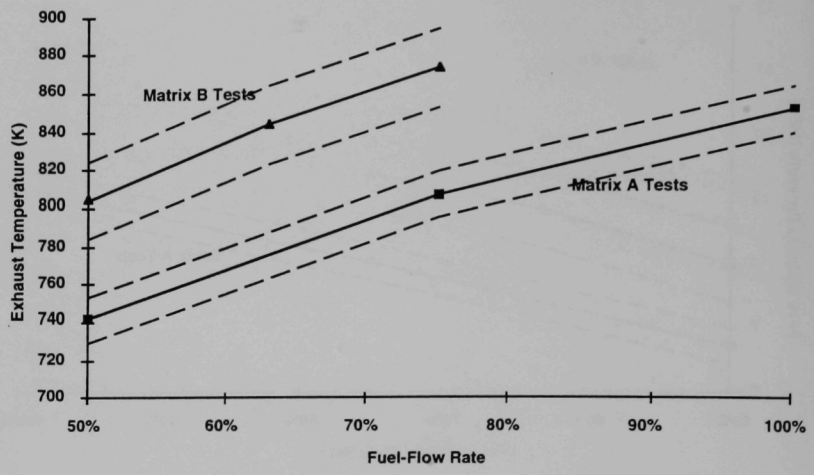

FIGURE 3.26 Effect of Fuel-Flow Rate on Exhaust Temperature, #6 Fuel

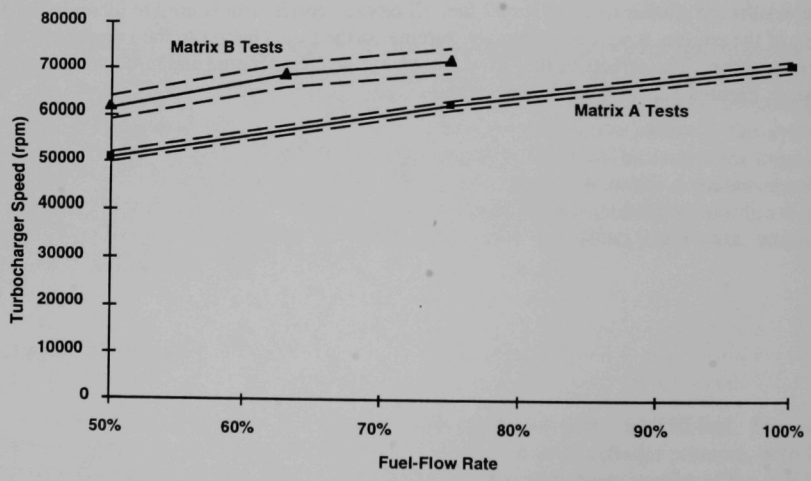

FIGURE 3.27 Effect of Fuel-Flow Rate on Turbocharger Speed, #6 Fuel

4 Conclusions and Recommendations

4.1 Conclusions

1. The scaled-up, multicylinder-engine tests proved that oxygen-enrichment technology is applicable to a self-sustaining product, such as the turbocharged heavy-duty engine used here. Previously reported tests were performed on an externally supercharged, single-cylinder engine. Most of the results are scalable from single-cylinder-engine tests. The slightly lower NO_x emissions measured with the single-cylinder engine are believed to be due to differences in the ways the two engines were supercharged.

2. As the oxygen content of the combustion air is increased to 30%, NO_x emissions increase by a factor of five or more, which is the same order of increase observed in single-cylinder-engine tests. The NO_x reduction due to fuel-injection retard is relatively small, and the NO_x reduction due to water-emulsified fuel is negligible. This leaves control of NO_x emissions as the major challenge in adapting oxygen-enrichment technology to diesel engines.

3. To the best of the investigators' knowledge, water-emulsified #6 fuel was successfully used in a high-speed diesel engine for the first time. Use of low-grade fuel offers considerable operating-cost savings potential. Oxygen enrichment can facilitate the use of heavy fuels in high-speed engines by (1) reducing smoke and particulate emissions and (2) improving thermal efficiency. The reduced thermal efficiency and high particulate emissions measured without added oxygen are an indication of incomplete combustion. However, additional research is necessary to further reduce emissions, improve combustion, and investigate the effect of these fuels on engine durability.

4. No adverse effect on turbocharger performance due to oxygen-enriched air was observed. If oxygen enrichment is used to produce additional power, the turbocharger must be rematched to the engine. This is a consequence of the increased fuel flow, rather than the added oxygen, and is normal procedure in the design of diesel engines.

5. The potential for increased power density and reduced particulate generation remains the same as was reported in the single-cylinder-engine tests.

4.2 Recommendations

1. The NO_x emissions and availability of a low-cost, compact membrane are the two major challenges in commercializing the oxygen-enrichment technology, and research efforts should focus on these two issues. Novel methods must be investigated to reduce the formation of NO_x during combustion, as well as in postcombustion equipment, such as a catalytic converter.

2. An advanced membrane design should be developed that uses materials highly permeable to oxygen. A full-scale cogeneration system should be designed to make full use of the oxygen-enrichment technology. Analytical and paper design should be subject to thorough design review by the industrial participants before a full-scale hardware system demonstration is commissioned.

3. Further investigation of water-emulsified fuel should be given a low priority. Up to 20% water emulsified with the fuel has little effect on NO_x emissions. Whether larger amounts of water would be effective in controlling NO_x is unknown, but such large amounts of water could be expected to cause longer ignition delays and corrosion in the fuel-injection system.

4. Use of heavy fuel, such as #6 diesel fuel, in a high-speed diesel engine has significant economic merit. Because the economic incentives are high, research is warranted on improved combustion efficiency, lower emissions, and engine durability with low-grade fuel.

5 References

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Appendix A:

Analysis of Data

TABLE A.1 Sample Analysis Table, Matrix A, #2 Diesel Fuel

a. Analysis of main effect

Trial No.	Injection Retard (°) 0, 4, 8	Oxygen Conc. (%) 21, 25, 30	Fuel Rate (%) 100, 75, 50	Water (%) 0, 10, 20	NO_x I (g/kWh)	NO_x II (g/kWh)	Mean	Factor
1	1	1	1	1	6.36	6.29	18.48	A_1
2	1	2	2	2	18.62	18.45	15.48	A_2
3	1	3	3	3	30.87	30.29	13.48	A_3
4	2	1	2	3	3.77	3.92	4.38	B_1
5	2	2	3	1	14.36	15.27	15.52	B_2
6	2	3	1	2	27.66	27.92	27.55	B_3
7	3	1	3	2	2.92	3.00	15.77	C_1
8	3	2	1	3	13.12	13.28	15.55	C_2
9	3	3	2	1	24.11	24.42	16.12	C_3
Total					141.79	142.84	15.13	D_1
CF[a]					2233.82	2267.03	16.43	D_2
Avg.					15.75	15.87	15.88	D_3

b. Analysis of variance

Source	f	S	V	F	S'	Contri-bution (%)
Timing	2	76.13	38.06	483.69	75.97	4.48
Oxygen	2	1611.10	805.55	10236.45	1610.95	95.10
Fuel	2	0.99	0.49	6.29	0.83	0.05
Water	2	5.05	2.53	32.11	4.90	0.29
Error, e	9	0.71	0.08		1.34	0.08
Total	17	1693.98				100.00

[a] Correction Factor. See Roy (Reference 1), pp. 50 and 112.

where

$F_\alpha(f_1,f_2)$ = variance ratio required for confidence level of $(1-\alpha)$,

f_1 = degrees of freedom for the mean ($f_1 = 1$),

f_2 = degrees of freedom for the error,

V_e = error variance, and

n = number of tests under that condition.

The definitions of the above terms are given in the next section. The variance ratio is determined from the same F-tables used in ANOVA (Reference 2). In the calculation of confidence intervals for this analysis, the variance ratio of 5.12, which corresponds to a 95% confidence, is used for all cases. The confidence intervals are shown in the main effect plots as two parallel curves bounding the curve of the main effects.

A.2 Analysis of Variance (ANOVA)

Results of the experiments were analyzed to estimate the contribution of individual factors to the performance and emissions of the engine. ANOVA is the statistical technique used for this purpose. The technique determines the variability (variance) of the data and provides a measure of confidence derived from the variance. In the analysis of variance many quantities, such as degrees of freedom, variation, variance, etc., are computed and organized in a standard tabular format, as shown in Table A.1b. A brief description of the various terms is provided below.

A.2.1 Degrees of Freedom (f)

The number of degrees of freedom is a measure of the amount of information that can be uniquely determined from a given set of data. For data concerning a factor, it is numerically equal to one less than the number of levels. For a factor A with three levels, A_1 data can be compared with A_2 and A_3 data and not itself. Thus, $f = 2$. For an experiment with n trials and r repetitions of each trial, the total number of trials is $n \times r$, and the total number of degrees of freedom is $n \times r - 1$.

In Table A.1, for example, $n = 9$, $r = 2$, and $f = 17$.

A.2.2 Variation (S)

Variation, or the sum of the squares of deviations, is a measure of the deviation of the experimental data from its mean value.

A.2.3 Variance (V)

Variance measures the distribution of the data about the mean of the data. It is the value of variation divided by the degrees of freedom, i.e., $V = S/f$. The variance associated with the error, V_e, signifies the extent of dispersion of individual measurements; a large V_e means a large difference between individual measurements.

A.2.4 Variance Ratio (F)

Variance ratios are used for the so-called significance test made prior to the calculation of the percentage of contribution to see if the variation is larger than the error (denoted by e in Table A.1b) variance. It is the ratio of variance due to the effect of a factor and variance due to the error term, $F = V/V_e$. This ratio is used to measure the significance of the factor under investigation with respect to the variance of all the factors included in the error term. The F-value obtained in the analysis is compared with a value from standard F-tables for a given statistical level of significance.

A.2.5 Pure Sum of Squares (S')

The variance due to a factor contains some amount due to error. The pure sum of squares is the expected amount of variation due solely to the factor by subtracting off the contribution from the error. It is determined by $S' = S - f \times V_e$.

A.2.6 Percent Contribution

The portion of the total variation observed in an experiment attributed to each significant factor is reflected in the percent contribution. The percent contribution for any factor is obtained by dividing the pure sum of squares for that factor by the total variation, S_T, and multiplying the result by 100. The percent contribution due to error (unknown and uncontrolled factors) provides an estimate of the adequacy of the experiment. If the percent contribution due to error is low, say 15% or less, then it is assumed that no important factors were omitted from the experiment. A high value (50% or more) would indicate that some important factors were left out, conditions were not precisely controlled, or measurement error was excessive.

A.3 Dummy Treatment

Because of the limitations of the operating system, it was necessary to modify the levels of oxygen and engine load in matrix B for the #2 fuel experiments. Dummy treatment accommodates two-level factors by using only two of the three possible levels for the factor, with the indicated third level simply repeating one of the previous two levels. Orthogonality is maintained with either one of the two levels for the factor being repeated, so whichever is easier, cheaper, or makes more sense should be repeated. In our experiments, level 3 of oxygen (i.e., 30%) was modified to assume the value of level 1 (i.e., 21%), and level 1 of the engine load (i.e., 100%) was modified to assume the value of level 2 (i.e., 75%). Analysis of main effects and variance follow the same procedures for cases without dummy treatment.

A.4 References for Appendix A

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Appendix B:

Data Sets from the Six-Cylinder Engine Tests with #2 Diesel Fuel

ARGONNE 6-CYLINDER ENGINE TEST MATRIX

SEQUENCE #1 (#2 FUEL)

ALI TEST #	ANL CODE	FUEL RATE OR EQU. RATIO	INJ. RETARD	OXYGEN %	LOAD %	WATER %
301C	B.L.	-	0	21	100	0
302C	B.L.	-	0	21	75	0
303C	B.L.	-	0	21	50	0
342	A2	FUEL*	0	25.5	75	10
351	B3	EQ.R.**	0	21	50	20
343	A3	FUEL	0	30	50	20
307C	B.L.	-	8	21	100	0
344	A8	FUEL	8	25.5	100	20
309A	B7	EQ.R.	8	21	50	10
310B	B9	EQ.R.	8	21	75	0
311A	B.L.	-	4	21	100	0
345	A6	FUEL	4	30	100	10
313A	B4	EQ.R.	4	21	75	20
346	A5	FUEL	4	25.5	50	0
347	A9	FUEL	8	30	75	0
352	B8	EQ.R.	8	25.5	75	20
348	A7	FUEL	8	21	50	10
349	A1	FUEL	0	21	100	0
319A	B2	EQ.R.	0	25.5	75	10
353	B1	EQ.R.	0	21	75	0
350	A4	FUEL	4	21	75	20
322A	B5	EQ.R.	4	25.5	50	0
323C	B6	EQ.R.	4	21	75	10

* Maintain baseline fuel rate measured at corresponding engine load.

** Maintain baseline equivalence ratio measured at corresponding engine load.

ARGONNE 6-CYLINDER ENGINE TEST MATRIX

SEQUENCE #2 (#2 FUEL)

ALI TEST #	ANL CODE	FUEL RATE OR EQUI. RATIO	INJ. RETARD	OXYGEN %	LOAD %	WATER %
324A	A8	FUEL*	8	25.5	100	20
325B	B9	EQ.R.**	8	21	75	0
326A	B7	EQ.R.	8	21	50	10
327	A5	FUEL	4	25.5	50	0
354	B6	EQ.R.	4	21	75	10
329	A4	FUEL	4	21	75	20
330	A1	FUEL	0	21	100	0
331	B2	EQ.R.	0	25.5	75	10
332	A3	FUEL	0	30	50	20
333	A6	FUEL	4	30	100	10
334	B4	EQ.R.	4	21	75	20
335	B5	EQ.R.	4	25.5	50	0
336	A7	FUEL	8	21	50	10
355	B8	EQ.R.	8	25.5	75	20
338	A9	FUEL	8	30	75	0
339	A2	FUEL	0	25.5	75	10
356	B1	EQ.R.	0	21	75	0
357	B3	EQ.R.	0	21	50	20

* Maintain baseline fuel rate measured at corresponding engine load.

** Maintain baseline equivalence ratio measured at corresponding engine load.

Comparison of Baseline Data At Different Engine Load Levels

Run #	301C	302C	303C
Test Matrix Data Point #	BL	BL	BL
Date	12/31/91	12/31/91	12/31/91
Fuel Type (#)	2	2	2
Injection Retard (deg./btdc)	0	0	0
O2 in Intake Air (Vol-%)	21	21	21
O2 in Exhaust Air (Vol-%)	11.4	12.1	13.4
Intake Air Flow (kg/min)	24.80	21.08	17.89
O2 Flow from Air (kg/min)	5.75	4.89	4.15
O2 Flow from Bottle (kg/min)	0.00	0.00	0.00
Total O2 Flow (kg/min)	5.75	4.89	4.15
Engine Load Level (%)	100	75	50
Power (kW)	223.6	167.7	111.9
H2O in Fuel (Wt-%) -- Planned	0	0	0
H2O in Fuel (Wt-%) -- Actual	0	0	0
Net Fuel Rate (kg/min)	0.770	0.591	0.429
Fuel-to-O2 Ratio	0.1339	0.1209	0.1033
BSFC (kg/kW-hr)	0.207	0.212	0.230
Turbo Speed (rpm)	65400	55900	45700
Intake Manifold Pressure (MPa)	0.19	0.16	0.14
Peak Cylinder Pressure (MPa)	10.48	8.97	7.41
Exhaust Temperature (K)	821.5	773.7	703.2
Thermal Efficiency (%)	40.9	39.9	36.7
Smoke (%)	1.1	1.7	2.3
Particulates (g/kWh)	0.227	0.309	0.440
NOx (g/kWh)	6.73	6.60	6.20
Ignition Delay (deg)	13.7	14.3	16

Comparison of Baseline Data for Different Injection Timing Retards

Run #	301C	311A	307C
Test Matrix Data Point #	BL	BL	BL
Date	12/31/91	01/22/92	01/30/92
Fuel Type (#)	2	2	2
Injection Retard (deg./btdc)	0	4	8
O2 in Intake Air (Vol-%)	21	20.9	21
O2 in Exhaust Air (Vol-%)	11.4	11.4	11.6
Intake Air Flow (kg/min)	24.80	24.93	25.97
O2 Flow from Air (kg/min)	5.75	5.78	6.02
O2 Flow from Bottle (kg/min)	0.00	0.00	0.00
Total O2 Flow (kg/min)	5.75	5.78	6.02
Engine Load Level (%)	100	100	100
Power (kW)	223.6	223.6	223.6
H2O in Fuel (Wt-%) -- Planned	0	0	0
H2O in Fuel (Wt-%) -- Actual	0	0	0
Net Fuel Rate (kg/min)	0.770	0.793	0.815
Fuel-to-O2 Ratio	0.1339	0.1372	0.1353
BSFC (kg/kW-hr)	0.207	0.213	0.219
Turbo Speed (rpm)	65400	68200	70100
Intake Manifold Pressure (MPa)	0.19	0.20	0.21
Peak Cylinder Pressure (MPa)	10.48	9.71	9.17
Exhaust Temperature (K)	821.5	845.4	856.5
Thermal Efficiency (%)	40.9	39.7	38.6
Smoke (%)	1.1	2.2	2.5
Particulates (g/kWh)	0.227	0.278	0.344
NOx (g/kWh)	6.73	5.11	4.12
Ignition Delay (deg)	13.7	14.3	16

No. 2 Fuel, Matrix A
0 Degree Retard, 21% Oxygen, 100% Load, 0% Water

Run #	349	330
Test Matrix Data Point #	A1	A1
Date	01/31/92	01/17/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	20.9	20.9
O2 in Exhaust Air (Vol-%)	11.4	11.5
Intake Air Flow (kg/min)	23.92	24.53
O2 Flow from Air (kg/min)	5.55	5.69
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	5.55	5.69
Engine Load Level (%)	100	100
Power (kW)	219.8	223.6
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.769	0.777
Fuel-to-O2 Ratio	0.1386	0.1366
BSFC (kg/kW-hr)	0.210	0.208
Turbo Speed (rpm)	65800	66400
Intake Manifold Pressure (MPa)	0.19	0.20
Peak Cylinder Pressure (MPa)	10.28	10.28
Exhaust Temperature (K)	834.3	830.9
Thermal Efficiency (%)	40.2	40.5
Smoke (%)	2.1	1.8
Particulates (g/kWh)	0.235	0.200
NOx (g/kWh)	6.36	6.29
Ignition Delay (deg)	14.2	14.3

No. 2 Fuel, Matrix A
0 Degree Retard, 25.5% Oxygen, 75% Load, 10% Water

Run #	339	342
Test Matrix Data Point #	A2	A2
Date	01/24/92	01/27/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	16.7	16.7
Intake Air Flow (kg/min)	20.24	20.31
O2 Flow from Air (kg/min)	4.40	4.42
O2 Flow from Bottle (kg/min)	1.27	1.27
Total O2 Flow (kg/min)	5.67	5.69
Engine Load Level (%)	75	75
Power (kW)	167.4	166.1
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10
Net Fuel Rate (kg/min)	0.589	0.590
Fuel-to-O2 Ratio	0.1039	0.1036
BSFC (kg/kW-hr)	0.211	0.213
Turbo Speed (rpm)	54500	54400
Intake Manifold Pressure (MPa)	0.16	0.16
Peak Cylinder Pressure (MPa)	9.45	9.35
Exhaust Temperature (K)	756.5	758.7
Thermal Efficiency (%)	40.0	39.6
Smoke (%)	1.5	0.9
Particulates (g/kWh)	0.174	0.156
NOx (g/kWh)	18.45	18.62
Ignition Delay (deg)	14	13.9

No. 2 Fuel, Matrix A
0 Degree Retard, 30% Oxygen, 50% Load, 20% Water

Run #	332	343
Test Matrix Data Point #	A3	A3
Date	01/17/92	01/27/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	30	30
O2 in Exhaust Air (Vol-%)	22.3	22
Intake Air Flow (kg/min)	17.24	17.32
O2 Flow from Air (kg/min)	3.50	3.52
O2 Flow from Bottle (kg/min)	2.15	2.15
Total O2 Flow (kg/min)	5.65	5.67
Engine Load Level (%)	50	50
Power (kW)	109.9	109.9
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	20	20
Net Fuel Rate (kg/min)	0.429	0.428
Fuel-to-O2 Ratio	0.0760	0.0754
BSFC (kg/kW-hr)	0.234	0.234
Turbo Speed (rpm)	44000	43600
Intake Manifold Pressure (MPa)	0.13	0.13
Peak Cylinder Pressure (MPa)	7.91	8.10
Exhaust Temperature (K)	684.8	684.8
Thermal Efficiency (%)	36.0	36.2
Smoke (%)	0.6	0.8
Particulates (g/kWh)	0.136	0.176
NOx (g/kWh)	30.29	30.87
Ignition Delay (deg)	14.4	15.6

No. 2 Fuel, Matrix A
4 Degree Retard, 21% Oxygen, 75% Load, 20% Water

Run #	329	350
Test Matrix Data Point #	A4	A4
Date	01/15/92	02/03/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	20.8	20.9
O2 in Exhaust Air (Vol-%)	12.3	12
Intake Air Flow (kg/min)	20.76	20.41
O2 Flow from Air (kg/min)	4.82	4.74
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	4.82	4.74
Engine Load Level (%)	75	75
Power (kW)	163.6	162.3
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	20	20
Net Fuel Rate (kg/min)	0.590	0.591
Fuel-to-O2 Ratio	0.1225	0.1247
BSFC (kg/kW-hr)	0.216	0.218
Turbo Speed (rpm)	56100	56000
Intake Manifold Pressure (MPa)	0.16	0.16
Peak Cylinder Pressure (MPa)	8.16	8.09
Exhaust Temperature (K)	758.2	769.8
Thermal Efficiency (%)	39.0	38.7
Smoke (%)	1.2	1.7
Particulates (g/kWh)	0.210	0.230
NOx (g/kWh)	3.92	3.77
Ignition Delay (deg)	16.6	17

No. 2 Fuel, Matrix A
4 Degree Retard, 25.5% Oxygen, 50% Load, 0% Water

Run #	327	346
Test Matrix Data Point #	A5	A5
Date	01/14/92	01/29/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	18.2	18
Intake Air Flow (kg/min)	17.59	17.69
O2 Flow from Air (kg/min)	3.83	3.85
O2 Flow from Bottle (kg/min)	1.10	1.11
Total O2 Flow (kg/min)	4.93	4.96
Engine Load Level (%)	50	50
Power (kW)	107.3	108.6
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.428	0.428
Fuel-to-O2 Ratio	0.0869	0.0864
BSFC (kg/kW-hr)	0.239	0.237
Turbo Speed (rpm)	45800	45900
Intake Manifold Pressure (MPa)	0.14	0.14
Peak Cylinder Pressure (MPa)	6.95	7.15
Exhaust Temperature (K)	703.7	705.9
Thermal Efficiency (%)	35.3	35.7
Smoke (%)	1.6	1.8
Particulates (g/kWh)	0.196	0.230
NOx (g/kWh)	15.27	14.36
Ignition Delay (deg)	13.9	14.8

No. 2 Fuel, Matrix A
4 Degree Retard, 30% Oxygen, 100% Load, 10% Water

Run #	333	345
Test Matrix Data Point #	A6	A6
Date	01/22/92	01/29/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	30	30
O2 in Exhaust Air (Vol-%)	20.3	20.5
Intake Air Flow (kg/min)	23.97	24.01
O2 Flow from Air (kg/min)	4.87	4.88
O2 Flow from Bottle (kg/min)	2.98	2.99
Total O2 Flow (kg/min)	7.85	7.87
Engine Load Level (%)	100	100
Power (kW)	221.1	221.1
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10
Net Fuel Rate (kg/min)	0.770	0.768
Fuel-to-O2 Ratio	0.0981	0.0976
BSFC (kg/kW-hr)	0.209	0.208
Turbo Speed (rpm)	64300	63700
Intake Manifold Pressure (MPa)	0.19	0.19
Peak Cylinder Pressure (MPa)	10.01	10.19
Exhaust Temperature (K)	814.8	809.3
Thermal Efficiency (%)	40.4	40.5
Smoke (%)	1.5	0.8
Particulates (g/kWh)	0.185	0.185
NOx (g/kWh)	27.92	27.66
Ignition Delay (deg)	12.7	12.3

No. 2 Fuel, Matrix A
8 Degree Retard, 21% Oxygen, 50% Load, 10% Water

Run #	336	348
Test Matrix Data Point #	A7	A7
Date	01/23/92	01/30/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	20.9	20.9
O2 in Exhaust Air (Vol-%)	13.6	13.6
Intake Air Flow (kg/min)	17.48	17.76
O2 Flow from Air (kg/min)	4.06	4.12
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	4.06	4.12
Engine Load Level (%)	50	50
Power (kW)	102.2	104.8
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10
Net Fuel Rate (kg/min)	0.430	0.429
Fuel-to-O2 Ratio	0.1059	0.1041
BSFC (kg/kW-hr)	0.252	0.246
Turbo Speed (rpm)	47200	47400
Intake Manifold Pressure (MPa)	0.14	0.14
Peak Cylinder Pressure (MPa)	6.29	6.44
Exhaust Temperature (K)	710.4	712.0
Thermal Efficiency (%)	33.5	34.4
Smoke (%)	2.6	4.2
Particulates (g/kWh)	0.501	0.568
NOx (g/kWh)	3.00	2.92
Ignition Delay (deg)	17.8	17.3

No. 2 Fuel, Matrix A
8 Degree Retard, 25.5% Oxygen, 100% Load, 20% Water

Run #	324A	344
Test Matrix Data Point #	A8	A8
Date	01/03/92	01/28/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	15.8	16.2
Intake Air Flow (kg/min)	24.31	24.54
O2 Flow from Air (kg/min)	5.29	5.34
O2 Flow from Bottle (kg/min)	1.52	1.54
Total O2 Flow (kg/min)	6.81	6.88
Engine Load Level (%)	100	100
Power (kW)	217.6	217.2
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	20	20
Net Fuel Rate (kg/min)	0.770	0.770
Fuel-to-O2 Ratio	0.1130	0.1120
BSFC (kg/kW-hr)	0.212	0.213
Turbo Speed (rpm)	65400	65000
Intake Manifold Pressure (MPa)	0.19	0.19
Peak Cylinder Pressure (MPa)	8.61	8.77
Exhaust Temperature (K)	819.3	813.2
Thermal Efficiency (%)	39.8	39.7
Smoke (%)	0.7	1.3
Particulates (g/kWh)	0.177	0.136
NOx (g/kWh)	13.28	13.12
Ignition Delay (deg)	12.9	13.7

No. 2 Fuel, Matrix A
8 Degree Retard, 30% Oxygen, 75% Load, 0% Water

Run #	338	347
Test Matrix Data Point #	A9	A9
Date	01/23/92	01/30/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	30	30
O2 in Exhaust Air (Vol-%)	21.1	21.4
Intake Air Flow (kg/min)	20.68	20.92
O2 Flow from Air (kg/min)	4.20	4.25
O2 Flow from Bottle (kg/min)	2.57	2.60
Total O2 Flow (kg/min)	6.77	6.85
Engine Load Level (%)	75	75
Power (kW)	158.5	161.0
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.592	0.591
Fuel-to-O2 Ratio	0.0875	0.0863
BSFC (kg/kW-hr)	0.224	0.220
Turbo Speed (rpm)	56300	56100
Intake Manifold Pressure (MPa)	0.16	0.16
Peak Cylinder Pressure (MPa)	7.60	7.82
Exhaust Temperature (K)	782.6	780.4
Thermal Efficiency (%)	37.6	38.3
Smoke (%)	0.4	1.6
Particulates (g/kWh)	0.141	0.171
NOx (g/kWh)	24.42	24.11
Ignition Delay (deg)	13.4	12.9

No. 2 Fuel, Matrix B
0 Degree Retard, 21% Oxygen, 75% Load, 0% Water

Run #	356	353
Test Matrix Data Point #	B1	B1
Date	02/25/92	02/26/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	21	20.9
O2 in Exhaust Air (Vol-%)	12	11.9
Intake Air Flow (kg/min)	21.53	20.70
O2 Flow from Air (kg/min)	4.99	4.80
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	4.99	4.80
Engine Load Level (%)	75	75
Power (kW)	167.4	161.0
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.614	0.587
Fuel-to-O2 Ratio	0.1229	0.1222
BSFC (kg/kW-hr)	0.220	0.219
Turbo Speed (rpm)	56500	55500
Intake Manifold Pressure (MPa)	0.16	0.16
Peak Cylinder Pressure (MPa)	8.99	8.77
Exhaust Temperature (K)	784.3	781.5
Thermal Efficiency (%)	38.4	38.6
Smoke (%)	2.4	1.8
Particulates (g/kWh)	0.348	0.326
NOx (g/kWh)	6.79	7.01
Ignition Delay (deg)	15.1	15.4

No. 2 Fuel, Matrix B
0 Degree Retard, 25.5% Oxygen, 75% Load, 10% Water

Run #	331	319A
Test Matrix Data Point #	B2	B2
Date	01/17/92	01/31/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	15.2	15.4
Intake Air Flow (kg/min)	26.13	24.88
O2 Flow from Air (kg/min)	5.68	5.41
O2 Flow from Bottle (kg/min)	1.64	1.56
Total O2 Flow (kg/min)	7.32	6.97
Engine Load Level (%)	75	75
Power (kW)	260.7	246.6
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10
Net Fuel Rate (kg/min)	0.888	0.842
Fuel-to-O2 Ratio	0.1213	0.1209
BSFC (kg/kW-hr)	0.204	0.205
Turbo Speed (rpm)	69900	67700
Intake Manifold Pressure (MPa)	0.21	0.20
Peak Cylinder Pressure (MPa)	11.44	11.06
Exhaust Temperature (K)	837.6	836.5
Thermal Efficiency (%)	41.3	41.2
Smoke (%)	0.4	1.1
Particulates (g/kWh)	0.126	0.196
NOx (g/kWh)	17.90	18.08
Ignition Delay (deg)	12.1	13.5

No. 2 Fuel, Matrix B
4 Degree Retard, 25.5% Oxygen, 50% Load, 0% Water

Run #	322A	335
Test Matrix Data Point #	B5	B5
Date	01/16/92	01/22/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	17.2	16.7
Intake Air Flow (kg/min)	20.19	20.72
O2 Flow from Air (kg/min)	4.39	4.51
O2 Flow from Bottle (kg/min)	1.27	1.30
Total O2 Flow (kg/min)	5.66	5.80
Engine Load Level (%)	50	50
Power (kW)	159.7	164.8
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.581	0.601
Fuel-to-O2 Ratio	0.1027	0.1036
BSFC (kg/kW-hr)	0.218	0.219
Turbo Speed (rpm)	54900	56500
Intake Manifold Pressure (MPa)	0.16	0.16
Peak Cylinder Pressure (MPa)	8.37	8.31
Exhaust Temperature (K)	766.5	782.6
Thermal Efficiency (%)	38.7	38.6
Smoke (%)	2.5	2.9
Particulates (g/kWh)	0.118	0.153
NOx (g/kWh)	17.55	15.54
Ignition Delay (deg)	13.2	13.3

No. 2 Fuel, Matrix B
4 Degree Retard, 21% Oxygen, 75% Load, 10% Water

Run #	323C	354
Test Matrix Data Point #	B6	B6
Date	02/25/92	02/26/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	20.8	20.9
O2 in Exhaust Air (Vol-%)	12.1	12.1
Intake Air Flow (kg/min)	21.91	21.77
O2 Flow from Air (kg/min)	5.08	5.05
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	5.08	5.05
Engine Load Level (%)	75	75
Power (kW)	166.1	166.1
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10
Net Fuel Rate (kg/min)	0.621	0.616
Fuel-to-O2 Ratio	0.1221	0.1219
BSFC (kg/kW-hr)	0.224	0.222
Turbo Speed (rpm)	57600	57800
Intake Manifold Pressure (MPa)	0.17	0.17
Peak Cylinder Pressure (MPa)	8.13	8.11
Exhaust Temperature (K)	783.7	785.9
Thermal Efficiency (%)	37.7	37.9
Smoke (%)	1.4	1.7
Particulates (g/kWh)	0.400	0.368
NOx (g/kWh)	4.51	4.37
Ignition Delay (deg)	16.2	16.1

No. 2 Fuel, Matrix B
8-Degree Retard, 21% Oxygen, 50% Load, 10% Water

Run #	326A	309A
Test Matrix Data Point #	B7	B7
Date	01/10/92	01/28/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	21	20.9
O2 in Exhaust Air (Vol-%)	13.8	13.7
Intake Air Flow (kg/min)	17.65	18.10
O2 Flow from Air (kg/min)	4.09	4.20
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	4.09	4.20
Engine Load Level (%)	50	50
Power (kW)	102.2	106.1
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10
Net Fuel Rate (kg/min)	0.421	0.430
Fuel-to-O2 Ratio	0.1028	0.1023
BSFC (kg/kW-hr)	0.247	0.243
Turbo Speed (rpm)	46300	47500
Intake Manifold Pressure (MPa)	0.14	0.14
Peak Cylinder Pressure (MPa)	6.37	6.46
Exhaust Temperature (K)	705.9	712.0
Thermal Efficiency (%)	34.2	34.7
Smoke (%)	3.1	3.8
Particulates (g/kWh)	0.507	0.562
NOx (g/kWh)	3.26	3.11
Ignition Delay (deg)	16.9	17.9

No. 2 Fuel, Matrix B
8-Degree Retard, 25.5% Oxygen, 75% Load, 20% Water

Run #	352	355
Test Matrix Data Point #	B8	B8
Date	02/17/92	02/21/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	14.9	15
Intake Air Flow (kg/min)	30.11	29.90
O2 Flow from Air (kg/min)	6.55	6.50
O2 Flow from Bottle (kg/min)	1.89	1.87
Total O2 Flow (kg/min)	8.43	8.38
Engine Load Level (%)	75	75
Power (kW)	287.5	286.2
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	20	20
Net Fuel Rate (kg/min)	1.034	1.028
Fuel-to-O2 Ratio	0.1226	0.1227
BSFC (kg/kW-hr)	0.216	0.215
Turbo Speed (rpm)	77700	77000
Intake Manifold Pressure (MPa)	0.24	0.24
Peak Cylinder Pressure (MPa)	10.70	10.67
Exhaust Temperature (K)	880.4	877.6
Thermal Efficiency (%)	39.1	39.2
Smoke (%)	0	1
Particulates (g/kWh)	0.150	0.165
NOx (g/kWh)	14.11	14.09
Ignition Delay (deg)	17.8	17.9

No. 2 Fuel, Matrix B
8-Degree Retard, 21% Oxygen, 75% Load, 0% Water

Run #	310B	325B
Test Matrix Data Point #	B9	B9
Date	02/19/92	02/21/92
Fuel Type (#)	2	2
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	20.9	20.9
O2 in Exhaust Air (Vol-%)	12.4	12.3
Intake Air Flow (kg/min)	21.92	22.21
O2 Flow from Air (kg/min)	5.09	5.15
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	5.09	5.15
Engine Load Level (%)	75	75
Power (kW)	158.5	159.7
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.612	0.620
Fuel-to-O2 Ratio	0.1204	0.1203
BSFC (kg/kW-hr)	0.232	0.233
Turbo Speed (rpm)	58500	58500
Intake Manifold Pressure (MPa)	0.17	0.17
Peak Cylinder Pressure (MPa)	7.44	7.51
Exhaust Temperature (K)	798.2	797.0
Thermal Efficiency (%)	36.4	36.2
Smoke (%)	3.4	3.3
Particulates (g/kWh)	0.678	0.632
NOx (g/kWh)	3.88	3.95
Ignition Delay (deg)	14.7	14.8

Six-Cylinder Diesel Engine Experiment

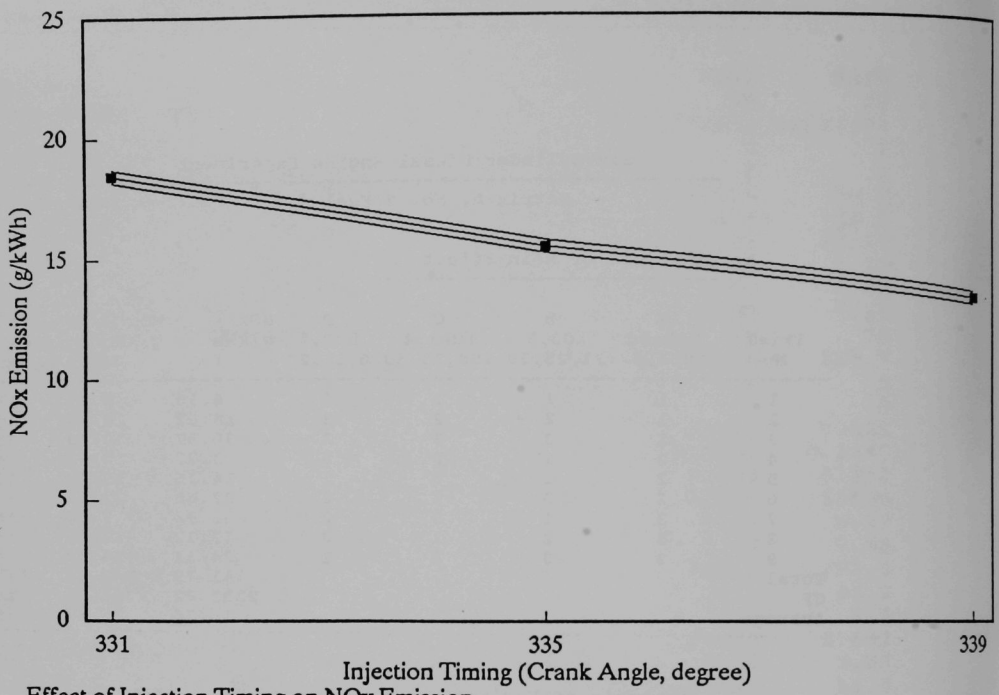
Matrix A, No. 2 Fuel

A. Analysis of Main Effect

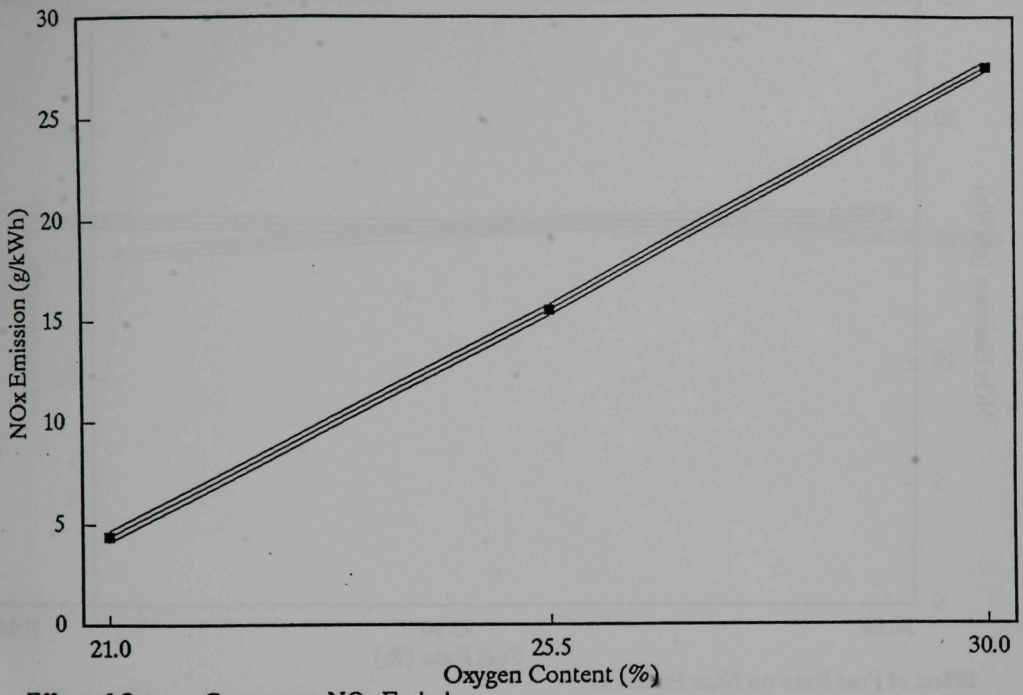
Trial No.	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	NOx g/kWh I	NOx g/kWh II	Mean
1	1	1	1	1	6.36	6.29	18.48
2	1	2	2	2	18.62	18.45	15.48
3	1	3	3	3	30.87	30.29	13.48
4	2	1	2	3	3.77	3.92	4.38
5	2	2	3	1	14.36	15.27	15.52
6	2	3	1	2	27.66	27.92	27.55
7	3	1	3	2	2.92	3.00	15.77
8	3	2	1	3	13.12	13.28	15.55
9	3	3	2	1	24.11	24.42	16.12
Total					141.79	142.84	15.13
CF					2233.82	2267.03	16.43
Average					15.75	15.87	15.88

B. Analysis of Variance

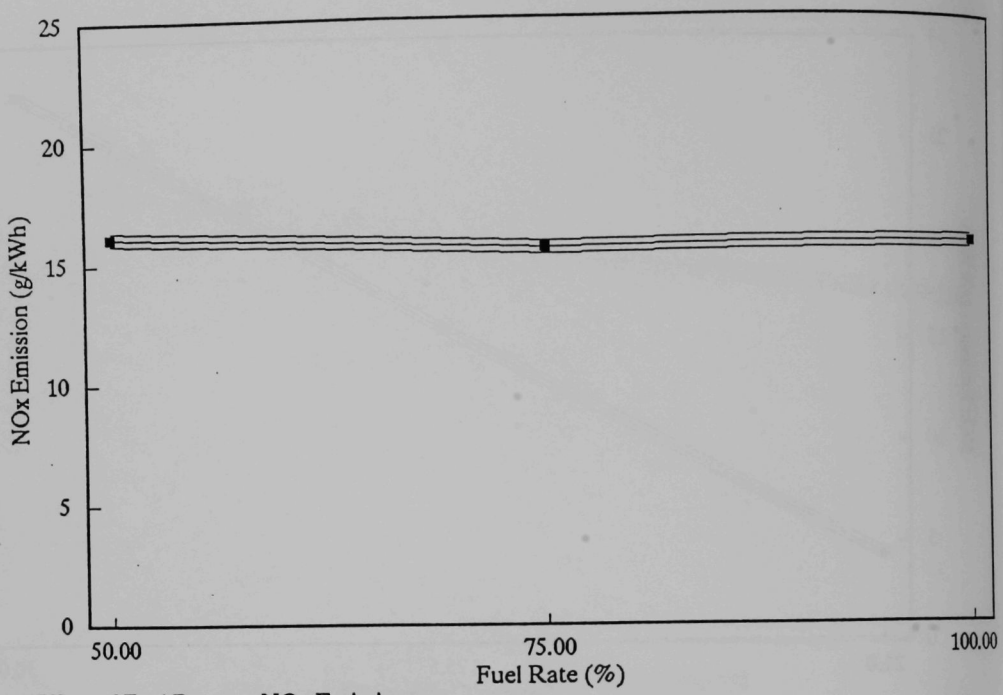
Source	f	S	V	F	S′	% contr.
Timing	2	76.13	38.06	483.69	75.97	4.48
Oxygen	2	1611.10	805.55	10236.45	1610.95	95.10
Fuel	2	0.99	0.49	6.29	0.83	0.05
Water	2	5.05	2.53	32.11	4.90	0.29
e	9	0.71	0.08			0.08
T	17	1693.98				100.00



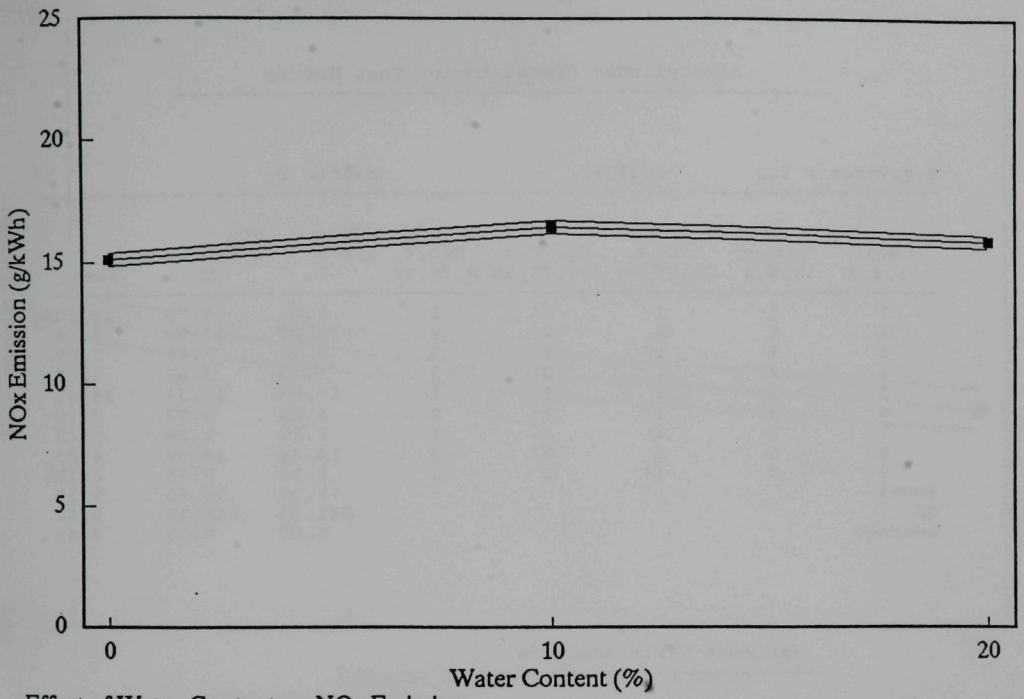
Effect of Injection Timing on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)

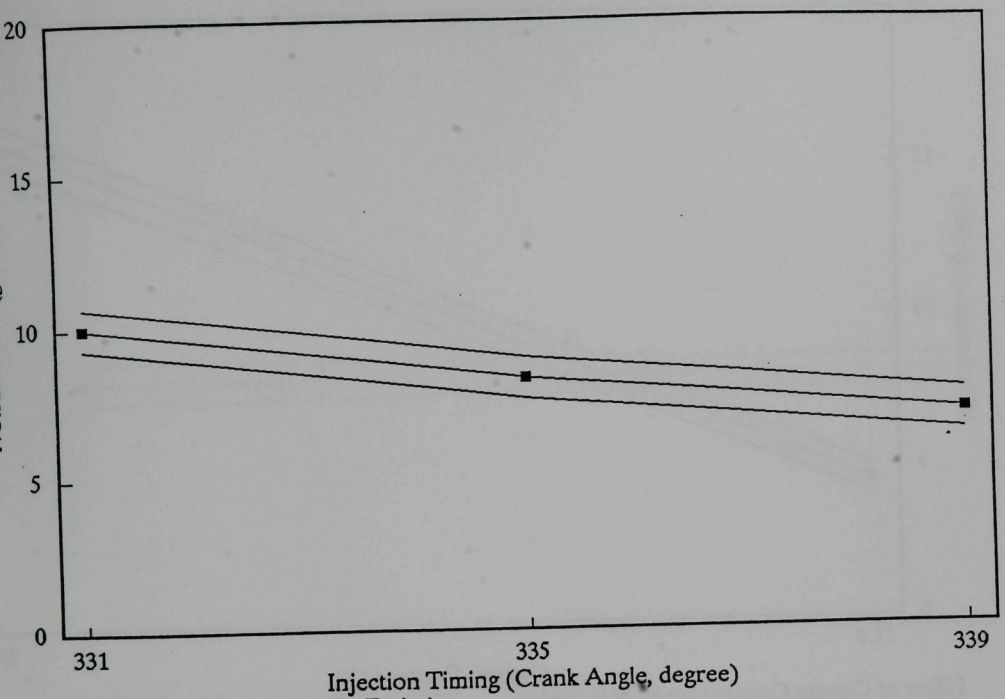
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel #2 Matrix B

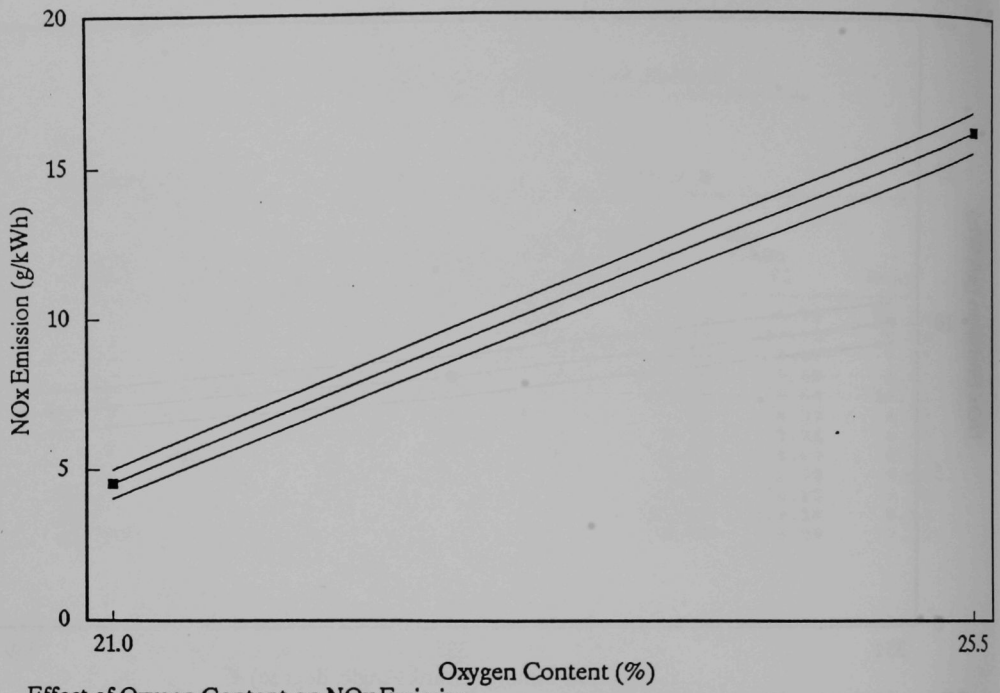
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	NOx g/kWh I	NOx g/kWh II	Mean
1	1	1	2′	1	7.01	6.79	10.00
2	1	2	2	2	18.08	17.90	8.24
3	1	1′	3	3	5.13	5.07	7.07
4	2	1	2	3	3.79	3.68	4.61
5	2	2	3	1	17.55	15.54	16.21
6	2	1′	2′	2	4.51	4.37	4.49
7	3	1	3	2	3.11	3.26	8.48
8	3	2	2′	3	14.11	14.09	8.55
9	3	1′	2	1	3.88	3.95	8.28
Total					77.17	74.65	9.12
CF					661.69	619.18	8.54
Average					8.57	8.29	7.65

Variance Table Analysis

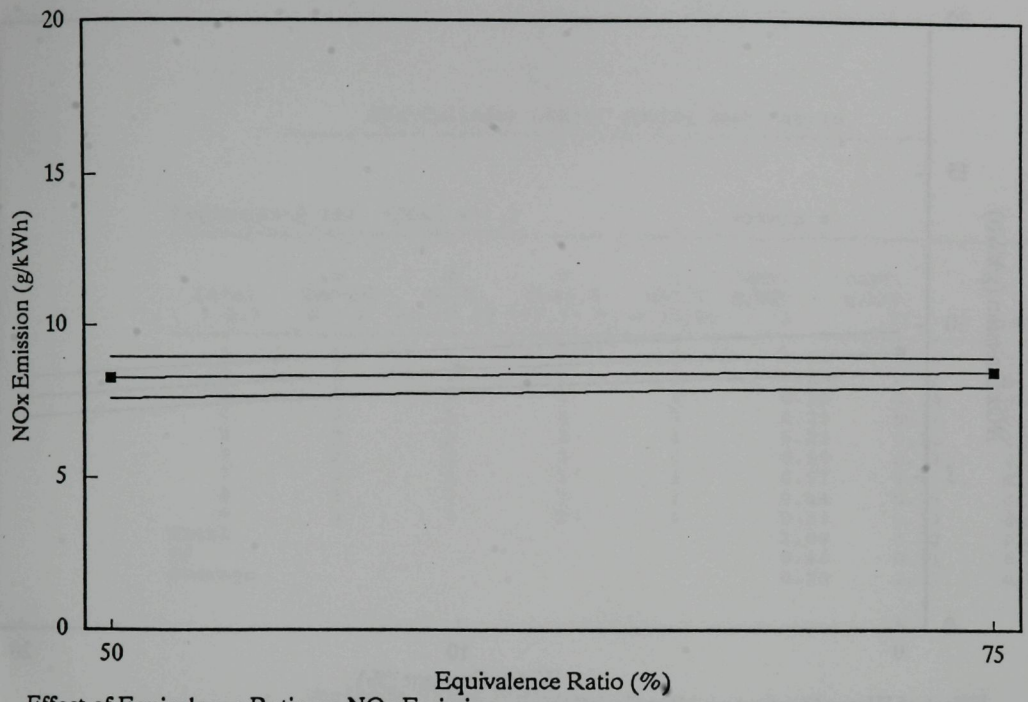
Source	f	S	V	F	S′	% contr.
Timing	2	26.09	13.05	72.61	25.74	4.44
Oxygen	1	544.37	544.37	3029.41	544.19	93.91
Eq. R	1	0.22	0.22	1.25	0.04	0.01
Water	2	6.62	3.31	18.43	6.26	1.08
Replicat.	1	0.35	0.35	1.96	0.17	0.03
e	10	1.80	0.18		3.05	0.53
Pooled e	11	2.15	0.53			
T	17	579.46			579.46	100.00



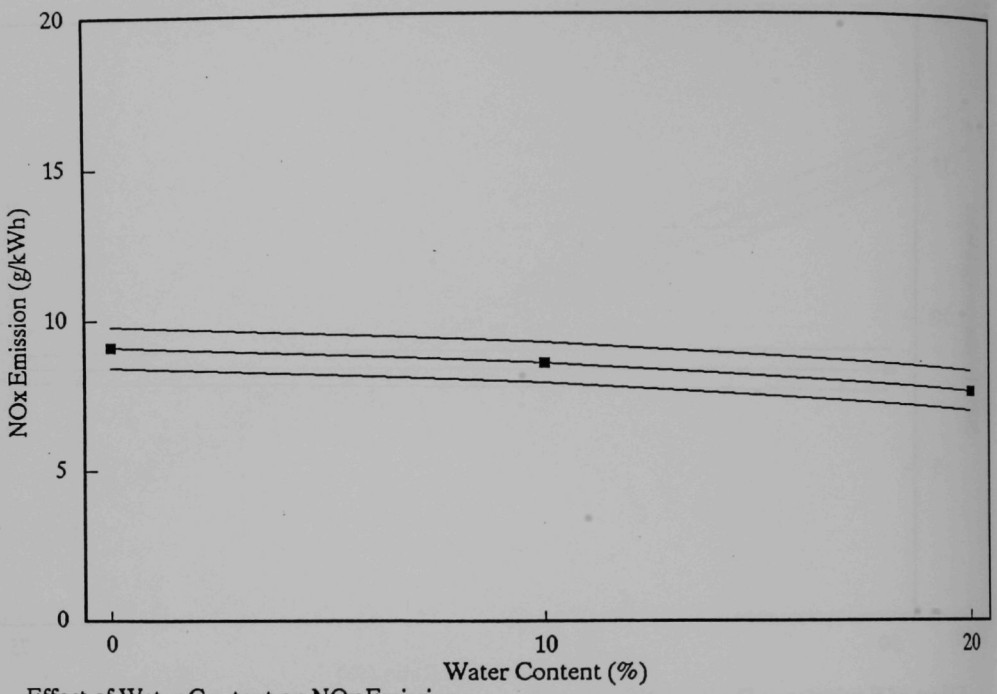
Effect of Injection Timing on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on NOx Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)

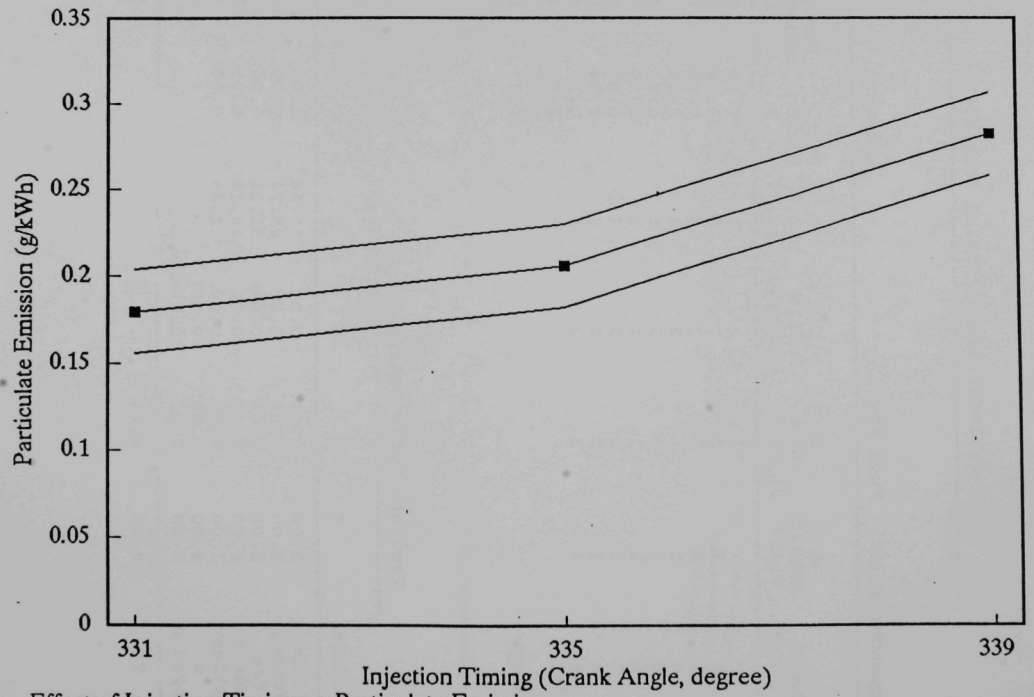
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

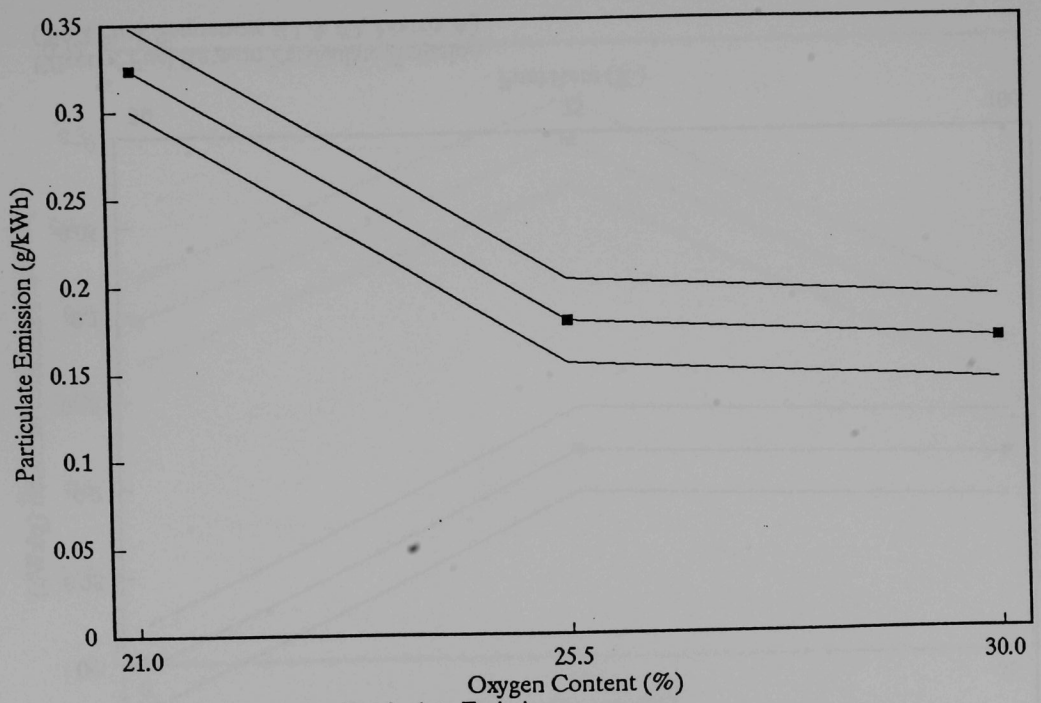
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Part. g/kWh I	Part. g/kWh II	Mean
1	1	1	1	1	0.24	0.20	0.18
2	1	2	2	2	0.16	0.17	0.21
3	1	3	3	3	0.18	0.14	0.28
4	2	1	2	3	0.23	0.21	0.32
5	2	2	3	1	0.23	0.20	0.18
6	2	3	1	2	0.19	0.19	0.17
7	3	1	3	2	0.57	0.50	0.19
8	3	2	1	3	0.14	0.18	0.18
9	3	3	2	1	0.17	0.14	0.30
Total					2.09	1.92	0.20
CF					0.48	0.41	0.29
Average					0.23	0.21	0.18

Variance Table Analysis

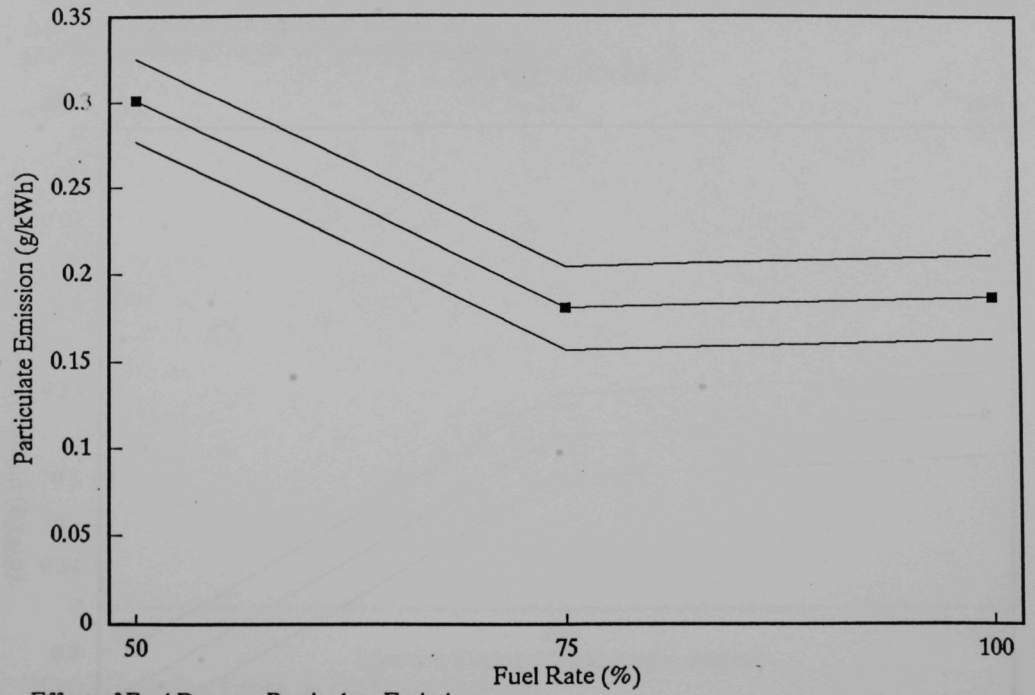
Source	f	S	V	F	S'	% contr.
Timing	2.00	0.03	0.02	31.54	0.03	14.00
Oxygen	2.00	0.09	0.05	85.74	0.09	38.84
Fuel	2.00	0.06	0.03	51.31	0.05	23.06
Water	2.00	0.05	0.02	44.18	0.05	19.79
Replicat.	1.00	0.00	0.00	2.86	0.00	0.43
e	8.00	0.00	0.00			3.90
Pooled e	9.00	0.01	0.00 ← 0.001			
T	17.00	0.24				100.00



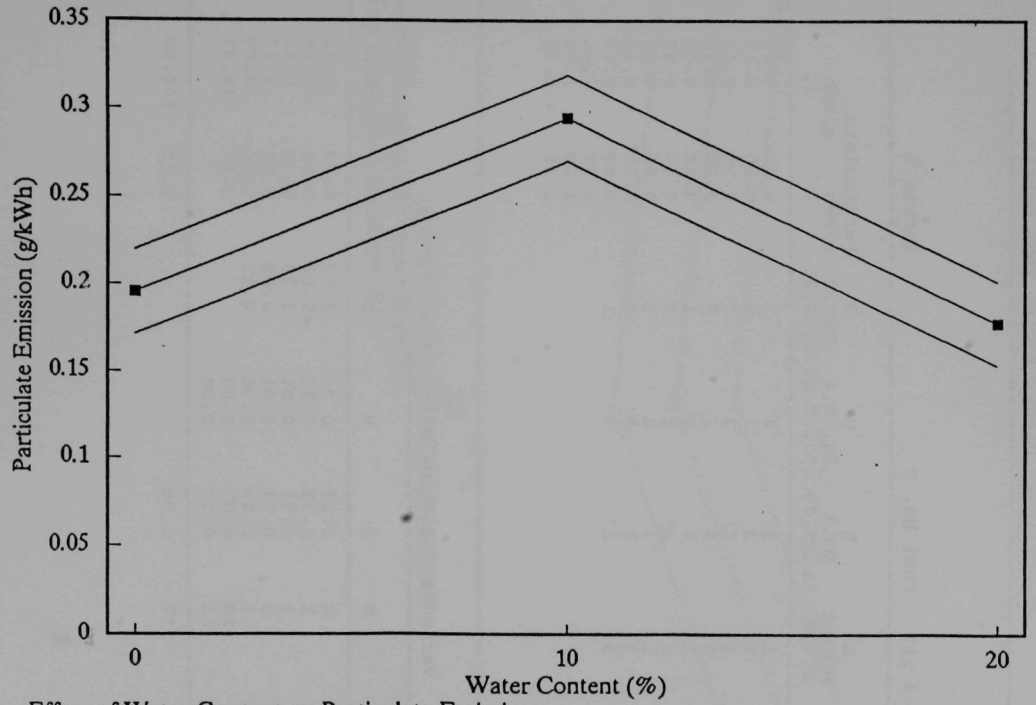
Effect of Injection Timing on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)

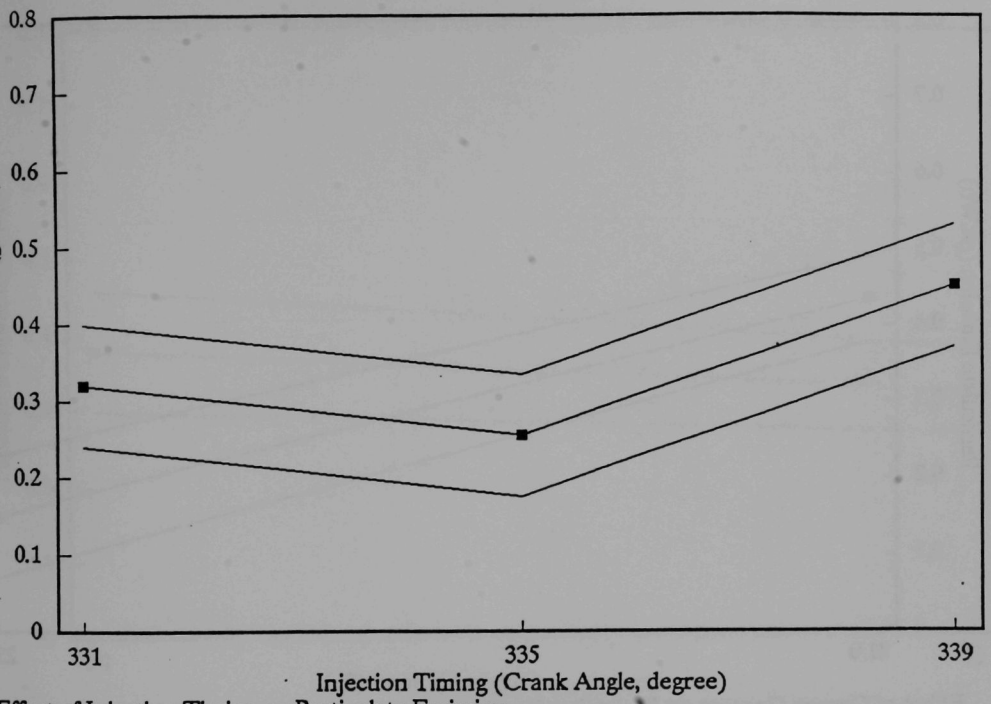
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

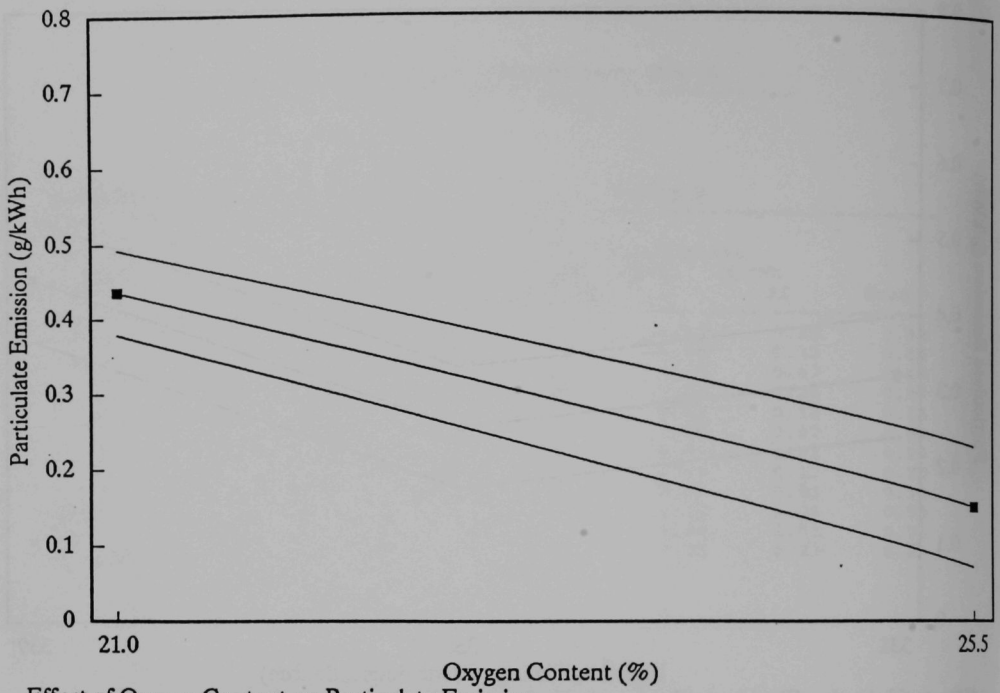
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	Particulate g/kWh I	g/kWh II	Mean
1	1	1	2′	1	0.33	0.35	0.32
2	1	2	2	2	0.20	0.13	0.25
3	1	1′	3	3	0.45	0.47	0.45
4	2	1	2	3	0.25	0.24	0.37
5	2	2	3	1	0.12	0.15	0.15
6	2	1′	2′	2	0.40	0.37	0.50
7	3	1	3	2	0.56	0.51	0.29
8	3	2	2′	3	0.15	0.17	0.35
9	3	1′	2	1	0.68	0.63	0.38
Total					3.13	3.01	0.38
CF					1.09	1.01	0.36
Average					0.35	0.33	0.29

Variance Table Analysis

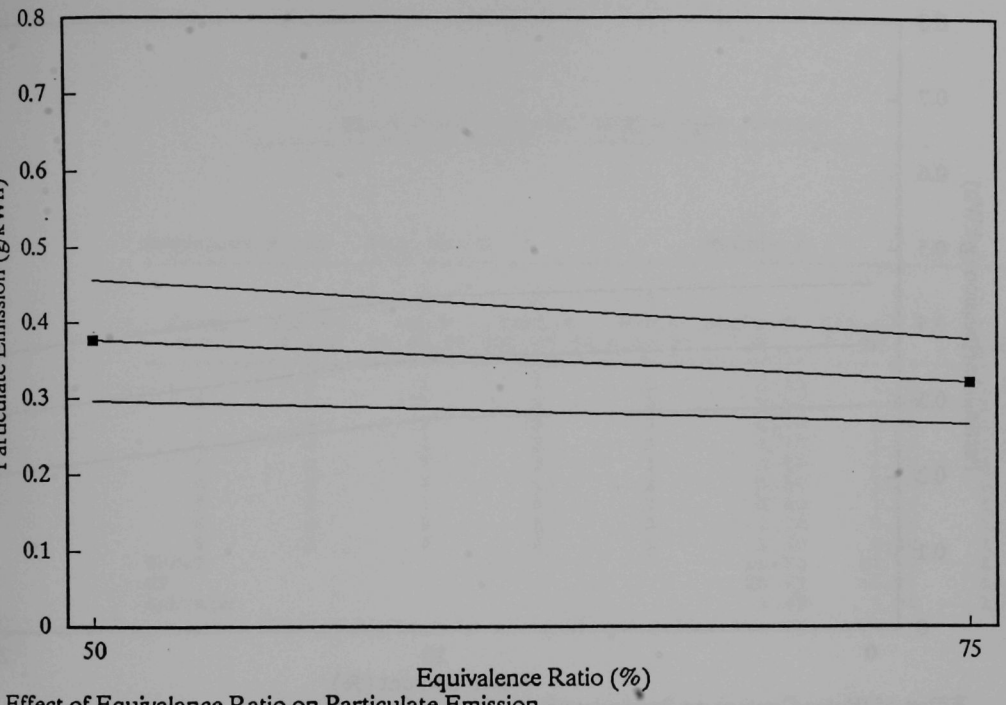
Source	f	S	V	F	S′	% contr.
Timing	2	0.12	0.06	8.92	0.10	19.11
Oxygen	1	0.32	0.32	49.07	0.32	58.04
Eq. R	1	0.01	0.01	1.75	0.00	0.91
Water	2	0.03	0.01	2.02	0.01	2.47
Replicat.	1	0.00	0.00	0.13	0.00	0.00
e	10	0.07	0.01		0.11	19.47
Pooled e	11	0.07	0.01			
T	17	0.55			0.55	100.00



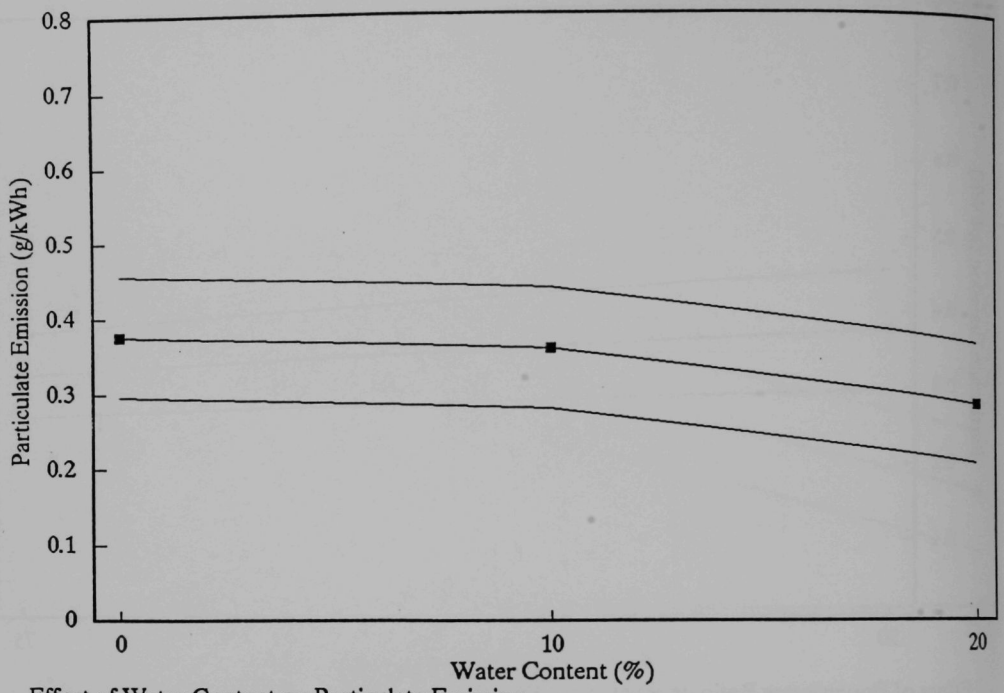
Effect of Injection Timing on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalance Ratio on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on Particulate Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)

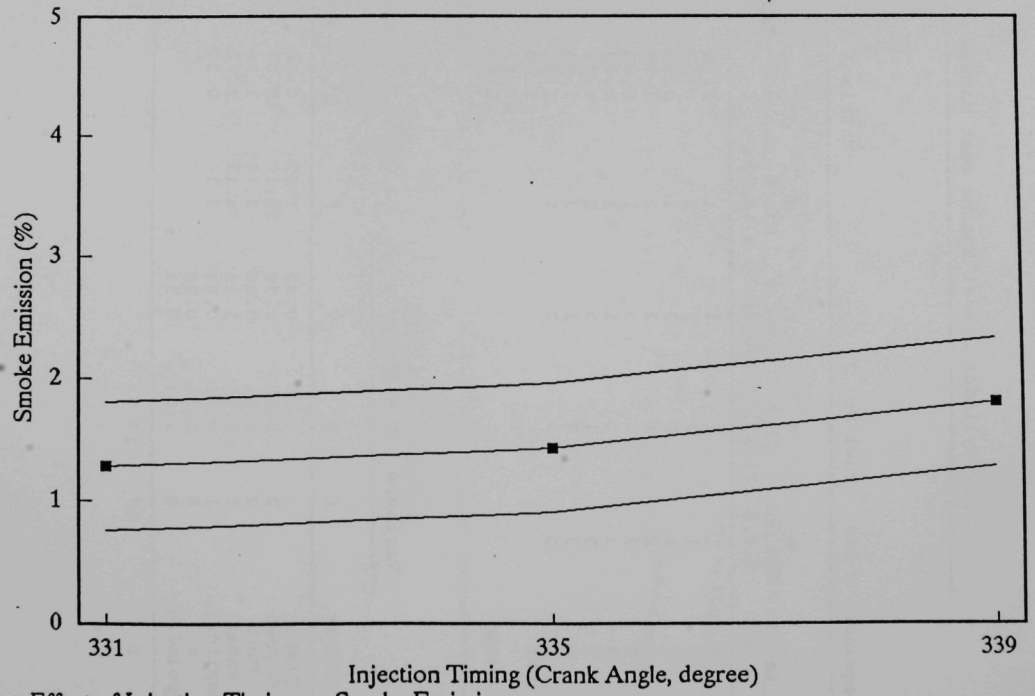
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

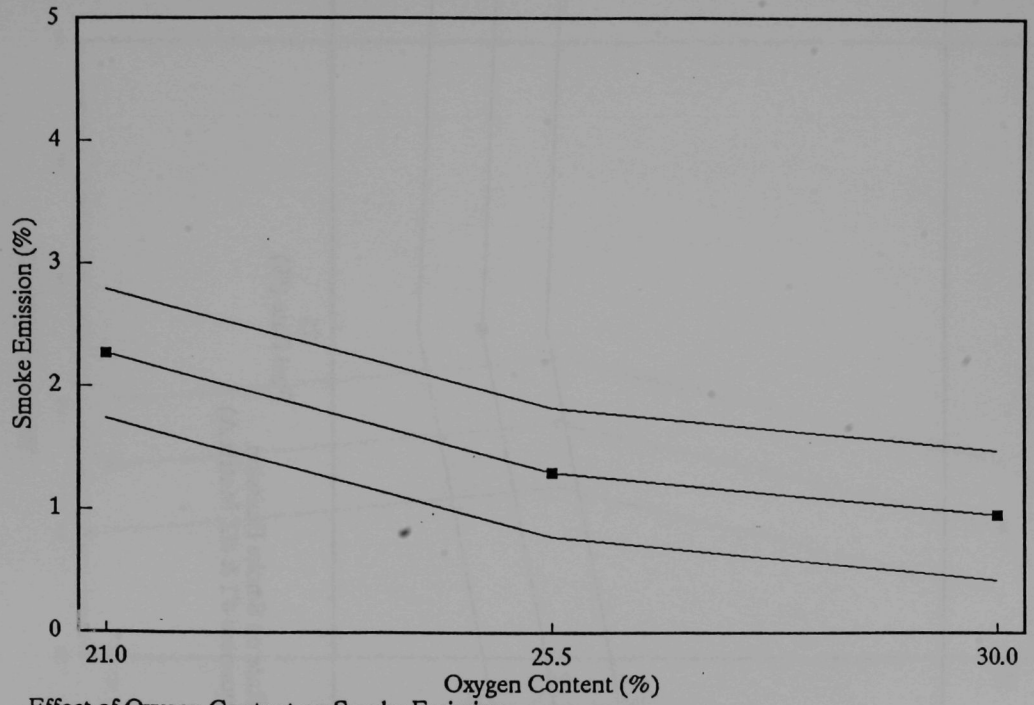
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Smoke,% I	Smoke,% II	Mean
1	1	1	1	1	2.10	1.80	1.28
2	1	2	2	2	0.90	1.50	1.43
3	1	3	3	3	0.80	0.60	1.80
4	2	1	2	3	1.70	1.20	2.27
5	2	2	3	1	1.80	1.60	1.30
6	2	3	1	2	0.80	1.50	0.95
7	3	1	3	2	4.20	2.60	1.37
8	3	2	1	3	1.30	0.70	1.22
9	3	3	2	1	1.60	0.40	1.93
Total					15.20	11.90	1.55
CF					25.67	15.73	1.92
Average					1.69	1.32	1.05

Variance Table Analysis

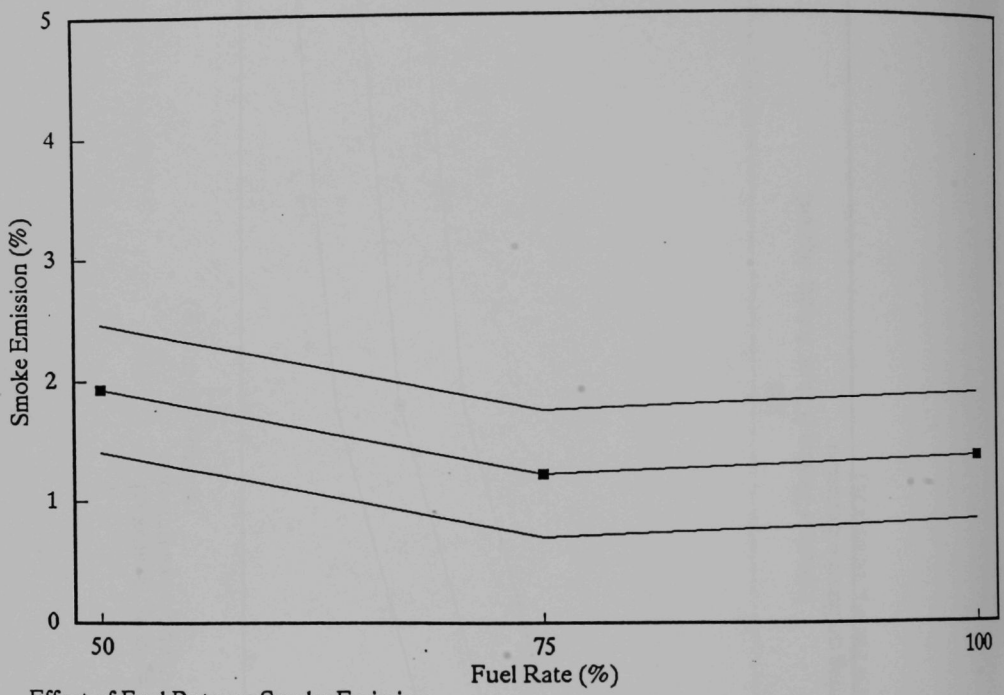
Source	f	S	V	F	S′	% contr.
Timing	2	0.85	0.42	1.53	0.30	2.23
Oxygen	2	5.58	2.79	10.10	5.03	38.01
Fuel	2	1.71	0.86	3.10	1.16	8.78
Water	2	2.27	1.14	4.11	1.72	12.99
Replicat.	1	0.61	0.61	2.19	0.33	2.48
e	8	2.21	0.28			35.50
Pooled e	9	2.81	0.31			
T	17	13.23				100.00



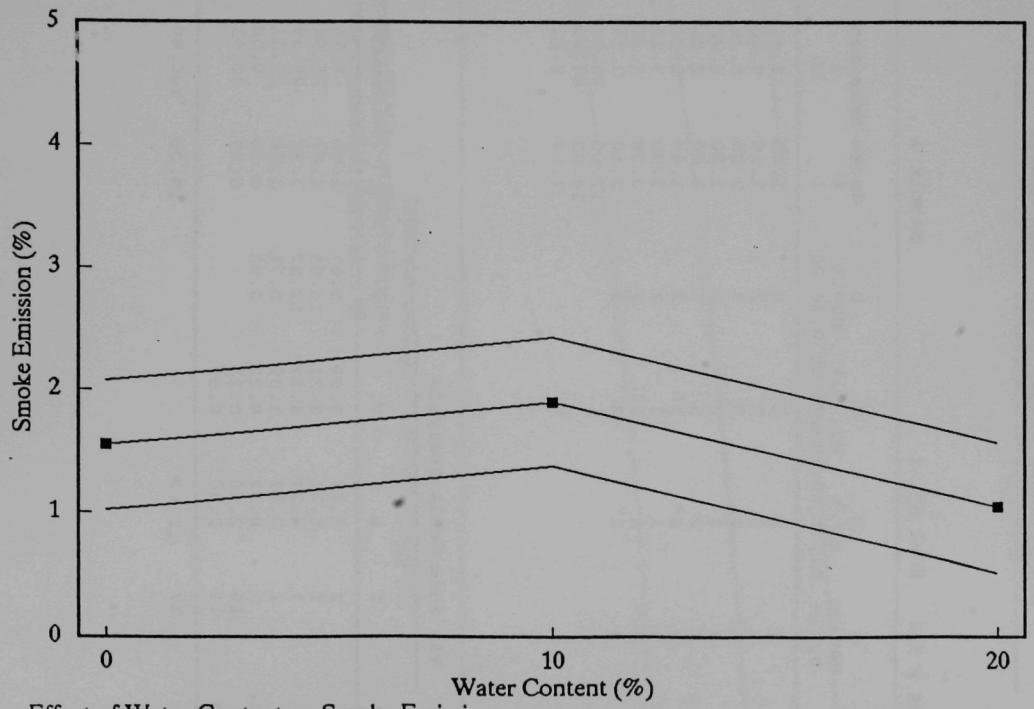
Effect of Injection Timing on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix A)

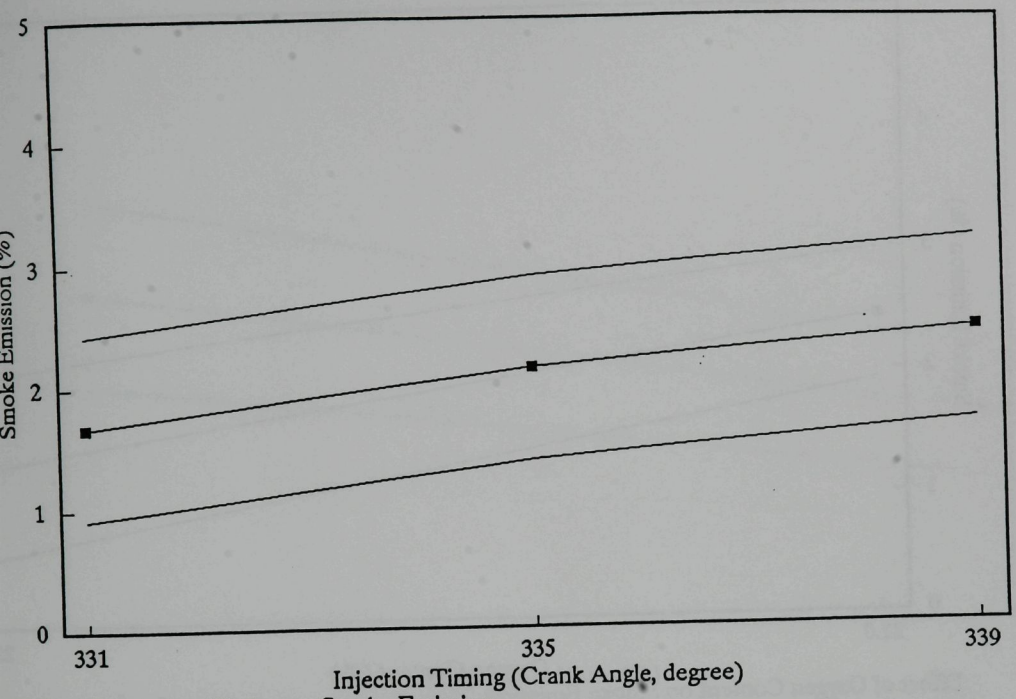
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

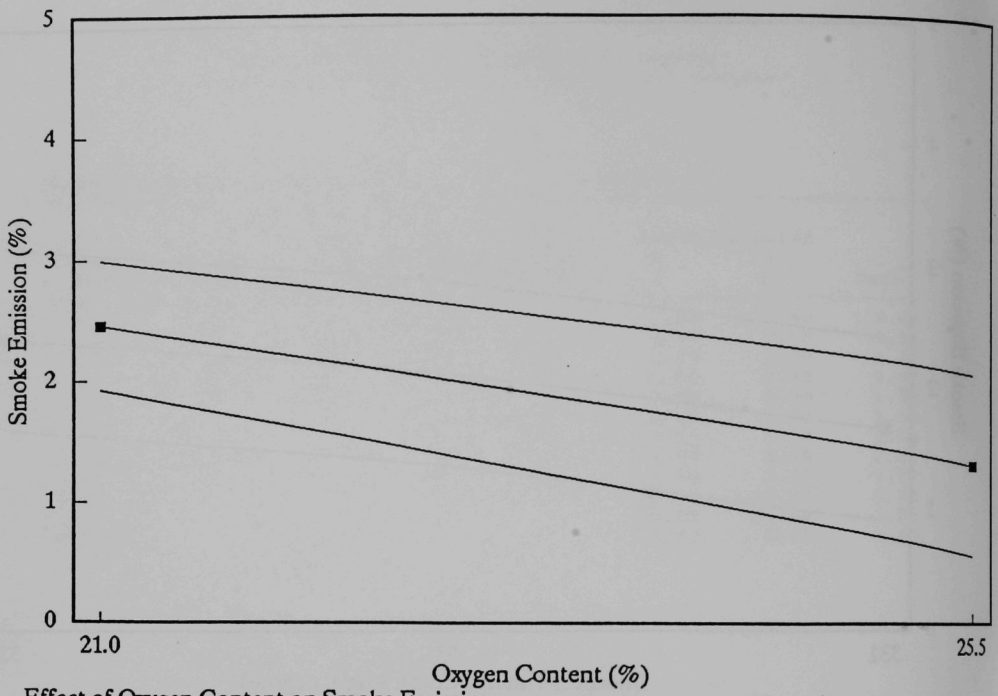
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	Smoke Emission % I	% II	Mean
1	1	1	2′	1	1.80	2.40	1.67
2	1	2	2	2	1.10	0.40	2.13
3	1	1′	3	3	2.00	2.30	2.43
4	2	1	2	3	1.50	2.80	2.57
5	2	2	3	1	2.50	2.90	1.32
6	2	1′	2′	2	1.40	1.70	2.35
7	3	1	3	2	3.80	3.10	1.38
8	3	2	2′	3	0.00	1.00	2.08
9	3	1′	2	1	3.40	3.30	2.77
Total					17.50	19.90	2.72
CF					34.03	44.00	1.92
Average					1.94	2.21	1.60

Variance Table Analysis

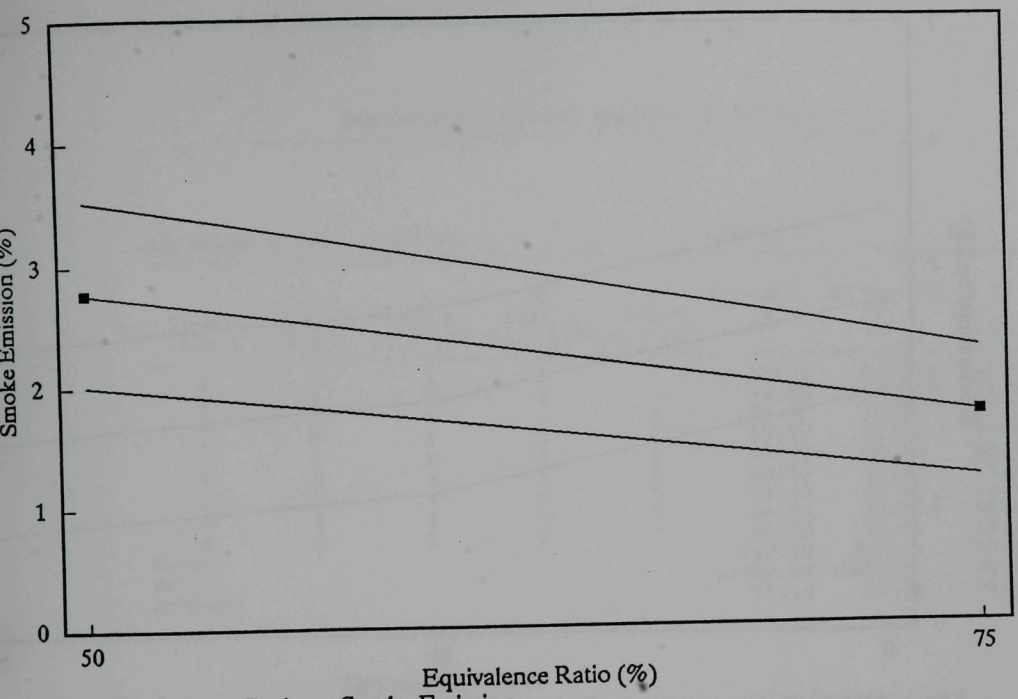
Source	f	S	V	F	S′	% contr.
Timing	2	1.79	0.90	2.57	1.09	5.75
Oxygen	1	5.21	5.21	14.98	4.87	25.54
Eq. R	1	4.27	4.27	12.27	3.92	20.59
Water	2	3.97	1.99	5.71	3.28	17.21
Replicat.	1	0.32	0.32	0.92	0.00	0.00
e	10	3.48	0.35		5.89	30.91
Pooled e	11	3.80	0.67			
T	17	19.05			19.05	100.00



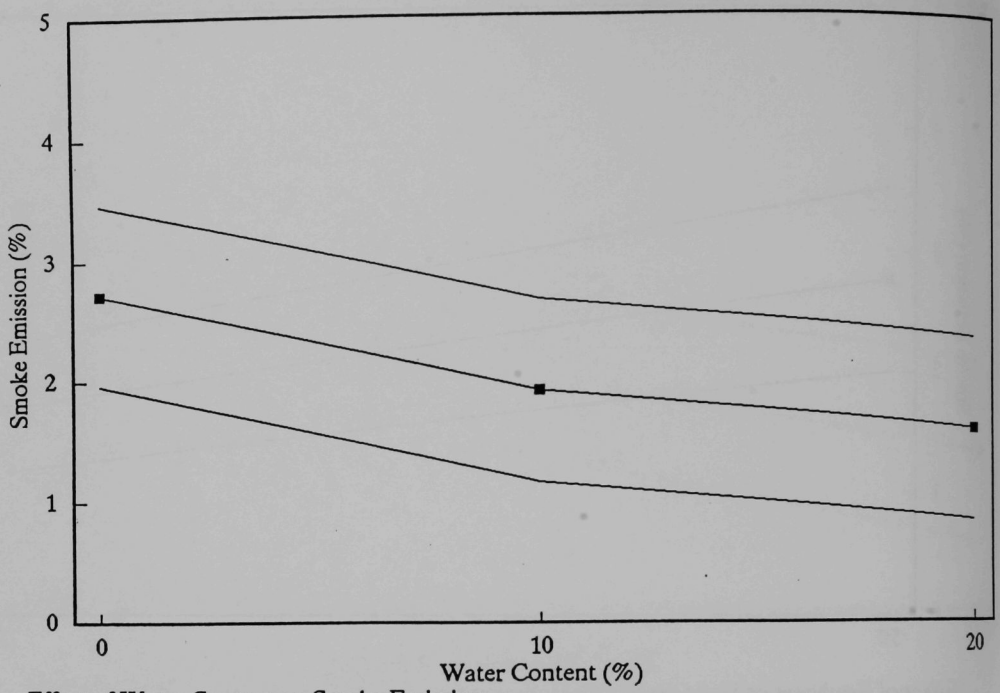
Effect of Injection Timing on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on Smoke Emission
(No.2 Fuel, Sequences #1 & #2, Matrix B)

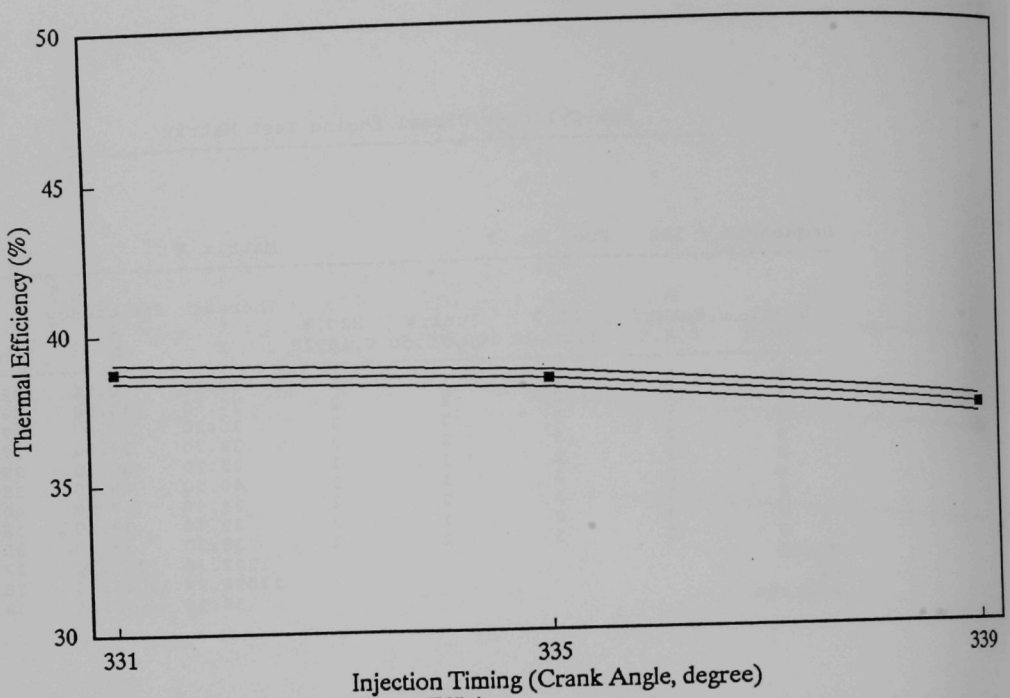
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

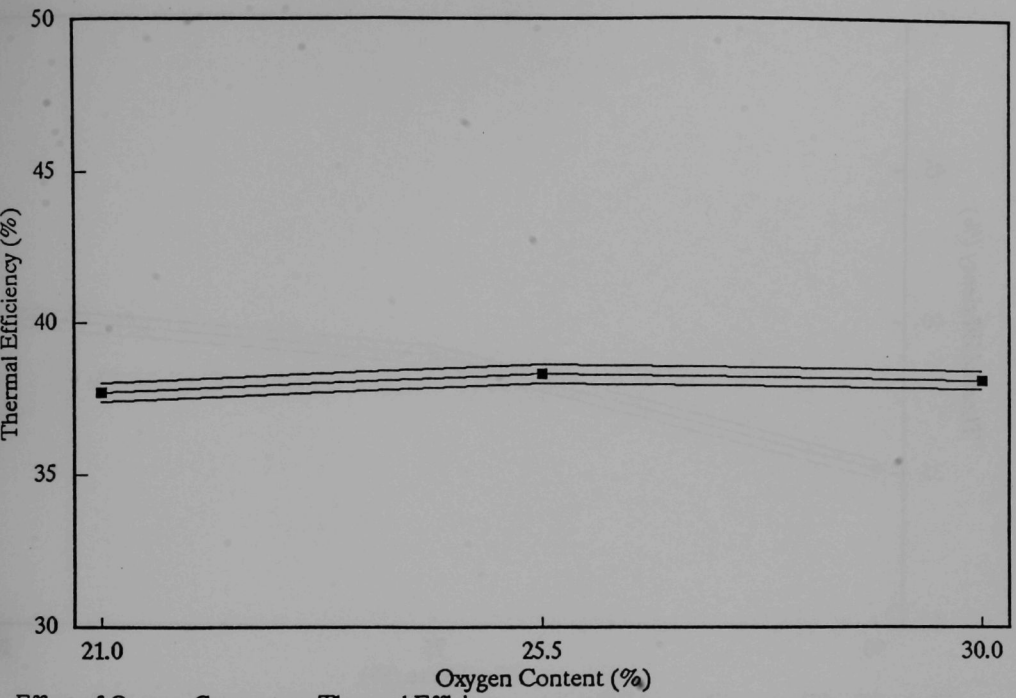
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Thermal % I	Efficiency % II	Mean
1	1	1	1	1	40.20	40.50	38.75
2	1	2	2	2	39.60	40.00	38.27
3	1	3	3	3	36.20	36.00	37.22
4	2	1	2	3	38.70	39.00	37.72
5	2	2	3	1	35.70	35.30	38.35
6	2	3	1	2	40.50	40.40	38.17
7	3	1	3	2	34.40	33.50	40.18
8	3	2	1	3	39.70	39.80	38.87
9	3	3	2	1	38.30	37.60	35.18
Total					343.30	342.10	37.93
CF					13094.99	13003.60	38.07
Average					38.14	38.01	38.23

Variance Table Analysis

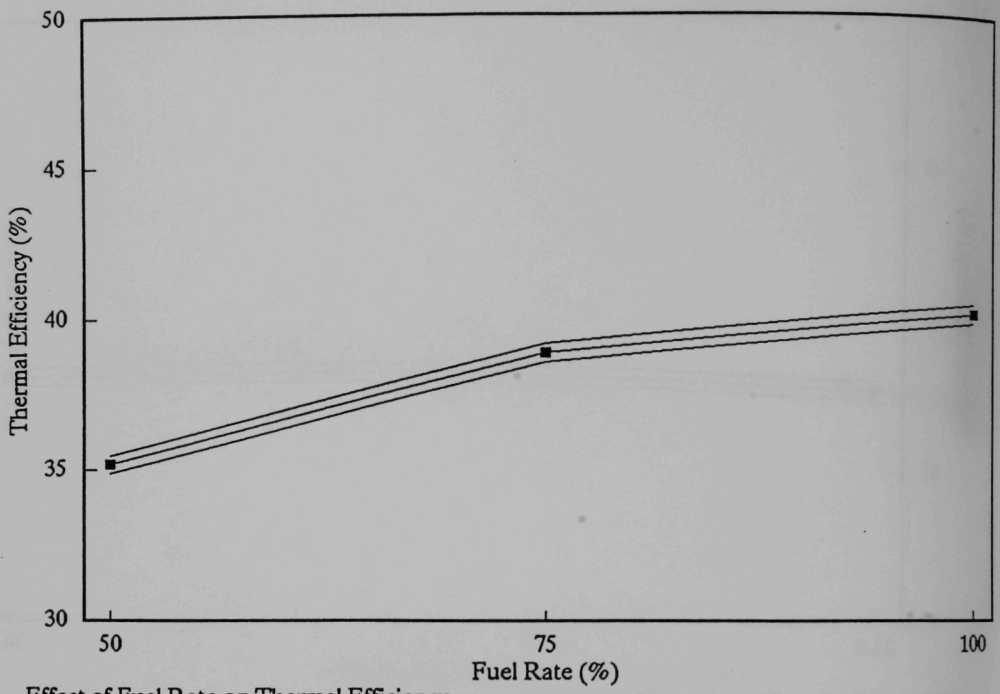
Source	f	S	V	F	S′	% contr.
Timing	2	7.37	3.69	34.70	7.16	7.92
Oxygen	2	1.27	0.64	6.00	1.06	1.17
Fuel	2	80.60	40.30	379.30	80.39	88.88
Water	2	0.27	0.14	1.28	0.06	0.06
Replicat.	1	0.08	0.08	0.75	0.00	0.00
e	8	0.85	0.11			1.97
Pooled e	9	0.93	0.10			
T	17	90.45				100.00



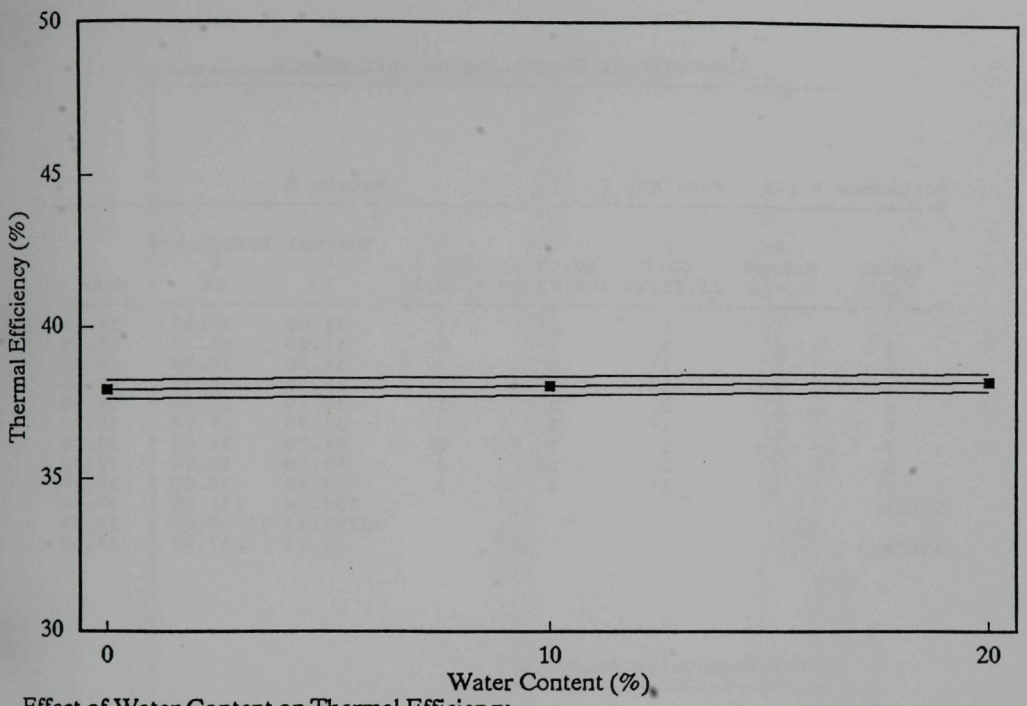
Effect of Injection Timing on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix A)

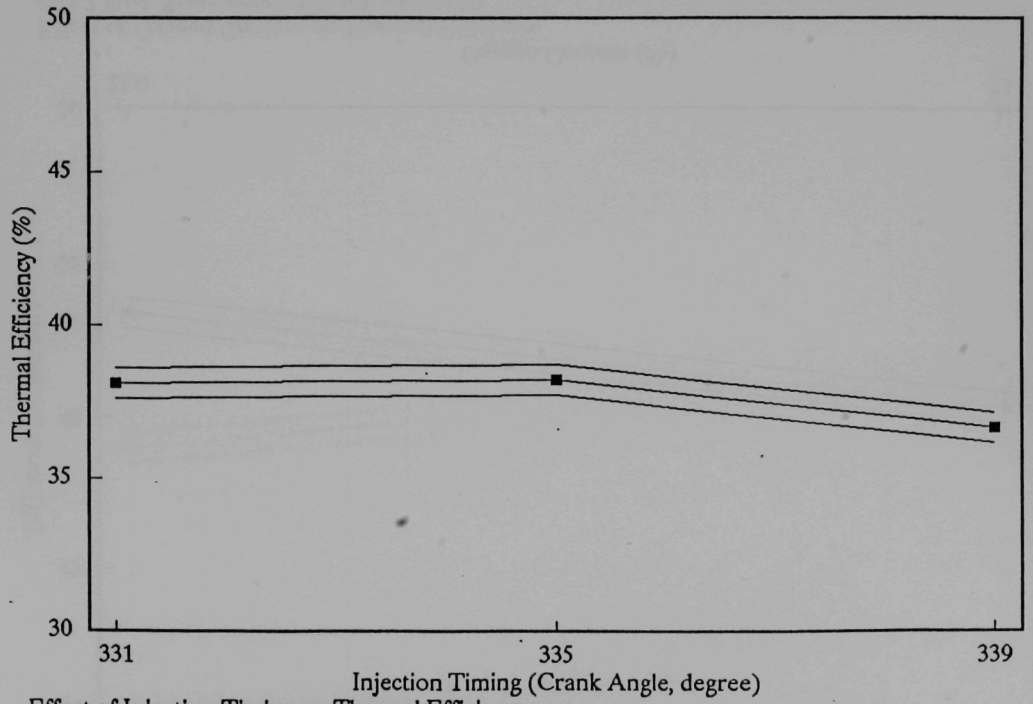
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

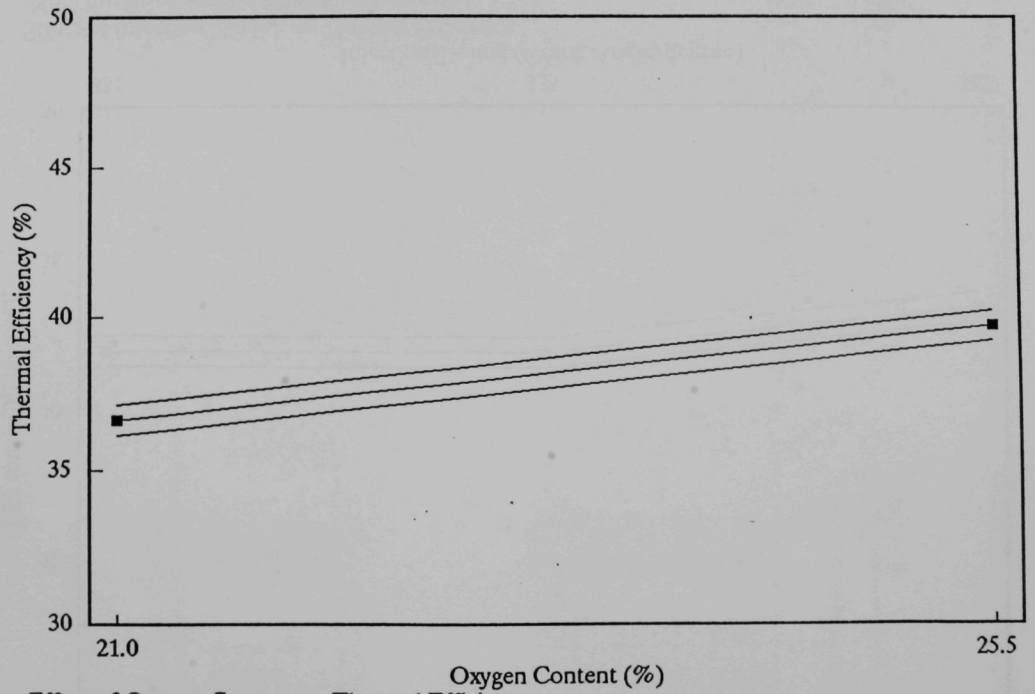
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	Thermal Efficiency % I	% II	Mean
1	1	1	2′	1	38.60	38.40	38.12
2	1	2	2	2	41.20	41.30	38.25
3	1	1′	3	3	34.50	34.70	36.63
4	2	1	2	3	38.50	38.10	37.08
5	2	2	3	1	38.70	38.60	39.68
6	2	1′	2′	2	37.70	37.90	36.23
7	3	1	3	2	34.70	34.20	38.48
8	3	2	2′	3	39.10	39.20	38.62
9	3	1′	2	1	36.40	36.20	35.90
Total					339.40	338.60	37.82
CF					12799.15	12738.88	37.83
Average					37.71	37.62	37.35

Variance Table Analysis

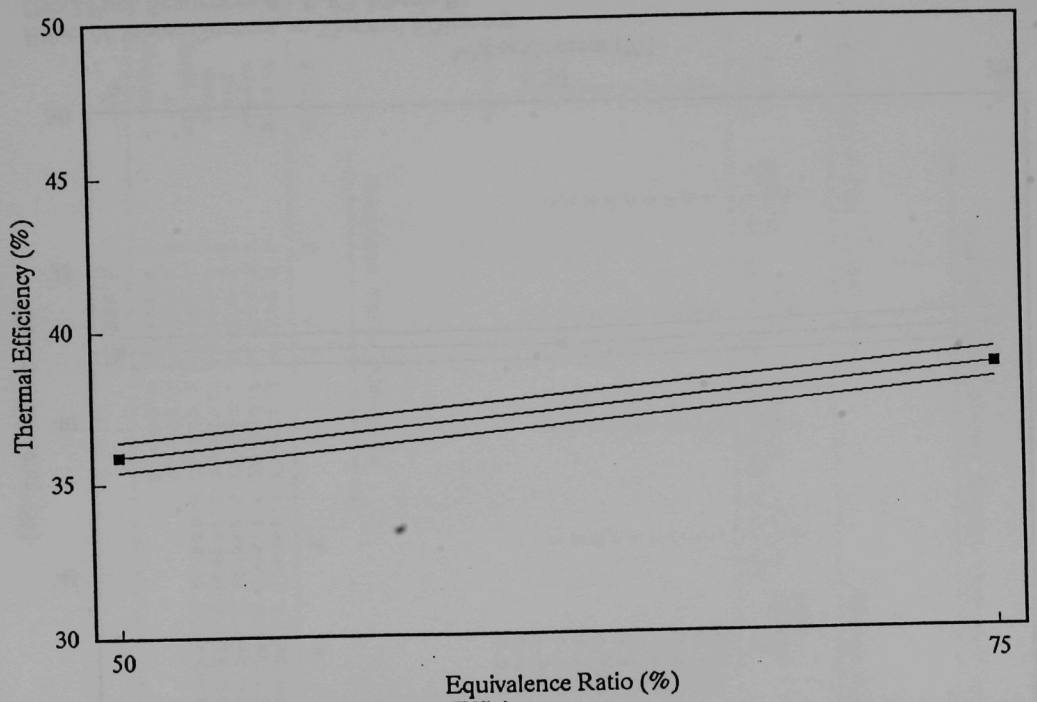
Source	f	S	V	F	S′	% contr.
Timing	2	9.66	4.83	19.44	9.17	11.78
Oxygen	1	36.60	36.60	147.28	36.35	46.74
Eq. R	1	28.09	28.09	113.03	27.84	35.80
Water	2	0.90	0.45	1.82	0.41	0.52
Replicat.	1	0.04	0.04	0.14	0.00	0.00
e	10	2.49	0.25		4.01	5.16
Pooled e	11	2.52	0.28			
T	17	77.78			77.78	100.00



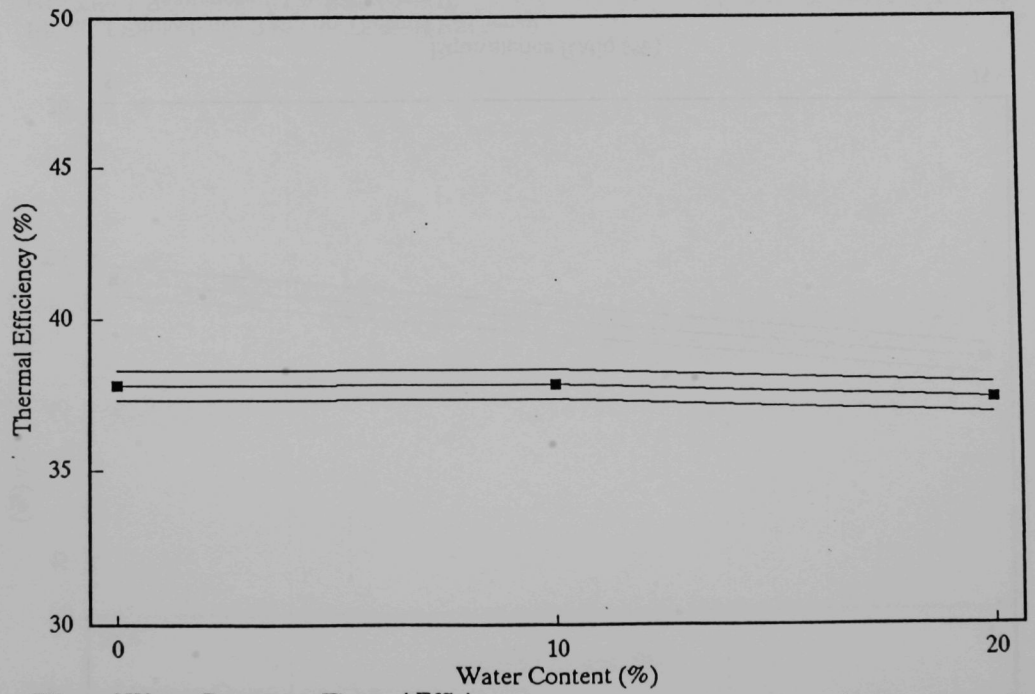
Effect of Injection Timing on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on Thermal Efficiency
(No.2 Fuel, Sequences #1 & #2, Matrix B)

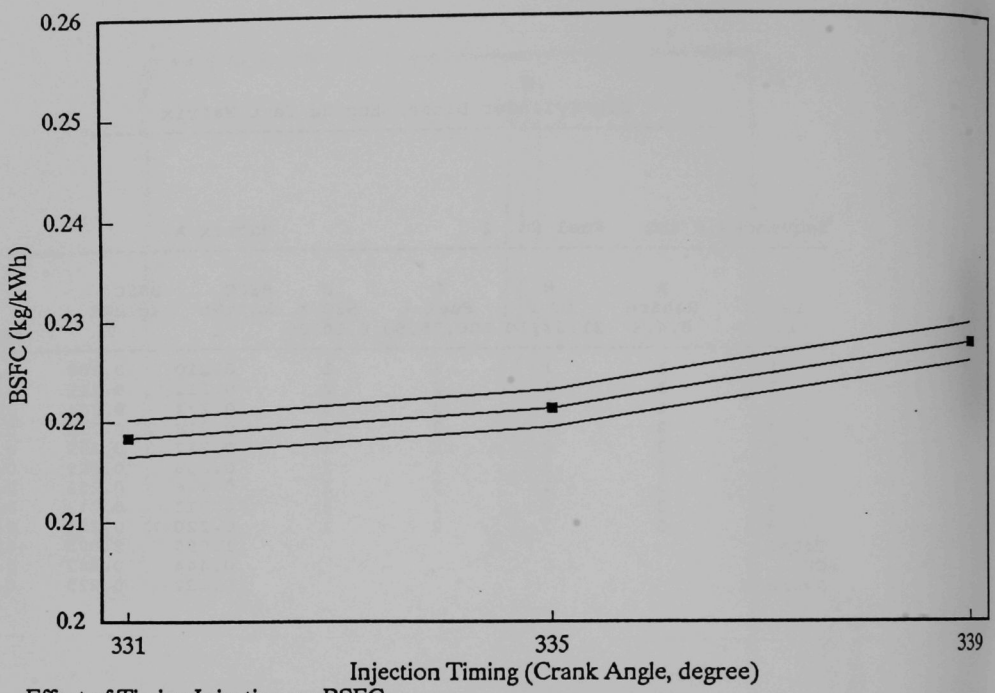
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

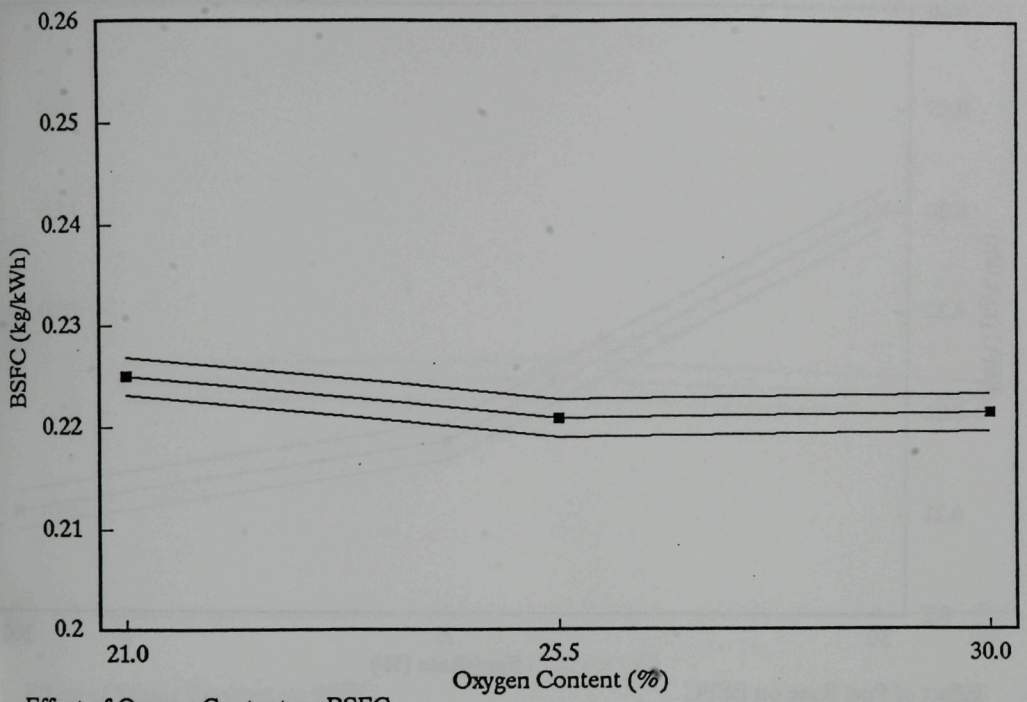
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	BSFC kg/kWh I	BSFC kg/kWh II	Mean
1	1	1	1	1	0.210	0.208	0.218
2	1	2	2	2	0.213	0.211	0.221
3	1	3	3	3	0.234	0.234	0.228
4	2	1	2	3	0.218	0.216	0.225
5	2	2	3	1	0.237	0.239	0.221
6	2	3	1	2	0.208	0.209	0.222
7	3	1	3	2	0.246	0.252	0.210
8	3	2	1	3	0.213	0.212	0.217
9	3	3	2	1	0.220	0.224	0.240
Total					1.999	2.005	0.223
CF					0.444	0.447	0.223
Average					0.222	0.223	0.221

Variance Table Analysis

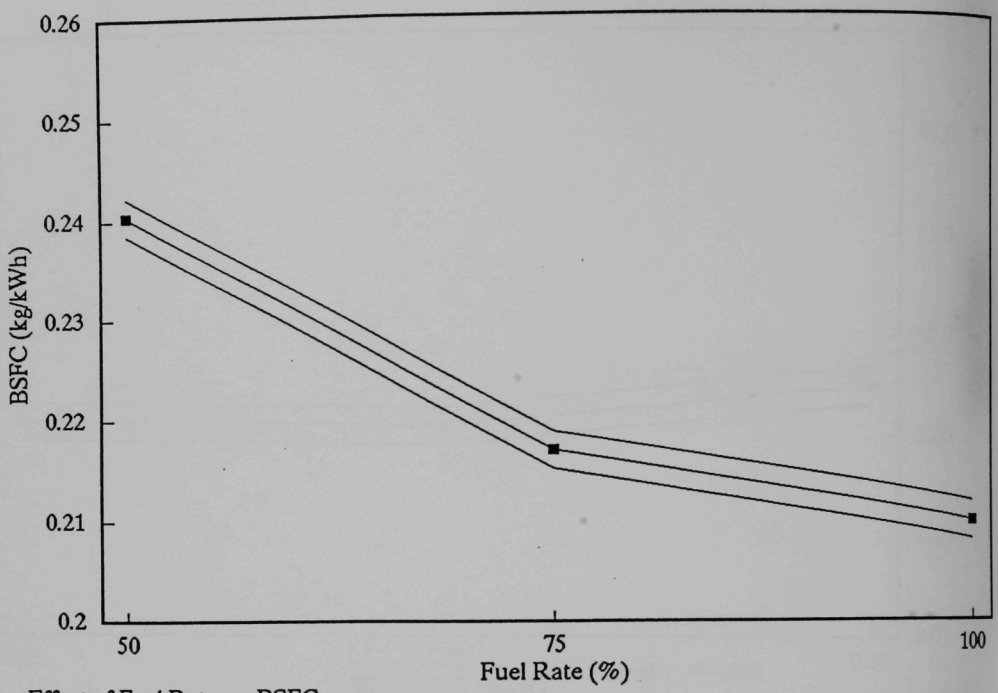
Source	f	S	V	F	S'	% contr.
Timing	2	2.85E-04	1.43E-04	3.46E+01	2.77E-04	8.10
Oxygen	2	6.01E-05	3.01E-05	7.29E+00	5.19E-05	1.52
Fuel	2	3.03E-03	1.51E-03	3.67E+02	3.02E-03	88.21
Water	2	1.48E-05	7.39E-06	1.79E+00	6.53E-06	0.19
Replicat.	1	2.00E-06	2.00E-06	4.85E-01	0.00E+00	0.00
e	8	3.30E-05	4.12E-06			1.99
Pooled e	9	3.50E-05	3.89E-06			
T	17	3.42E-03				100.00



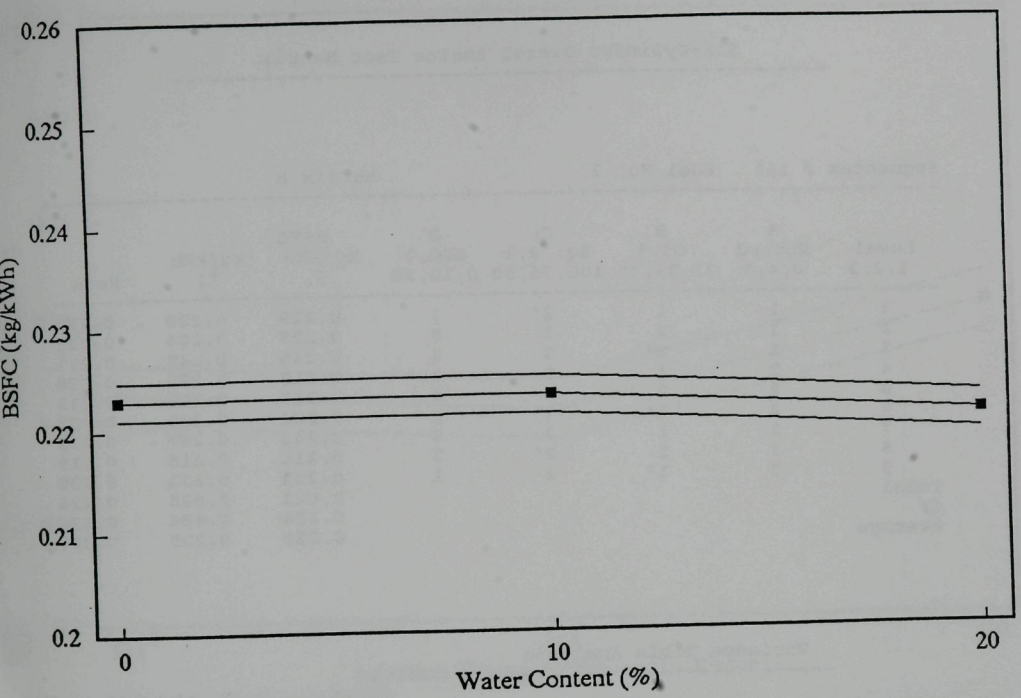
Effect of Timing Injection on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix A)

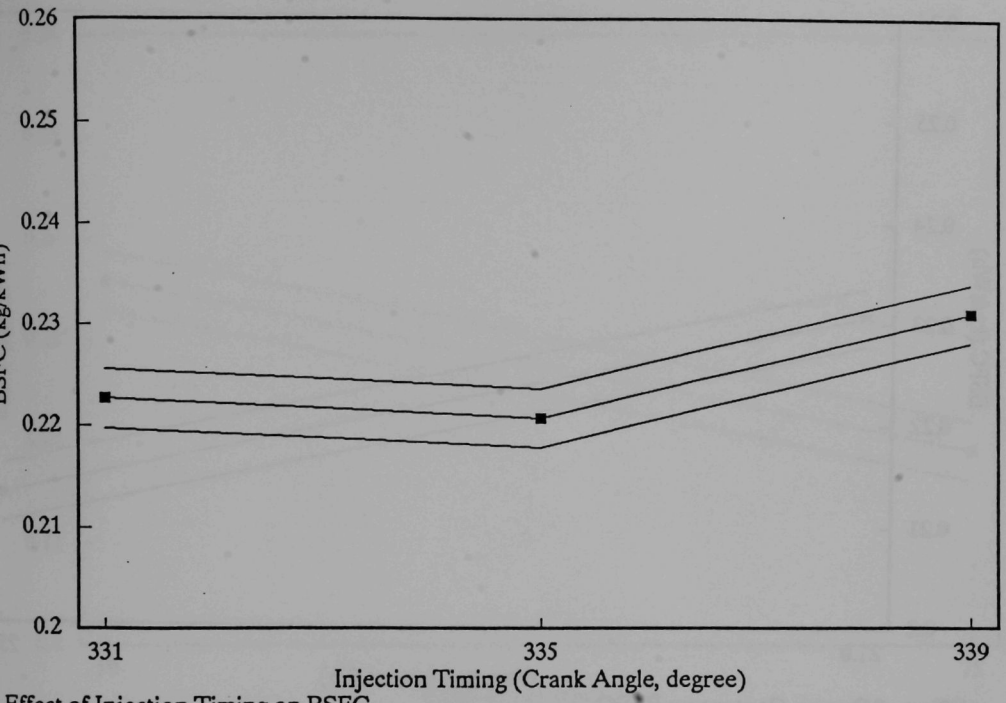
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

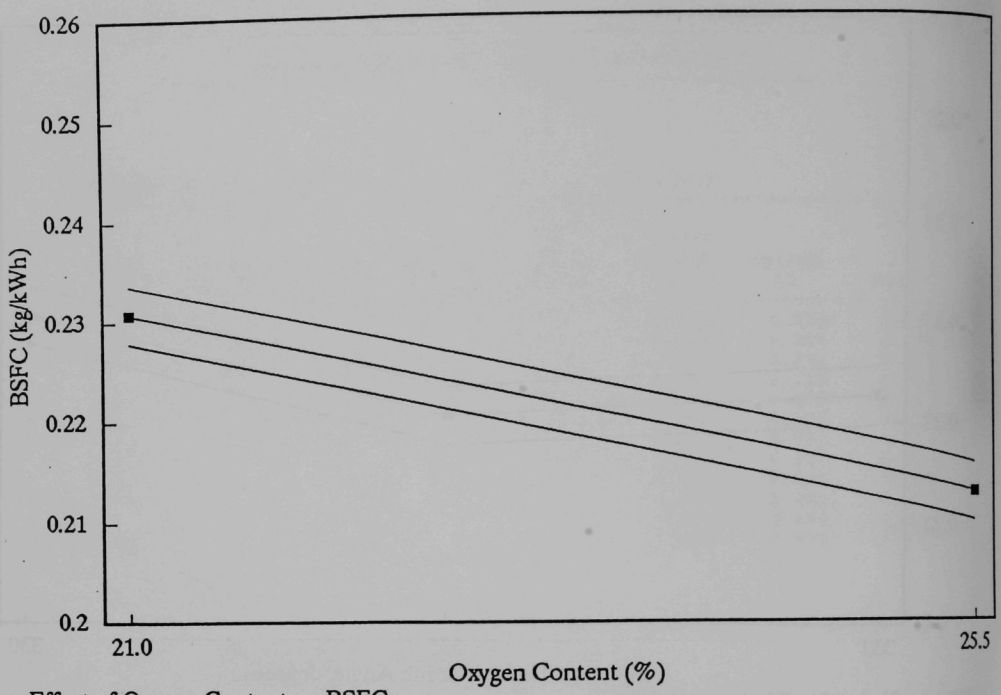
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	BSFC kg/kWh I	kg/kWh II	Mean
1	1	1	2′	1	0.219	0.220	0.223
2	1	2	2	2	0.205	0.204	0.221
3	1	1′	3	3	0.245	0.243	0.231
4	2	1	2	3	0.219	0.222	0.228
5	2	2	3	1	0.218	0.219	0.213
6	2	1′	2′	2	0.224	0.222	0.233
7	3	1	3	2	0.243	0.247	0.219
8	3	2	2′	3	0.216	0.215	0.219
9	3	1′	2	1	0.232	0.233	0.236
Total					2.021	2.025	0.224
CF					0.454	0.456	0.224
Average					0.225	0.225	0.227

Variance Table Analysis

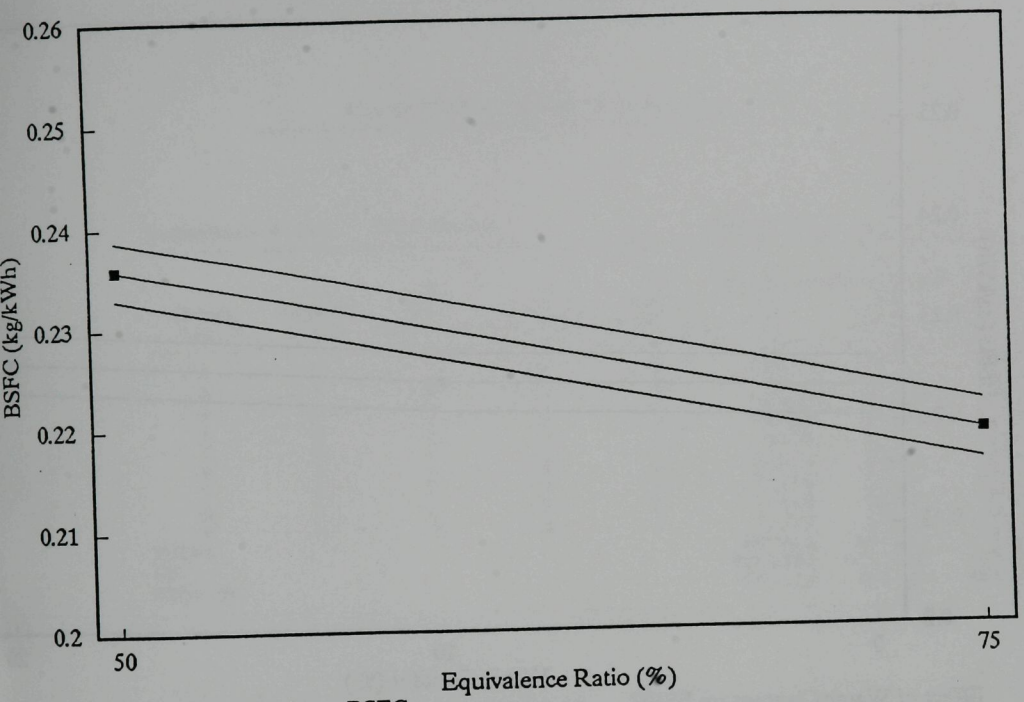
Source	f	S	V	F	S′	% contr.
Timing	2	3.60E-04	1.80E-04	2.04E+01	3.43E-04	11.96
Oxygen	1	1.28E-03	1.28E-03	1.45E+02	1.28E-03	44.48
Eq. R	1	1.10E-03	1.10E-03	1.25E+02	1.09E-03	38.06
Water	2	3.34E-05	1.67E-05	1.89E+00	1.58E-05	0.55
Replicat.	1	8.89E-07	8.89E-07	1.01E-01	0.00E+00	0.00
e	10	8.83E-05	8.83E-06		1.42E-04	4.96
Pooled e	11	8.92E-05	9.72E-06			
T	17	2.87E-03			2.87E-03	100.00



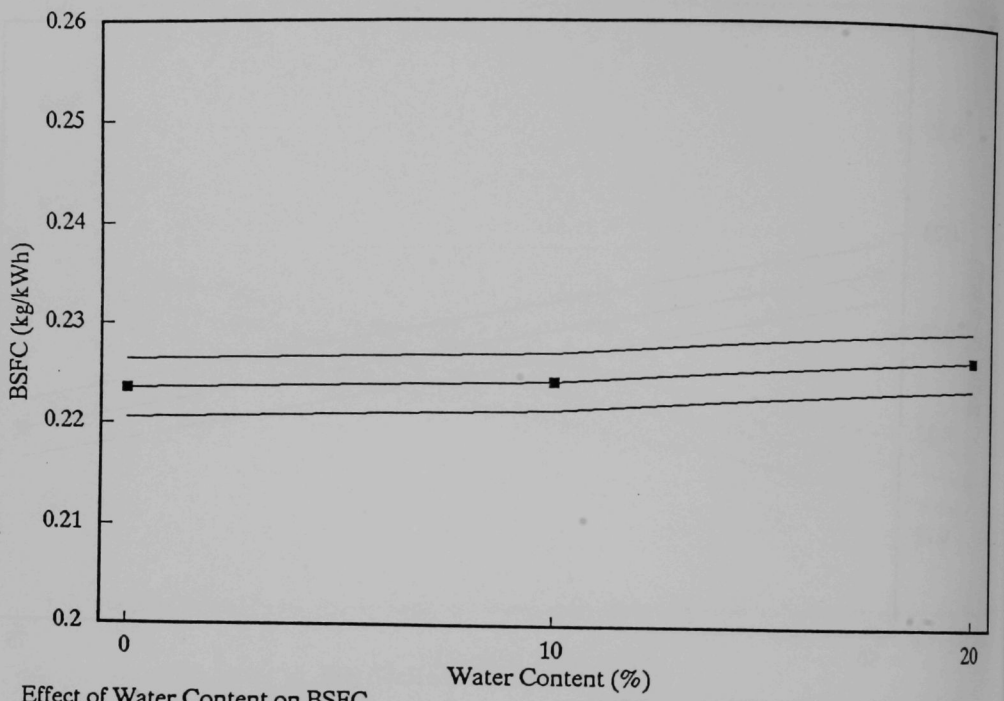
Effect of Injection Timing on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on BSFC
(No.2 Fuel, Sequences #1 & #2, Matrix B)

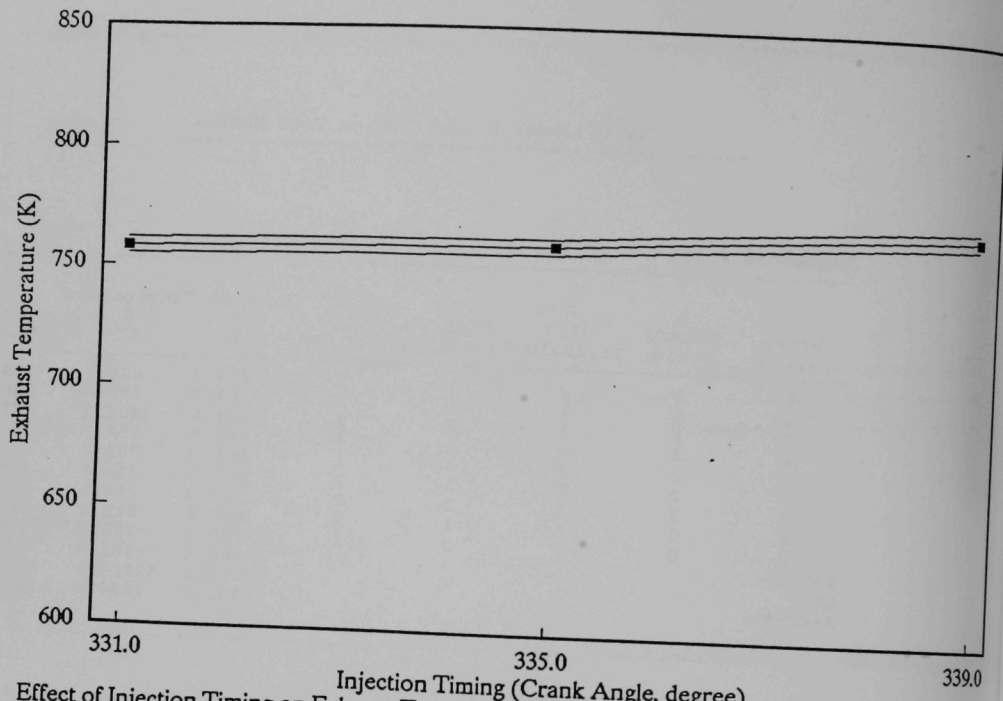
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

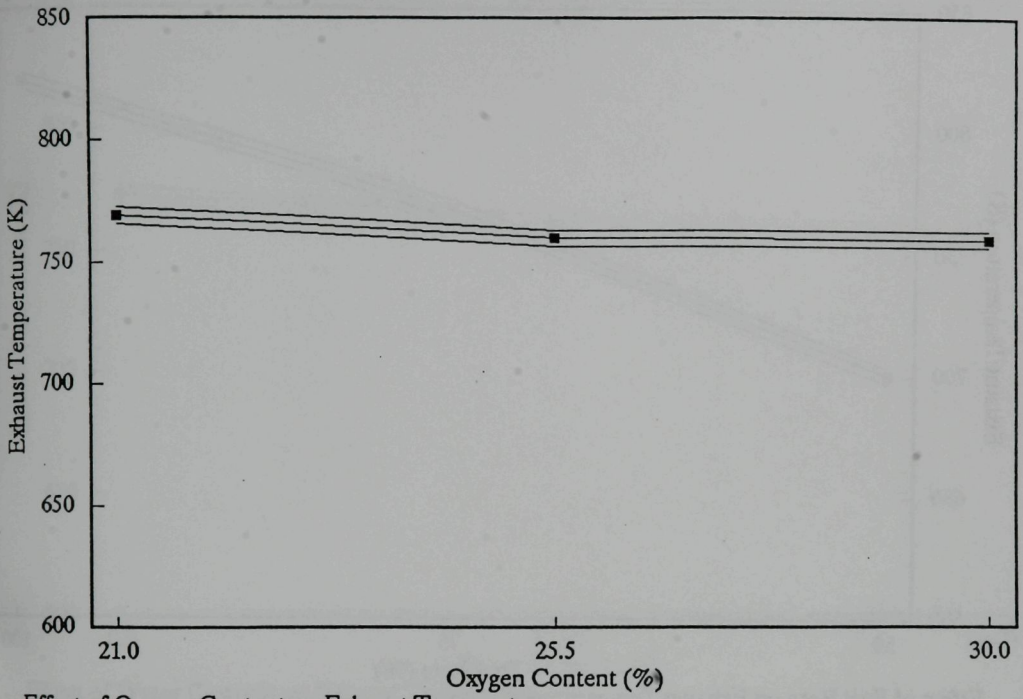
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Exhaust Temperature K I	K II	Mean
1	1	1	1	1	834.3	830.9	758.3
2	1	2	2	2	758.7	756.5	760.3
3	1	3	3	3	684.8	684.8	769.6
4	2	1	2	3	769.8	758.2	769.3
5	2	2	3	1	705.9	703.7	759.6
6	2	3	1	2	809.3	814.8	759.5
7	3	1	3	2	712.0	710.4	820.3
8	3	2	1	3	813.2	819.3	767.7
9	3	3	2	1	780.4	782.6	700.3
Total					6868.4	6861.2	773.0
CF					5241658	5230674	760.28
Average					763.16	762.36	755.02

Variance Table Analysis

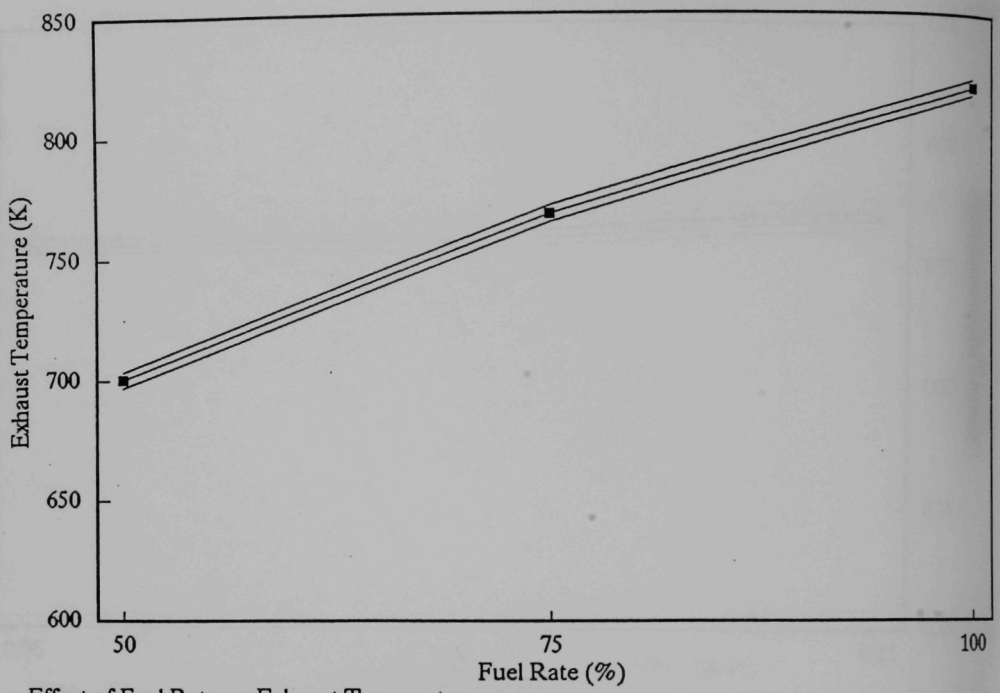
Source	f	S	V	F	S'	% contr.
Timing	2	439.21	219.60	15.62	411.10	0.91
Oxygen	2	381.58	190.79	13.57	353.47	0.78
Fuel	2	43444.03	21722.02	1545.36	43415.92	95.63
Water	2	1021.61	510.81	36.34	993.50	2.19
Replicat.	1	2.88	2.88	0.20	0.00	0.00
e	8	112.45	14.06			0.50
Pooled e	9	115.33	12.81			
T	17	45401.76				100.00



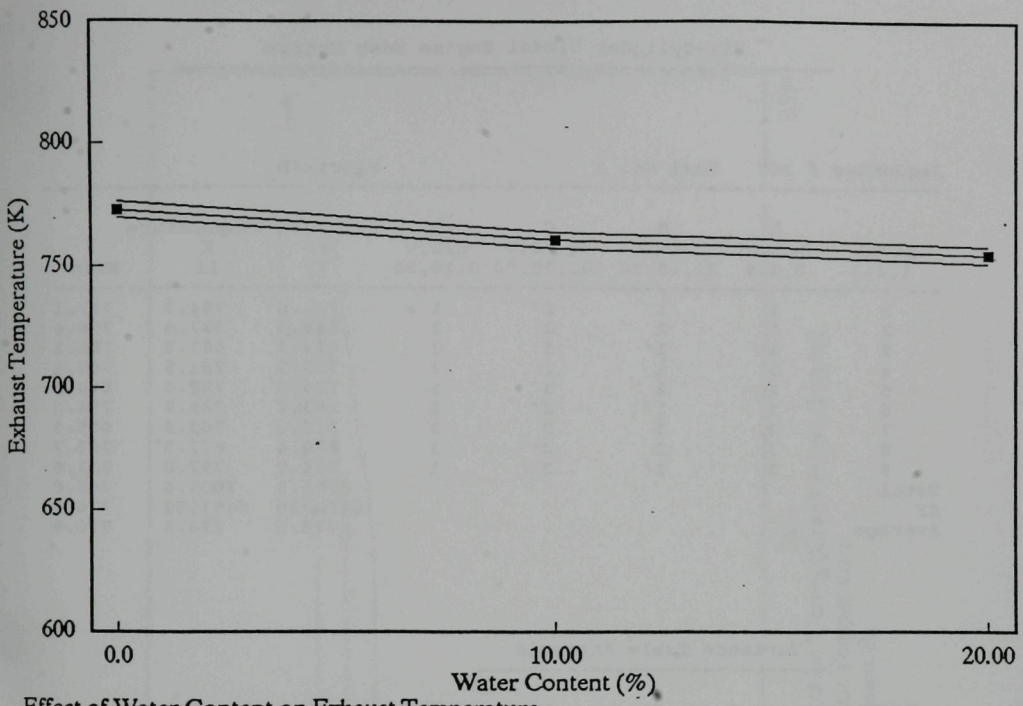
Effect of Injection Timing on Exhaust Temperature
(No.2 Fuel Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix A)

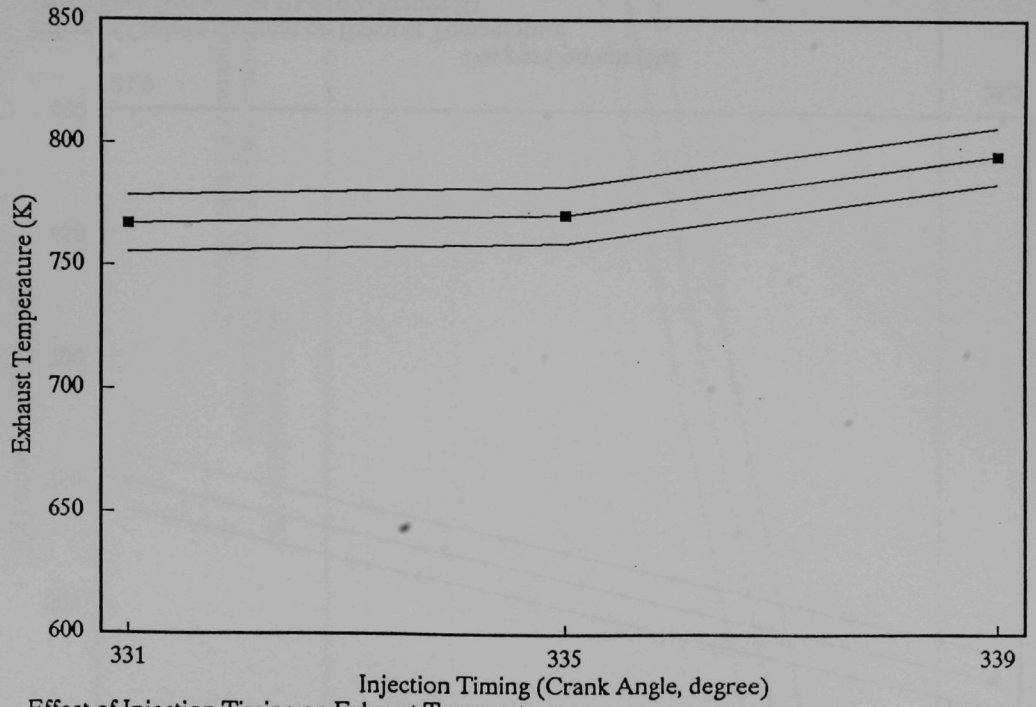
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

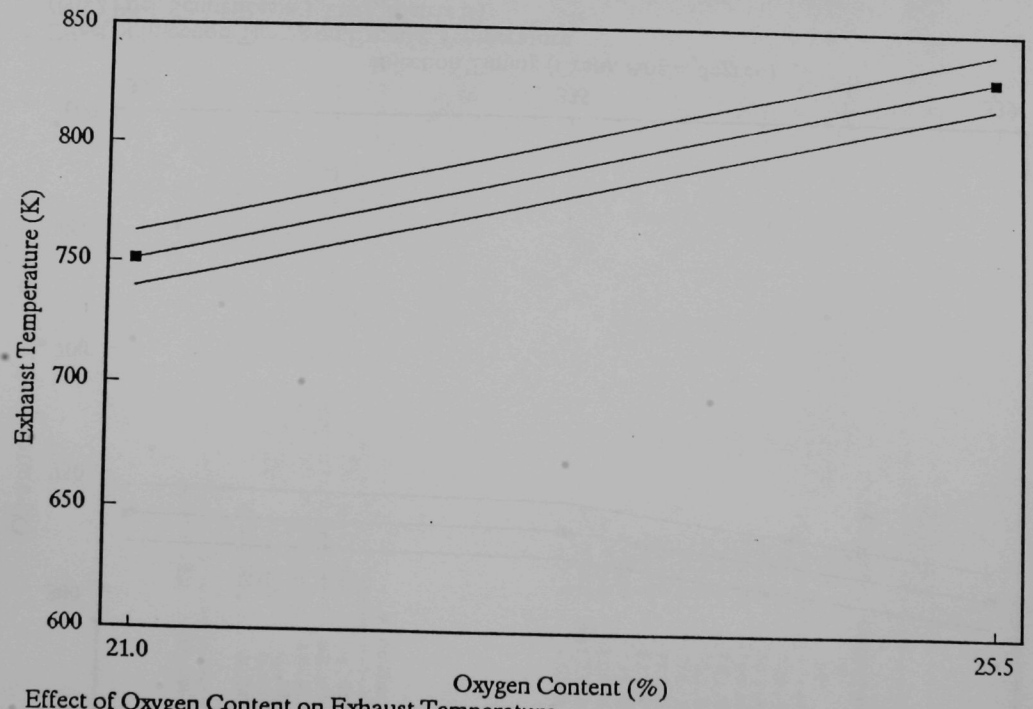
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	Exhaust Temperature K I	K II	Mean
1	1	1	2′	1	781.5	784.3	767.1
2	1	2	2	2	836.5	837.6	770.6
3	1	1′	3	3	679.3	683.2	795.2
4	2	1	2	3	753.2	751.5	748.1
5	2	2	3	1	766.5	782.6	830.2
6	2	1′	2′	2	783.7	785.9	754.6
7	3	1	3	2	712.0	705.9	815.6
8	3	2	2′	3	880.4	877.6	795.7
9	3	1′	2	1	798.2	797.0	721.6
Total					6991.3	7005.6	785.0
CF					5430920	5453159	776.9
Average					776.8	778.4	770.9

Variance Table Analysis

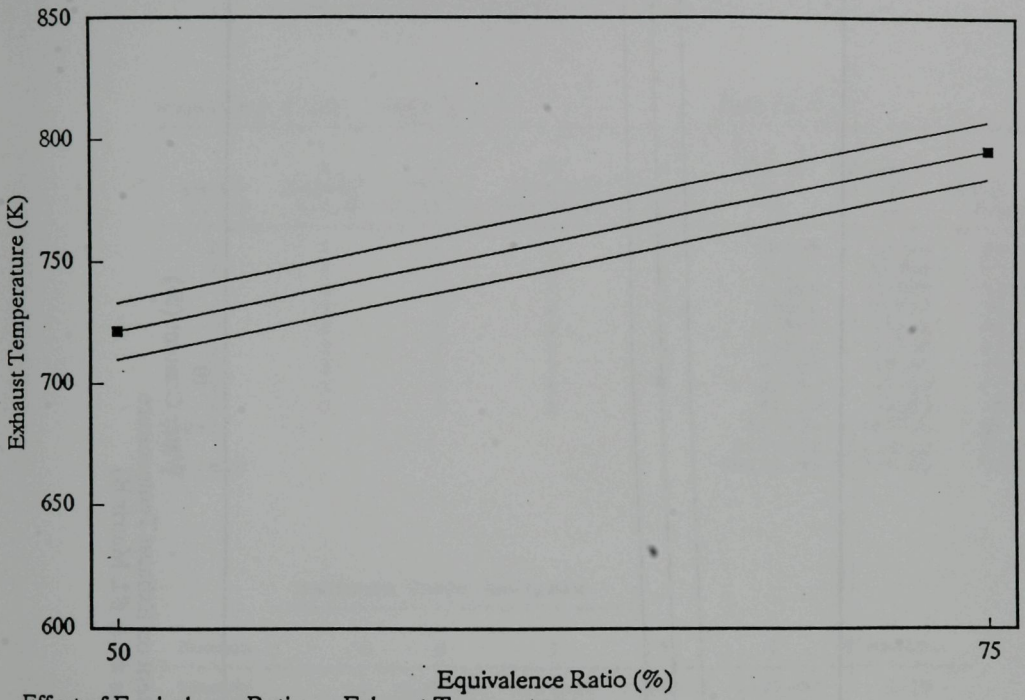
Source	f	S	V	F	S′	% contr.
Timing	2	2817.55	1408.78	9.57	2523.23	4.35
Oxygen	1	24895.58	24895.58	169.17	24748.42	42.63
Eq. R	1	28246.40	28246.40	191.94	28099.24	48.41
Water	2	604.73	302.37	2.05	310.41	0.53
Replicat.	1	11.36	11.36	0.08	0.00	0.00
e	10	1471.62	147.16		2365.95	4.08
Pooled e	11	1482.98	158.52			
T	17	58047.25			58047.25	100.00



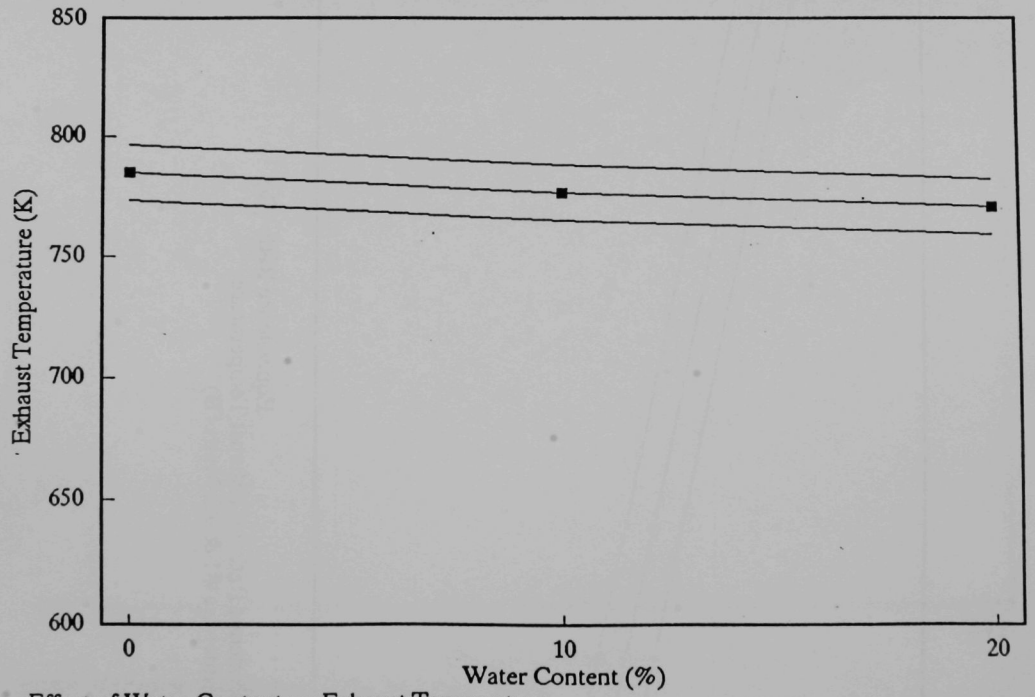
Effect of Injection Timing on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on Exhaust Temperature
(No.2 Fuel, Sequences #1 & #2, Matrix B)

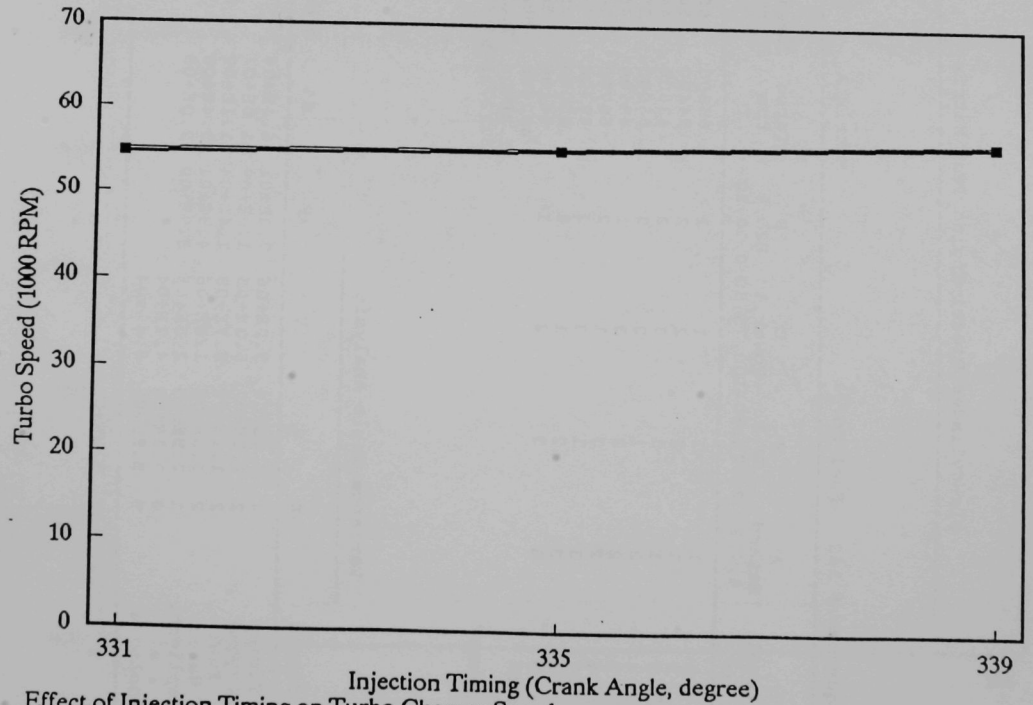
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

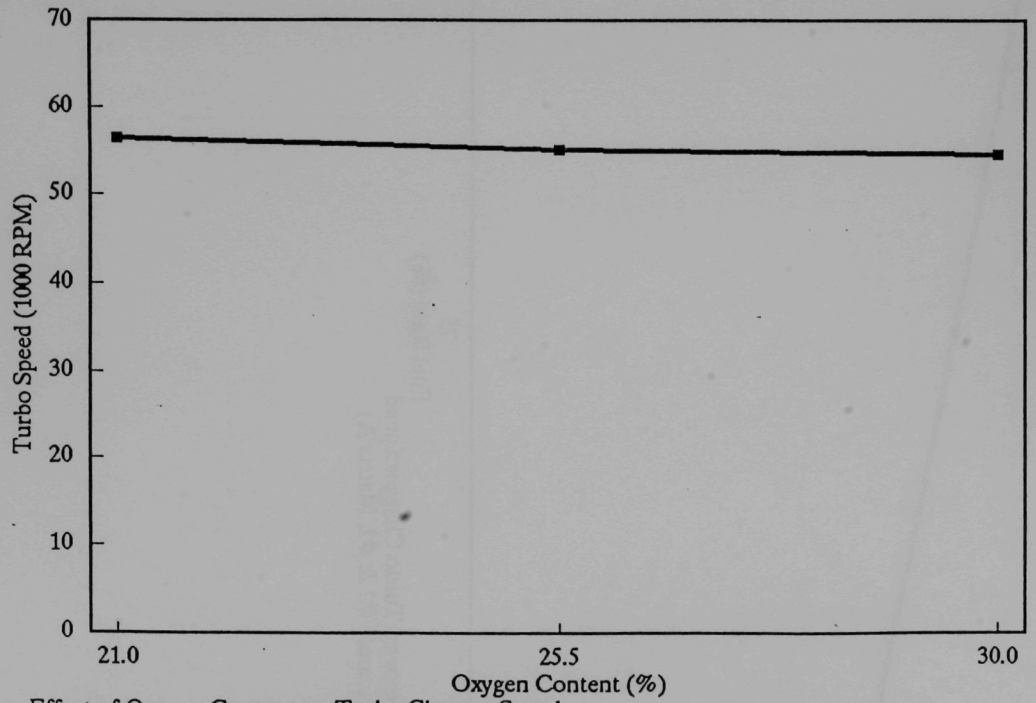
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Power,% 100,75,50	D H2O,% 0,10,20	Turbo Speed rpm I	rpm II	10E+3 Mean
1	1	1	1	1	65800	66400	54.78
2	1	2	2	2	54400	54500	55.30
3	1	3	3	3	43600	44000	56.23
4	2	1	2	3	56000	56100	56.48
5	2	2	3	1	45900	45800	55.17
6	2	3	1	2	63700	64300	54.67
7	3	1	3	2	47400	47200	65.10
8	3	2	1	3	65000	65400	55.57
9	3	3	2	1	56100	56300	45.65
Total					497900	500000	56.05
CF					2.8E+10	2.8E+10	55.25
Average					55322.22	55555.56	55.02

Variance Table Analysis

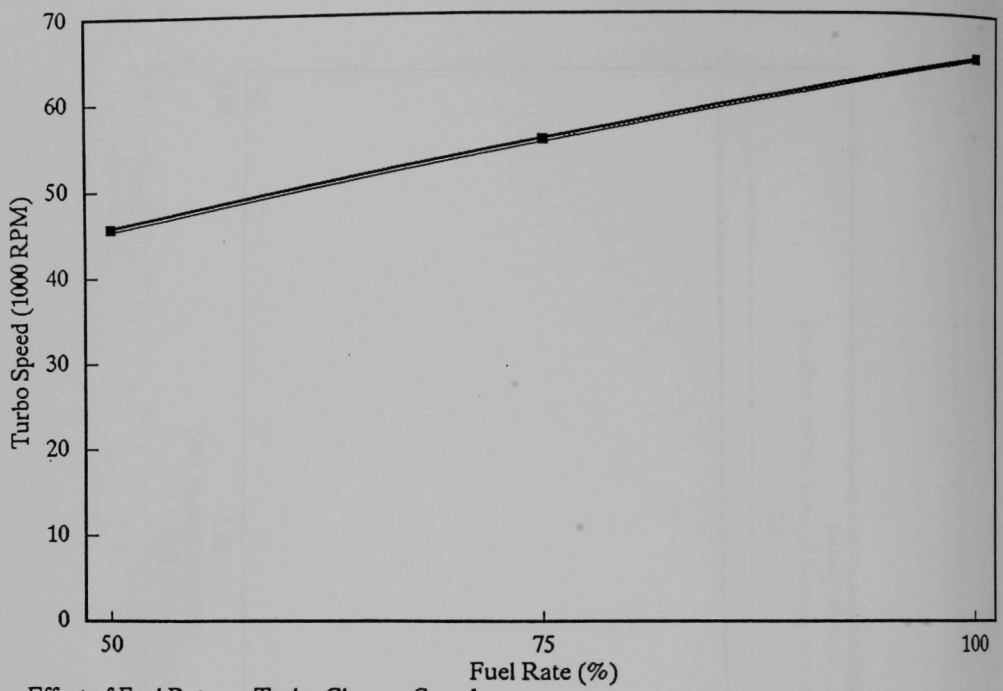
Source	f	S	V	F	S'	% contr.
Timing	2	6.5E+06	3.2E+06	7.9E+01	6.4E+06	0.55
Oxygen	2	1.1E+07	5.3E+06	1.3E+02	1.0E+07	0.91
Fuel	2	1.1E+09	5.7E+08	1.4E+04	1.1E+09	98.16
Water	2	3.5E+06	1.8E+06	4.3E+01	3.4E+06	0.30
Replicat.	1	2.5E+05	2.5E+05	5.9E+00	2.0E+05	0.02
e	8	3.3E+05	4.1E+04			0.06
Pooled e	9	5.8E+05	6.4E+04			
T	17	1.2E+09				100.00



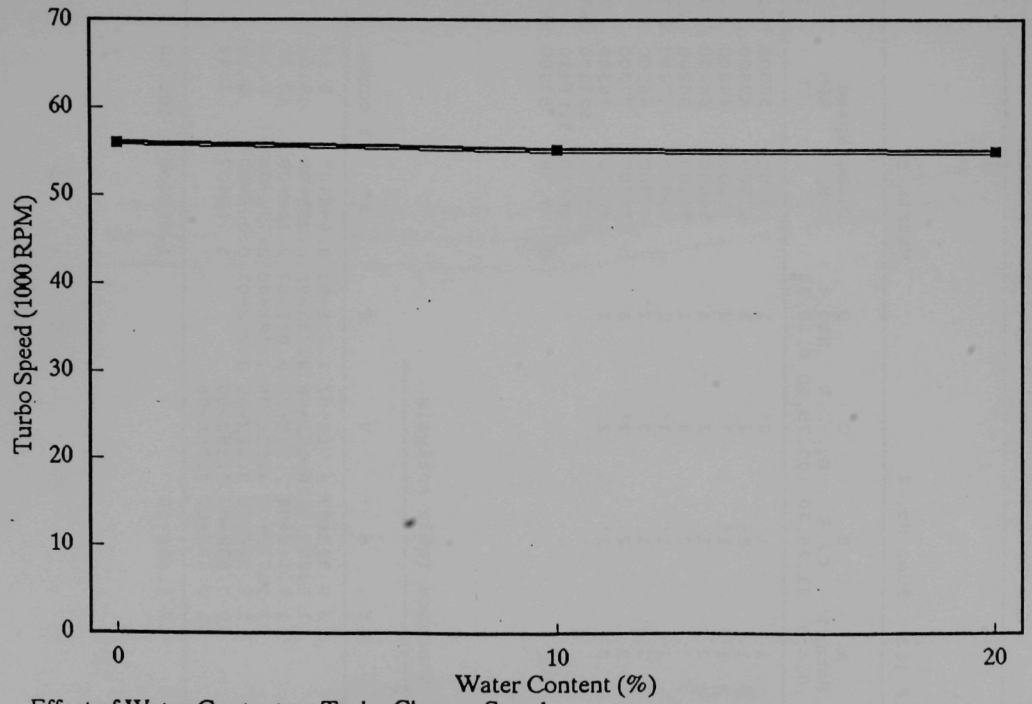
Effect of Injection Timing on Turbo Charger Speed
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Turbo Charger Speed
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Turbo Charger Speed
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Turbo Charger Speed
(No.2 Fuel, Sequences #1 & #2, Matrix A)

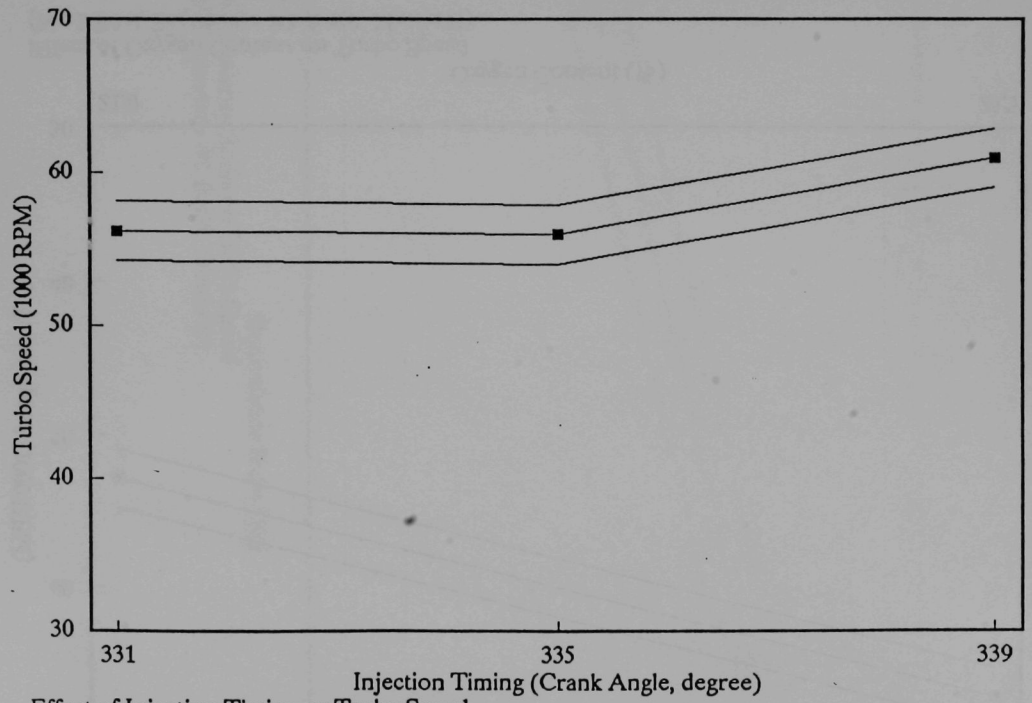
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

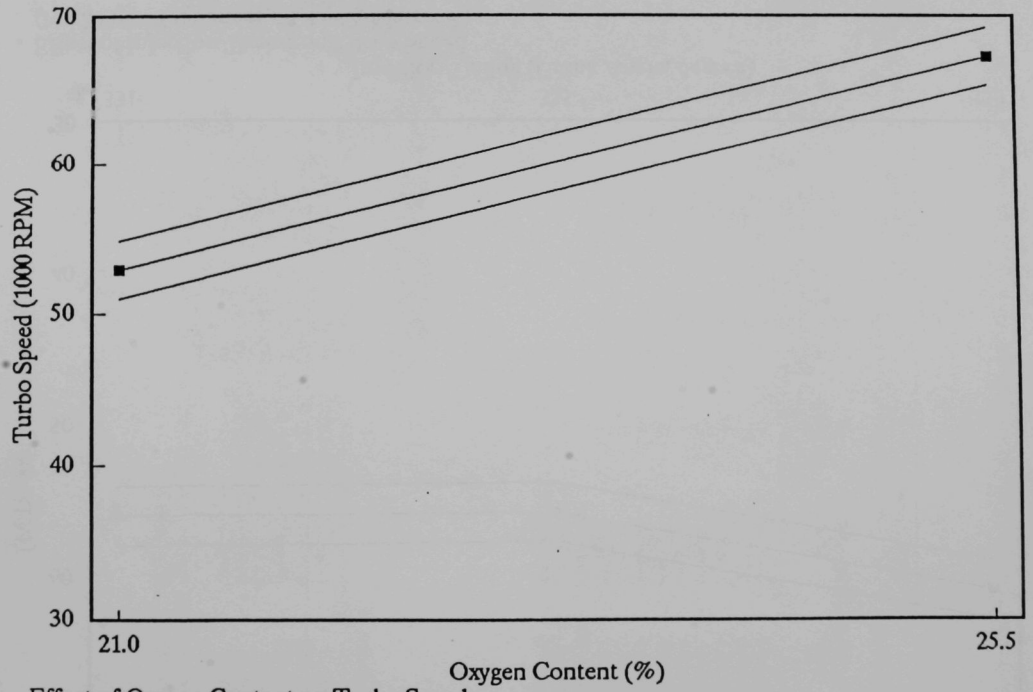
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	Turbo Speed RPM I	RPM II	Mean
1	1	1	2′	1	55500	56500	56183.33
2	1	2	2	2	67700	69900	55966.67
3	1	1′	3	3	43300	44200	60916.67
4	2	1	2	3	54600	54400	52466.67
5	2	2	3	1	54900	56500	67283.33
6	2	1′	2′	2	57600	57800	53316.67
7	3	1	3	2	47500	46300	63683.33
8	3	2	2′	3	77700	77000	60600
9	3	1′	2	1	58500	58500	48783.33
Total					517300	521100	56733.33
CF					3.0E+10	3.0E+10	57800
Average					57477.78	57900	58533.33

Variance Table Analysis

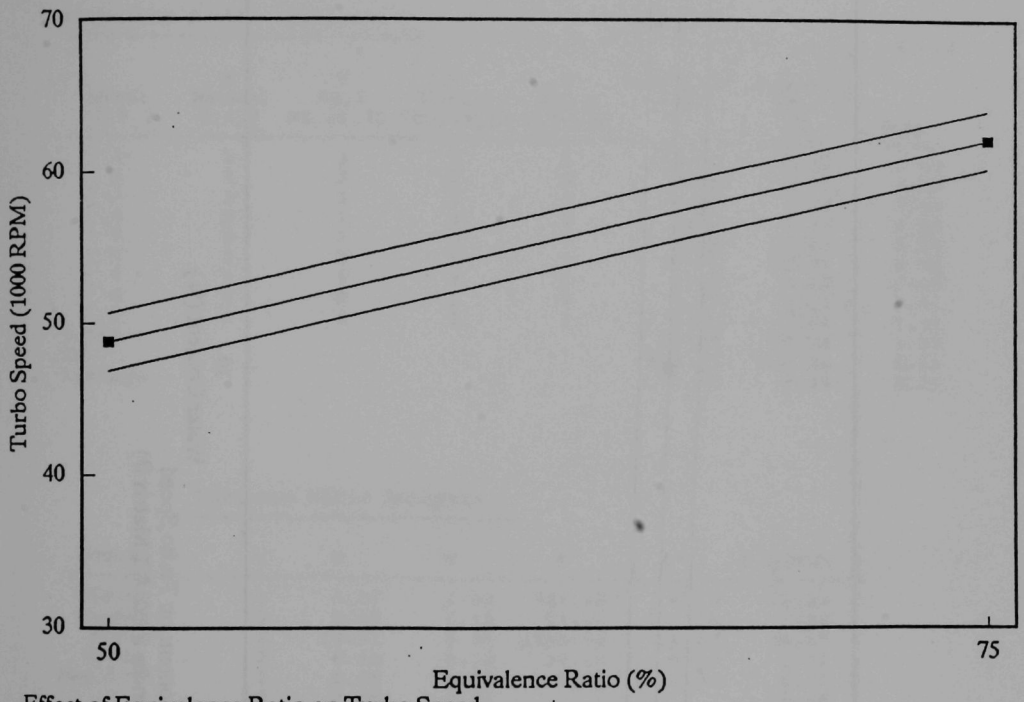
Source	f	S	V	F	S′	% contr.
Timing	2	9.39E+07	4.70E+07	1.32E+01	8.68E+07	5.16
Oxygen	1	8.28E+08	8.28E+08	2.33E+02	8.25E+08	49.04
Eq. R	1	7.14E+08	7.14E+08	2.01E+02	7.10E+08	42.22
Water	2	9.83E+06	4.92E+06	1.38E+00	2.73E+06	0.16
Replicat.	1	8.02E+05	8.02E+05	2.26E-01	0.00E+00	0.00
e	10	3.55E+07	3.55E+06		5.76E+07	3.42
Pooled e	11	3.63E+07	4.35E+06			
T	17	1.68E+09			1.68E+09	100.00



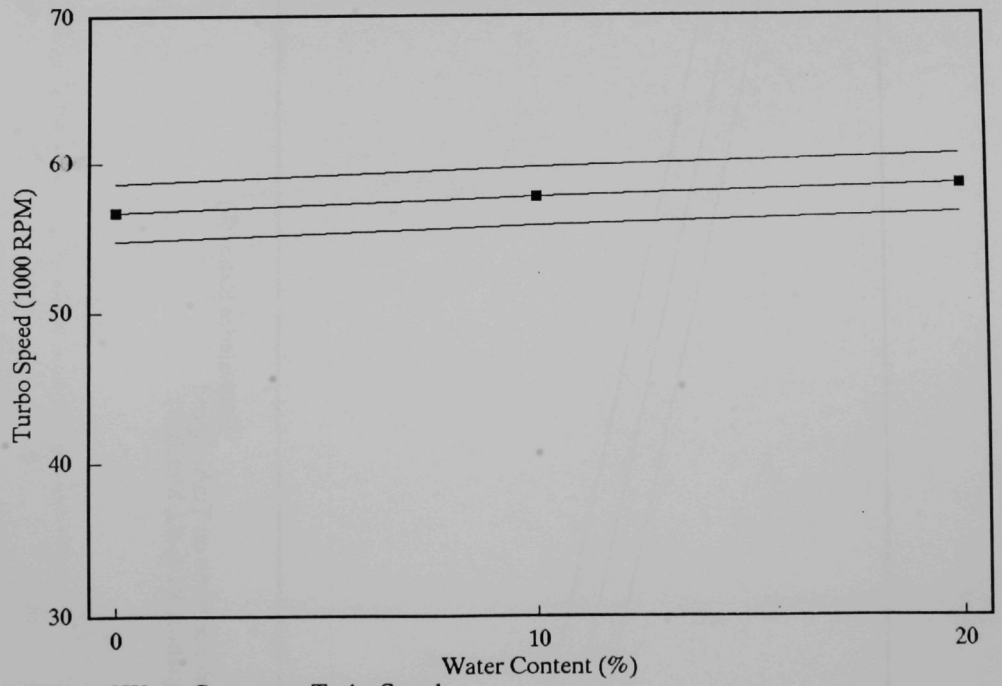
Effect of Injection Timing on Turbo Speed
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on Turbo Speed
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on Turbo Speed
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on Turbo Speed
(No.2 Fuel, Sequences #1 & #2, Matrix B)

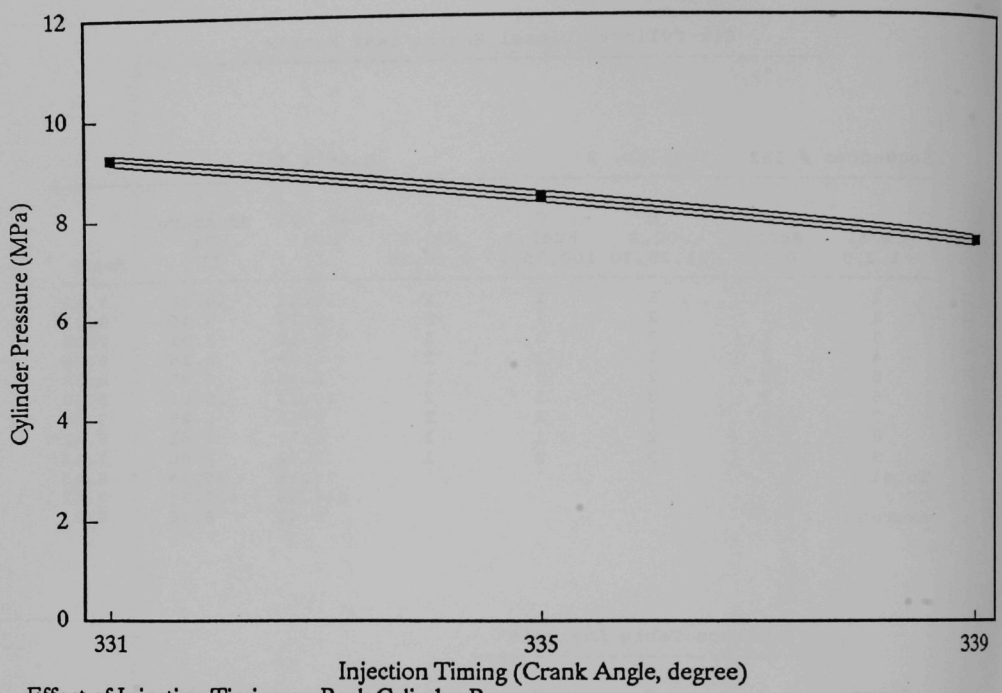
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

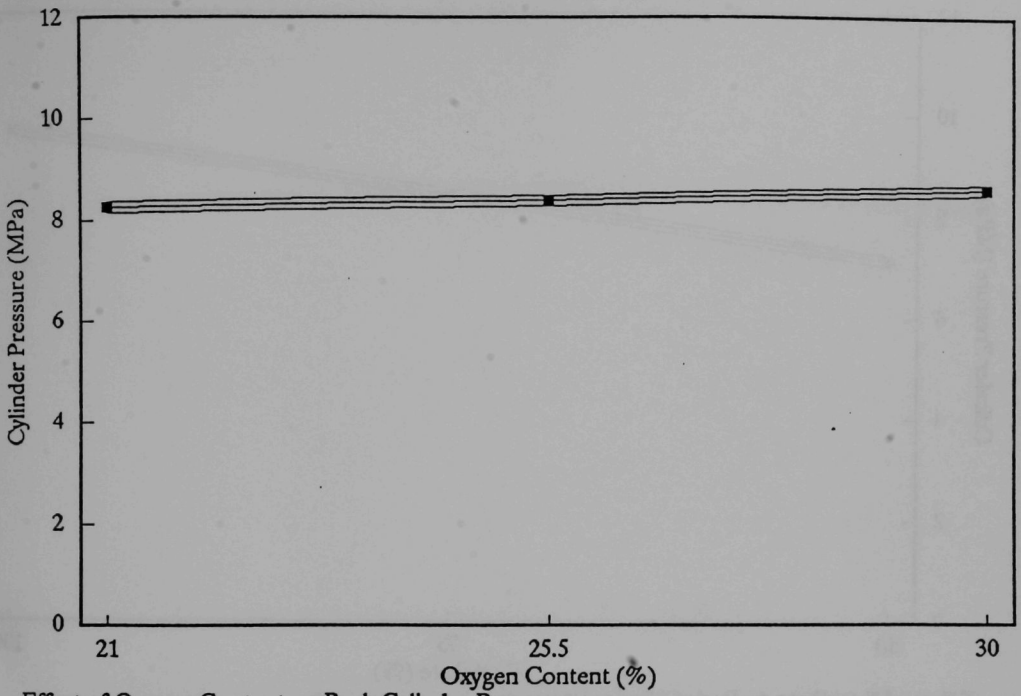
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Peak Cyl. Pressure MPa I	MPa II	Mean
1	1	1	1	1	10.28	10.28	9.23
2	1	2	2	2	9.35	9.45	8.43
3	1	3	3	3	8.10	7.91	7.59
4	2	1	2	3	8.09	8.16	8.26
5	2	2	3	1	7.15	6.95	8.38
6	2	3	1	2	10.19	10.01	8.60
7	3	1	3	2	6.44	6.29	9.69
8	3	2	1	3	8.77	8.61	8.41
9	3	3	2	1	7.82	7.60	7.14
Total					76.19	75.26	8.35
CF					644.99	629.34	8.62
Average					8.47	8.36	8.27

Variance Table Analysis

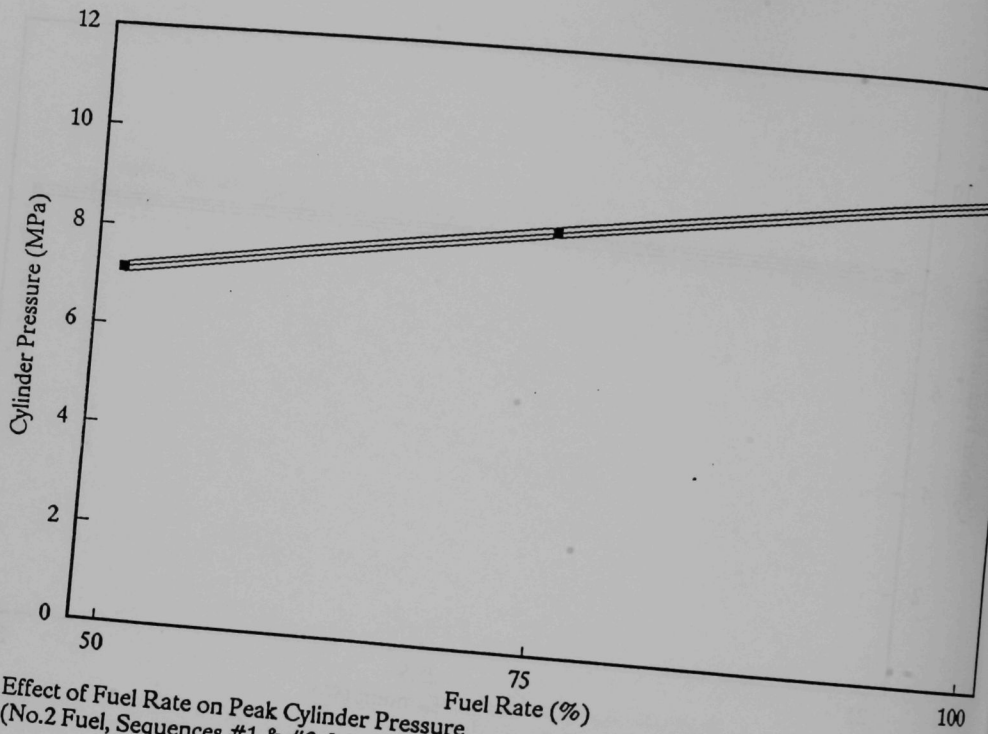
Source	f	S	V	F	S'	% contr.
Timing	2	8.07	4.03	521.48	8.05	28.29
Oxygen	2	0.37	0.19	24.19	0.36	1.26
Fuel	2	19.51	9.75	1260.58	19.49	68.47
Water	2	0.40	0.20	26.15	0.39	1.37
Replicat.	1	0.05	0.05	6.21	0.04	0.14
e	8	0.06	0.01			0.46
Pooled e	9	0.11	0.01			
T	17	28.47				100.00



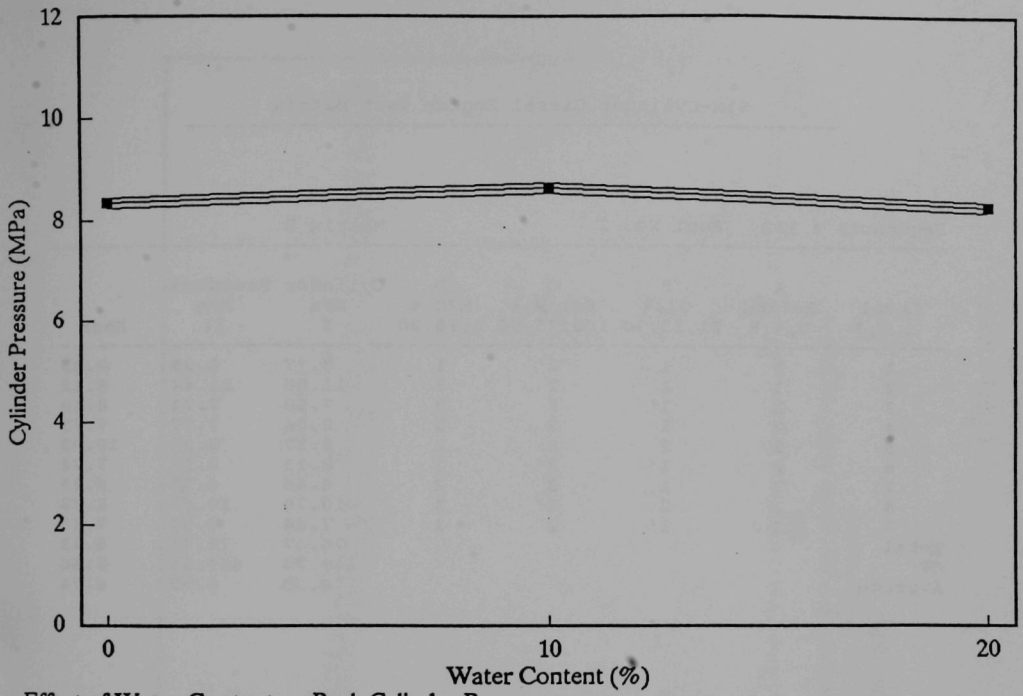
Effect of Injection Timing on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix A)

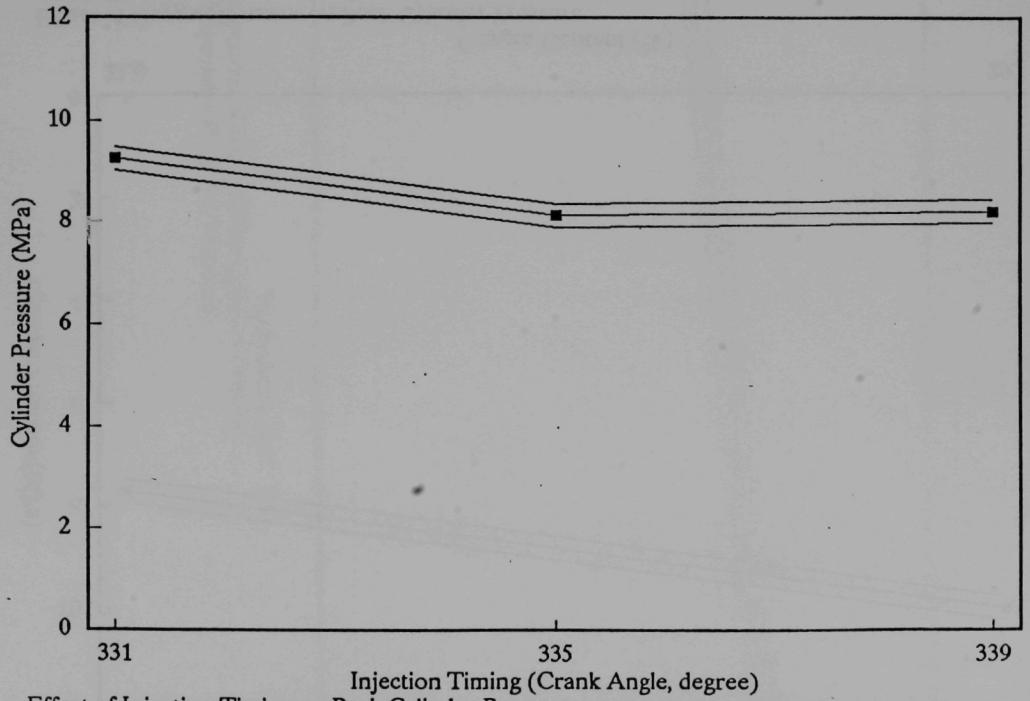
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

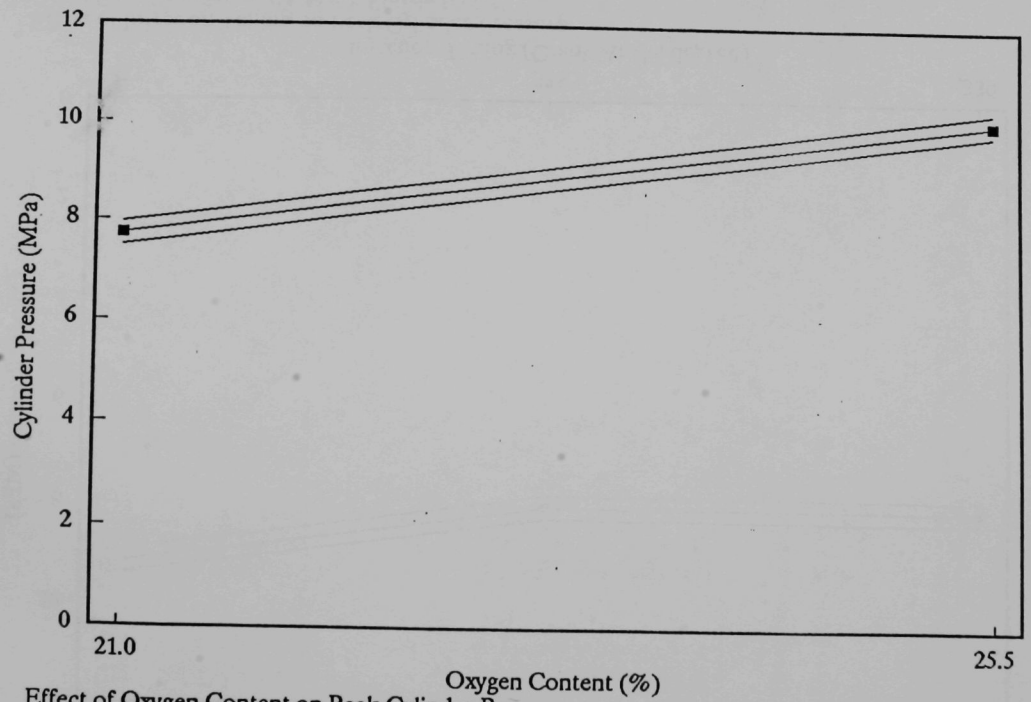
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Eq. R,% 100,75,50	D H2O,% 0,10,20	Cylinder Pressure MPa I	MPa II	Mean
1	1	1	2′	1	8.77	8.99	9.25
2	1	2	2	2	11.06	11.44	8.12
3	1	1′	3	3	7.50	7.74	8.19
4	2	1	2	3	8.04	7.77	7.73
5	2	2	3	1	8.37	8.31	10.09
6	2	1′	2′	2	8.13	8.11	7.74
7	3	1	3	2	6.46	6.37	9.23
8	3	2	2′	3	10.70	10.67	8.88
9	3	1′	2	1	7.44	7.51	7.46
Total					76.47	76.91	8.23
CF					649.74	657.24	8.60
Average					8.50	8.55	8.74

Variance Table Analysis

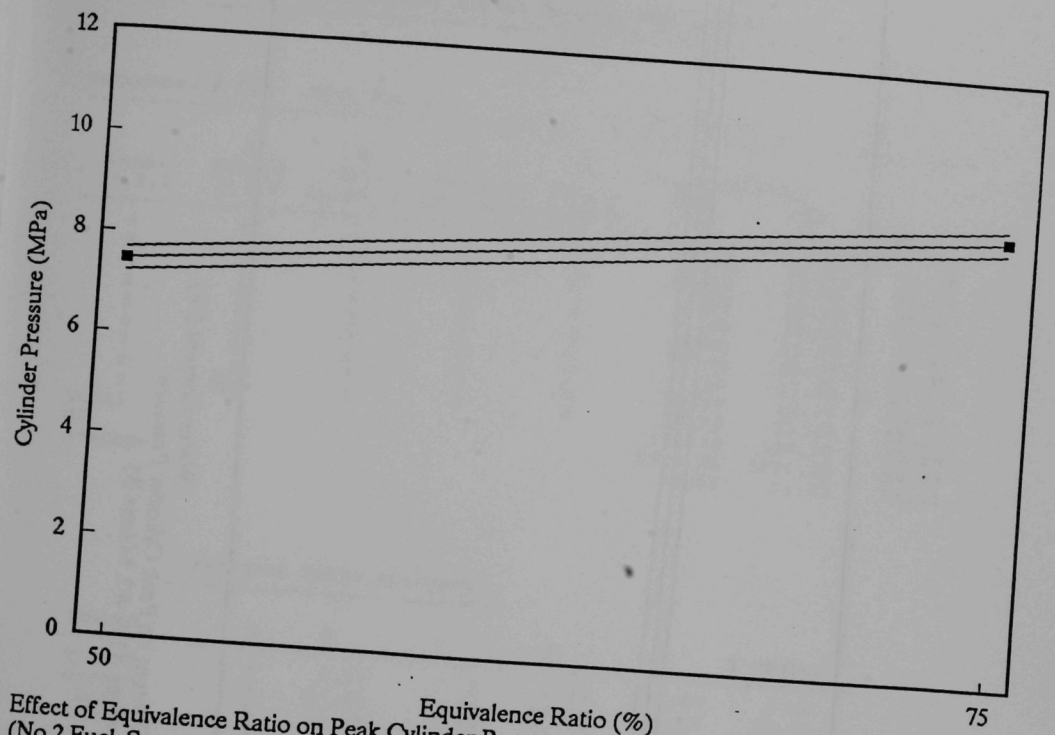
Source	f	S	V	F	S′	% contr.
Timing	2	4.80	2.40	45.17	4.69	12.18
Oxygen	1	22.20	22.20	418.13	22.15	57.50
Eq. R	1	10.17	10.17	191.47	10.11	26.25
Water	2	0.81	0.41	7.67	0.71	1.84
Replicat.	1	0.01	0.01	0.20	0.00	0.00
e	10	0.53	0.05		0.86	2.23
Pooled e	11	0.54	0.06			
T	17	38.52			38.52	100.00



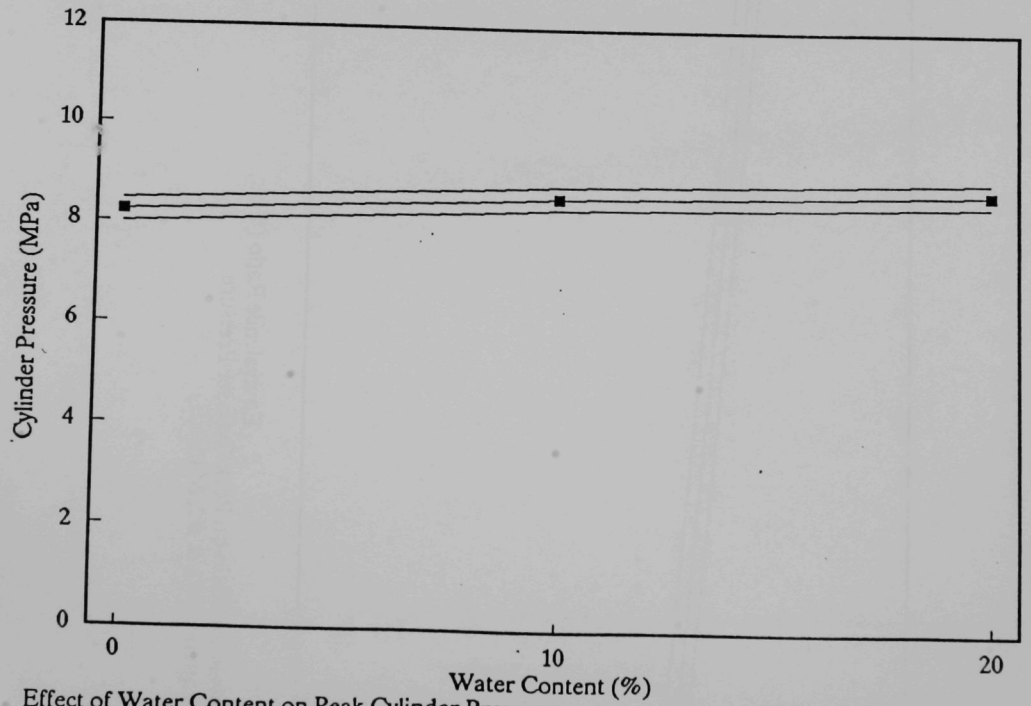
Effect of Injection Timing on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Oxygen Content on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Equivalence Ratio on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix B)



Effect of Water Content on Peak Cylinder Pressure
(No.2 Fuel, Sequences #1 & #2, Matrix B)

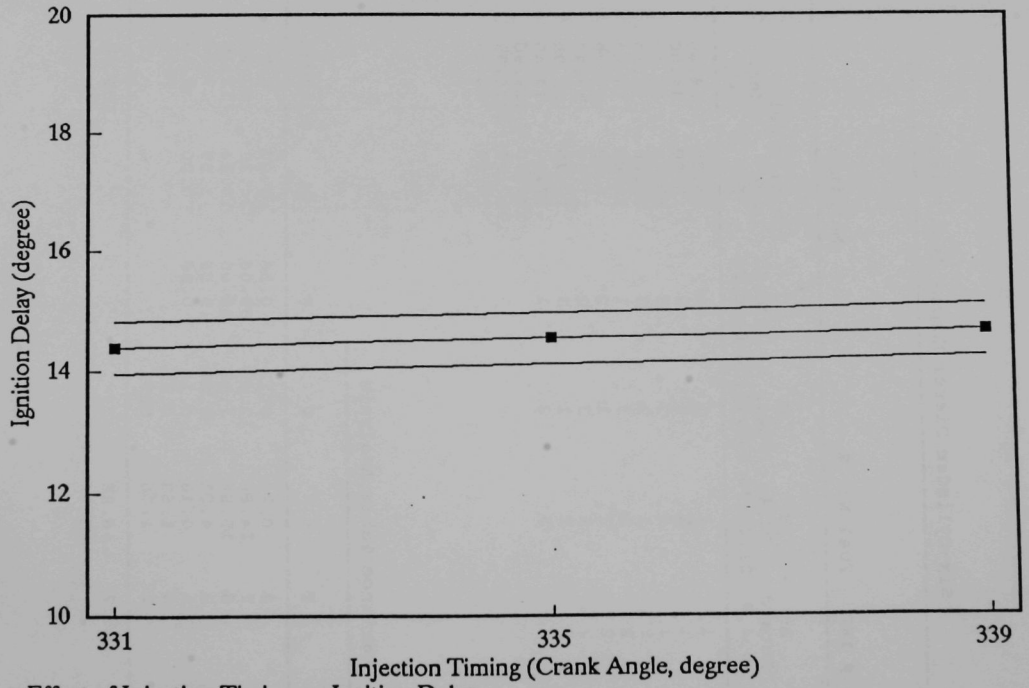
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix A

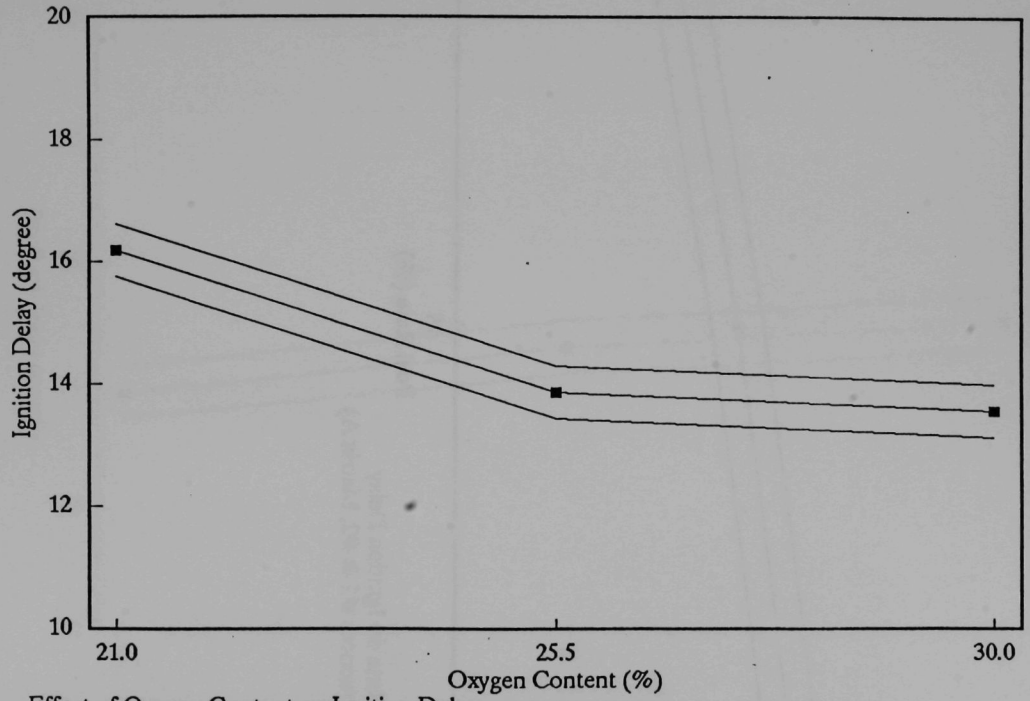
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Power,% 100,75,50	D H2O,% 0,10,20	Ignition Delay deg. I	Ignition Delay deg. II	Mean
1	1	1	1	1	14.20	14.20	14.38
2	1	2	2	2	13.90	14.00	14.55
3	1	3	3	3	15.60	14.40	14.67
4	2	1	2	3	17.00	16.60	16.18
5	2	2	3	1	14.80	13.90	13.87
6	2	3	1	2	12.30	12.70	13.55
7	3	1	3	2	17.30	17.80	13.33
8	3	2	1	3	13.70	12.90	14.63
9	3	3	2	1	12.90	13.40	15.63
Total					131.70	129.90	13.90
CF					1927.21	1874.89	14.67
Average					14.63	14.43	15.03

Variance Table Analysis

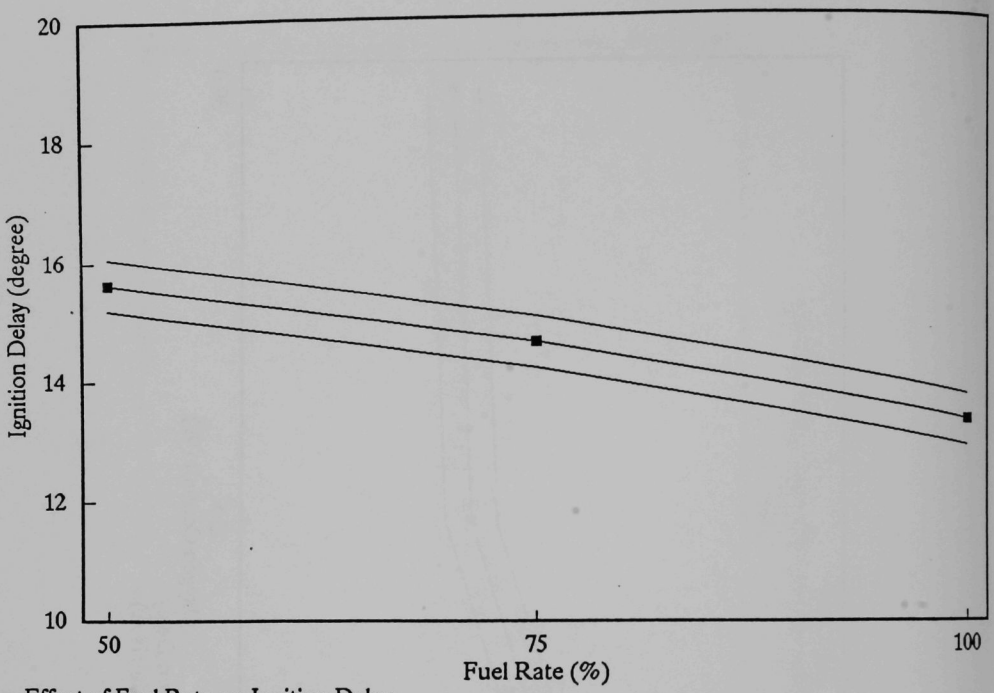
Source	f	S	V	F	S'	% contr.
Timing	2	0.24	0.12	0.58	0.00	0.00
Oxygen	2	24.80	12.40	59.06	24.38	52.01
Load	2	15.96	7.98	38.00	15.54	33.15
Water	2	4.01	2.01	9.56	3.59	7.66
Replicat.	1	0.18	0.18	0.86	0.00	0.00
e	8	1.68	0.21			7.17
Pooled e	9	1.86	0.21			
T	17	46.88				100.00



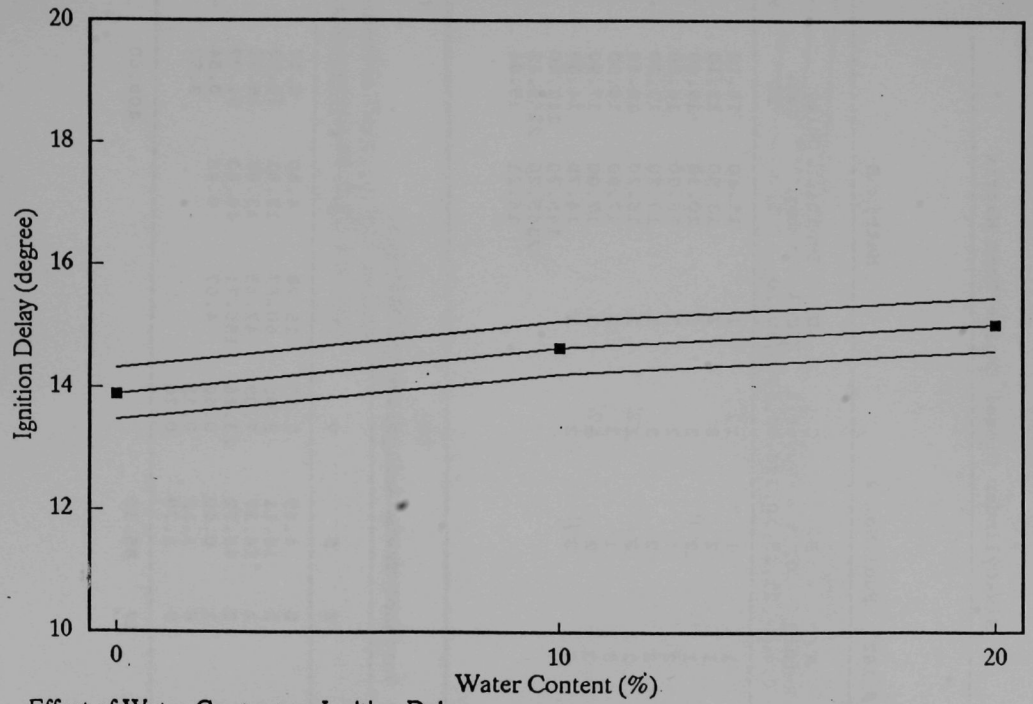
Effect of Injection Timing on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Oxygen Content on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Fuel Rate on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix A)



Effect of Water Content on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix A)

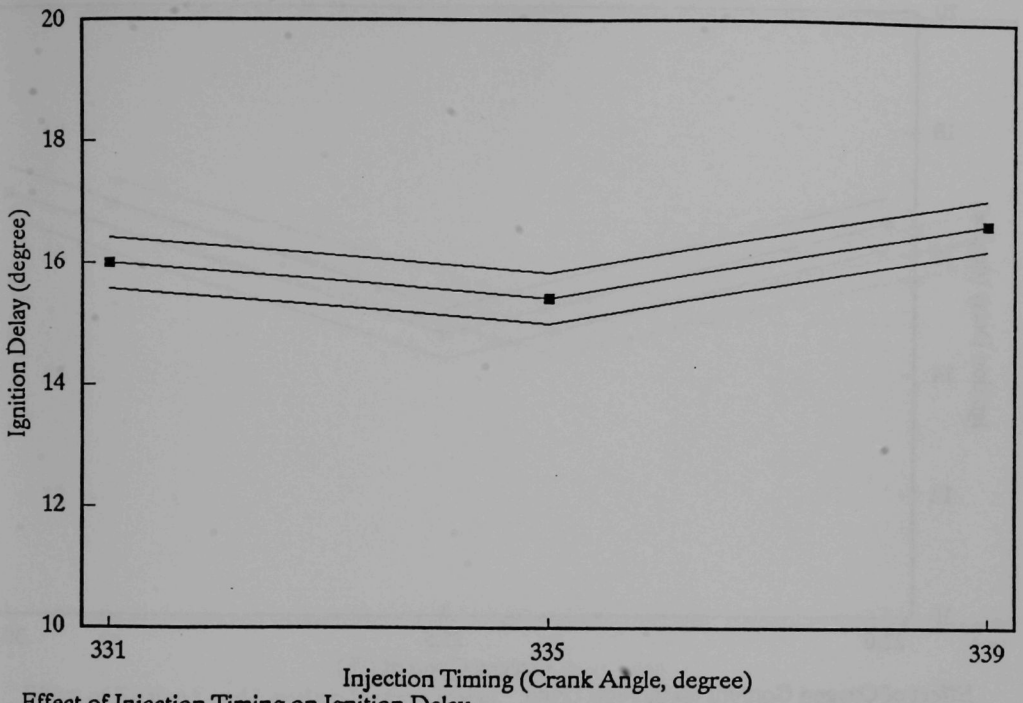
Six-Cylinder Diesel Engine Test Matrix

Sequences # 1&2 Fuel No. 2 Matrix B

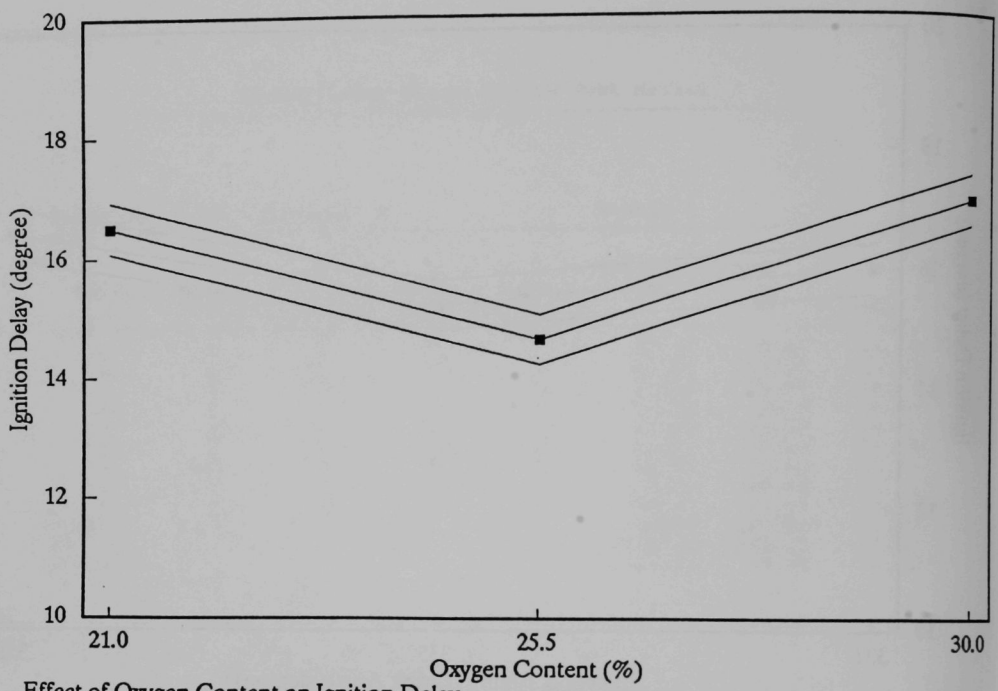
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Power,% 100,75,50	D H2O,% 0,10,20	Ignition Delay deg. I	Ignition Delay deg. II	Mean
1	1	1	~~1~~ 2'	1	15.40	15.10	16.00
2	1	2	2	2	13.50	12.10	15.42
3	1	~~2~~ 1'	3	3	20.30	19.60	16.67
4	2	1	2	3	16.90	16.80	16.50
5	2	2	3	1	13.20	13.30	14.63
6	2	~~2~~ 1'	~~1~~ 2'	2	16.20	16.10	16.95
7	3	1	3	2	17.90	16.90	16.42
8	3	2	~~1~~ 2'	3	17.80	17.90	14.80
9	3	~~2~~ 1'	2	1	14.70	14.80	16.87
Total					145.90	142.60	14.42
CF					2365.20	2259.42	15.45
Average					16.21	15.84	18.22

Variance Table Analysis

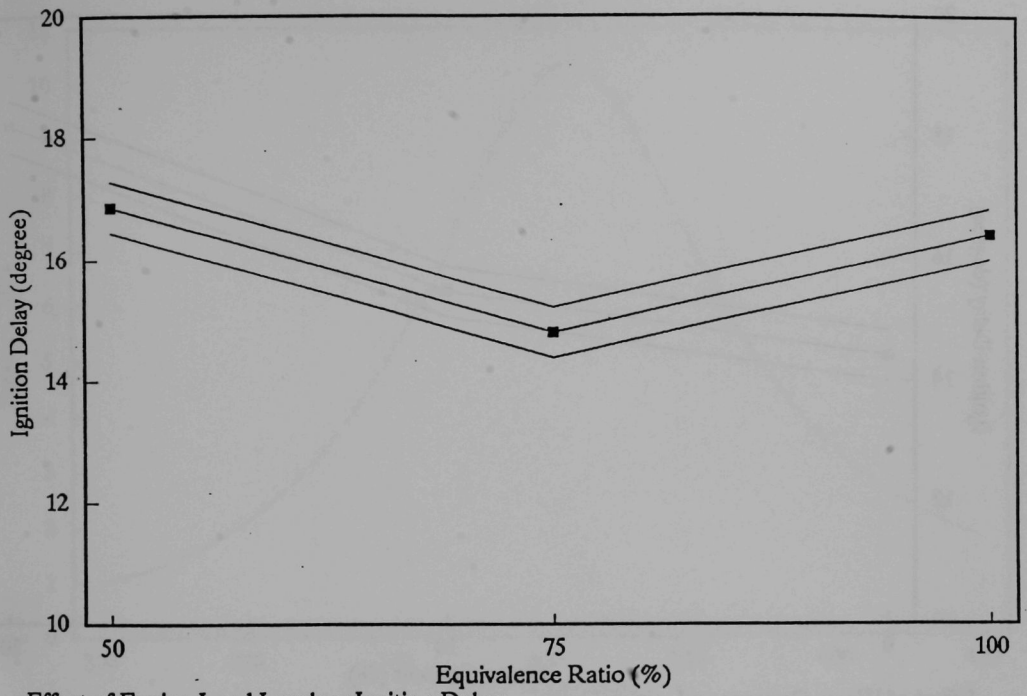
Source	f	S	V	F	S'	% contr.
Timing	2	4.69	2.35	15.78	4.40	5.17
Oxygen	2	18.11	9.05	60.87	17.81	20.93
Load	2	14.17	7.09	47.65	13.88	16.31
Water	2	46.32	23.16	155.71	46.03	54.09
Replicat.	1	0.60	0.60	4.07	0.46	0.54
e	8	1.19	0.15			2.97
Pooled e	9	1.79	0.20			
T	17	85.10				100.00



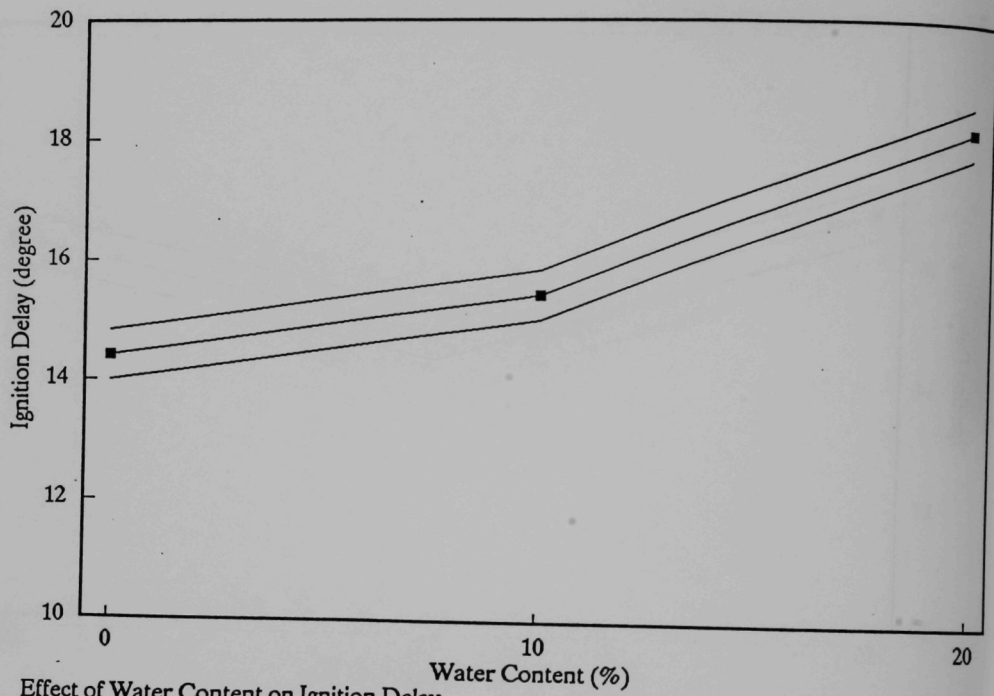
Effect of Injection Timing on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix B)



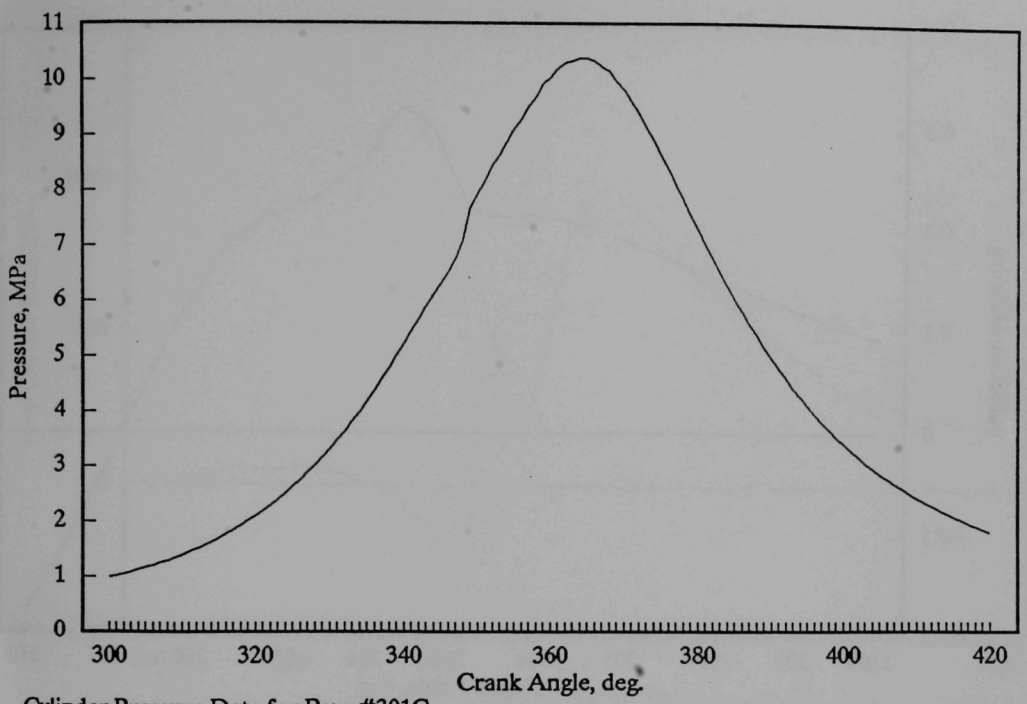
Effect of Oxygen Content on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix B)



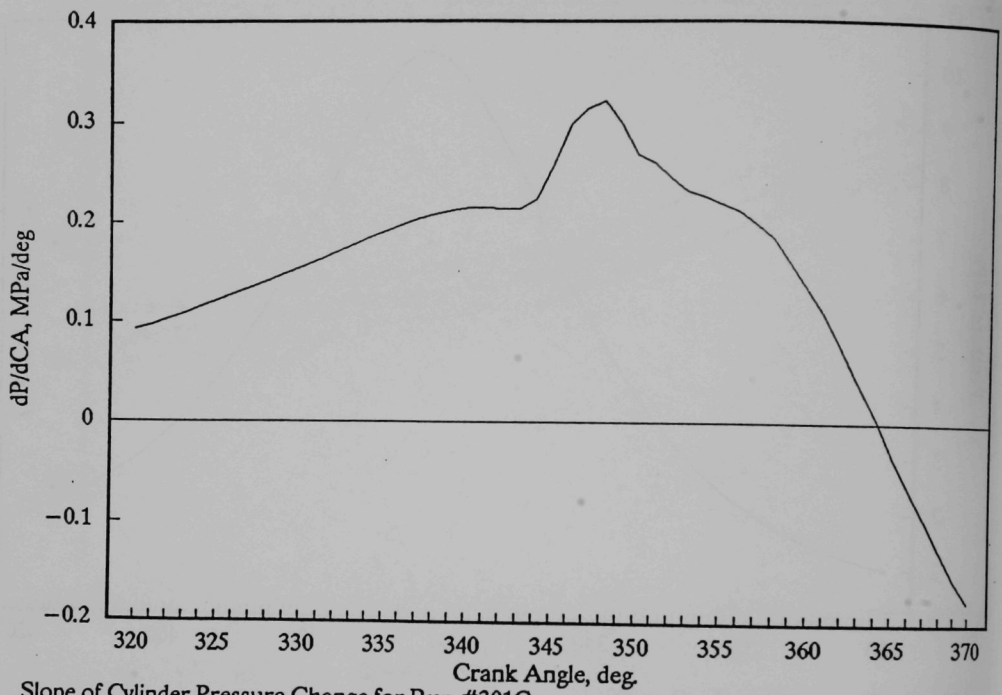
Effect of Engine Load Level on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix B)



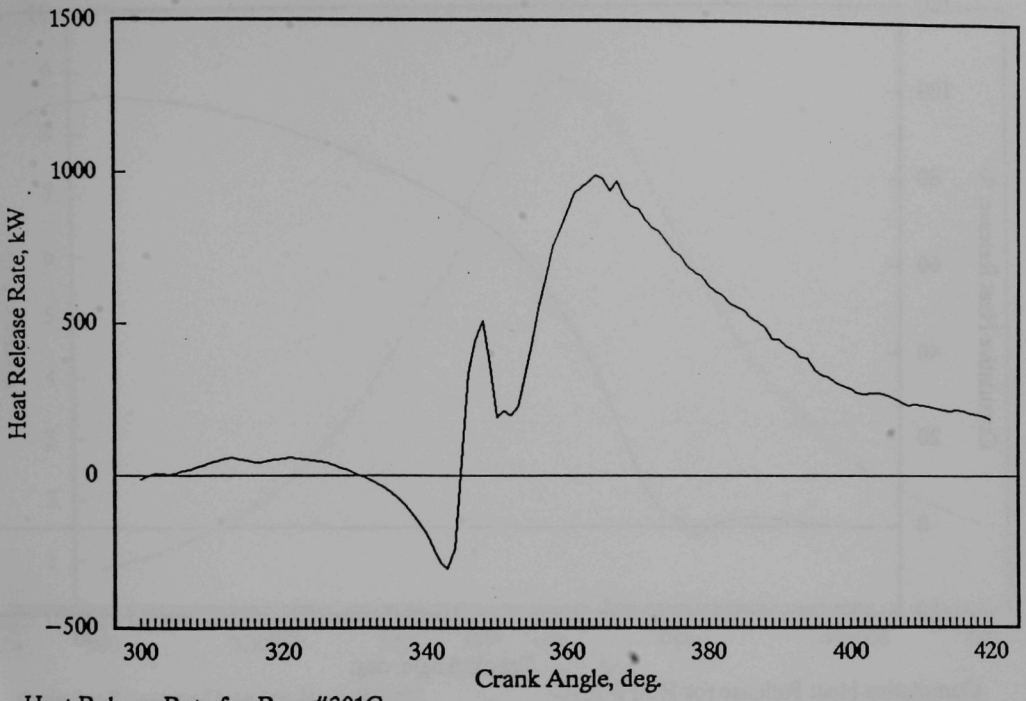
Effect of Water Content on Ignition Delay
(No.2 Fuel, Sequences #1 & #2, Matrix B)



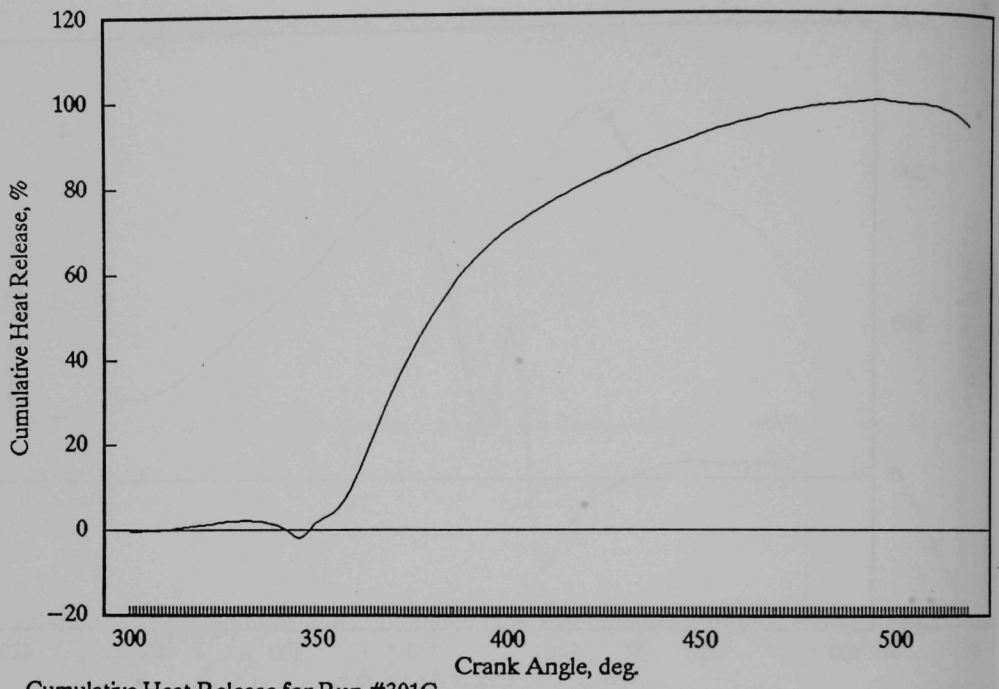
Cylinder Pressure Data for Run #301C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



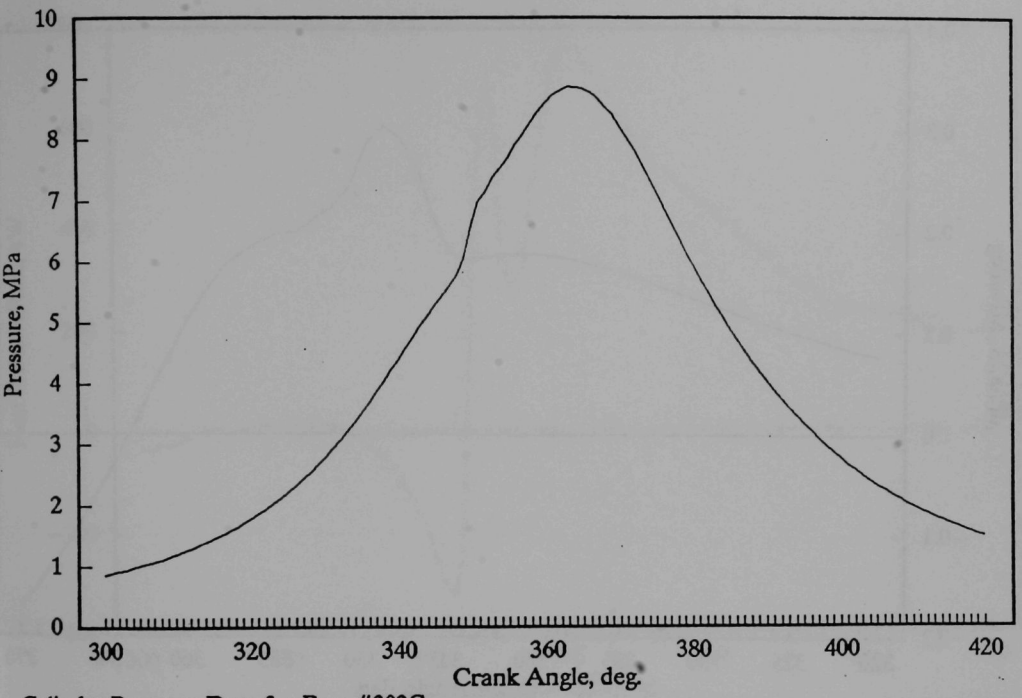
Slope of Cylinder Pressure Change for Run #301C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 100% Engine Load, 0% Water)



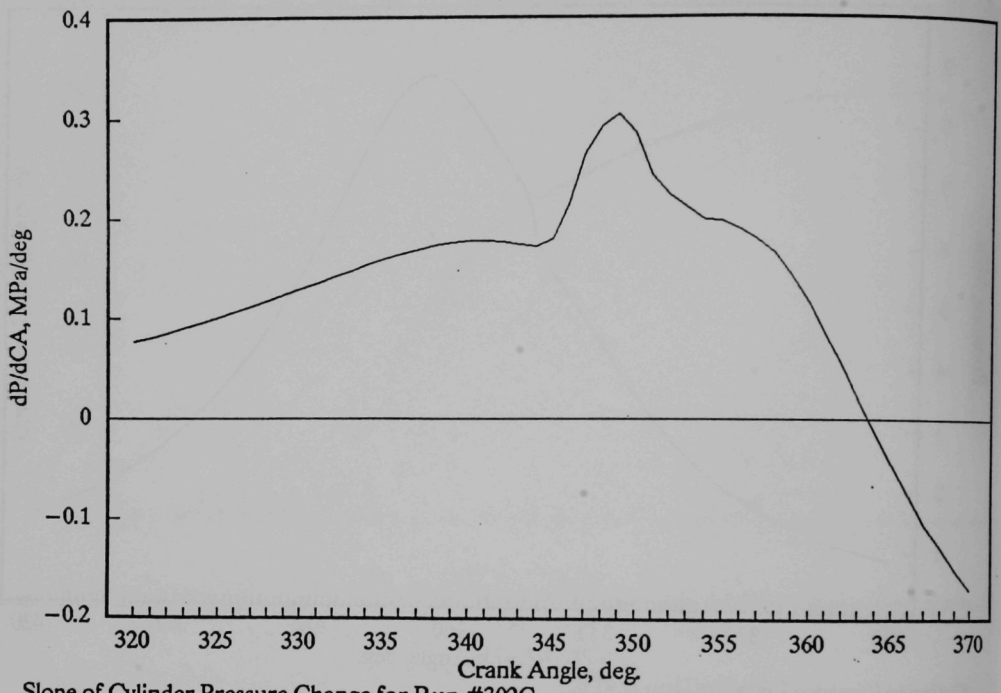
Heat Release Rate for Run #301C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



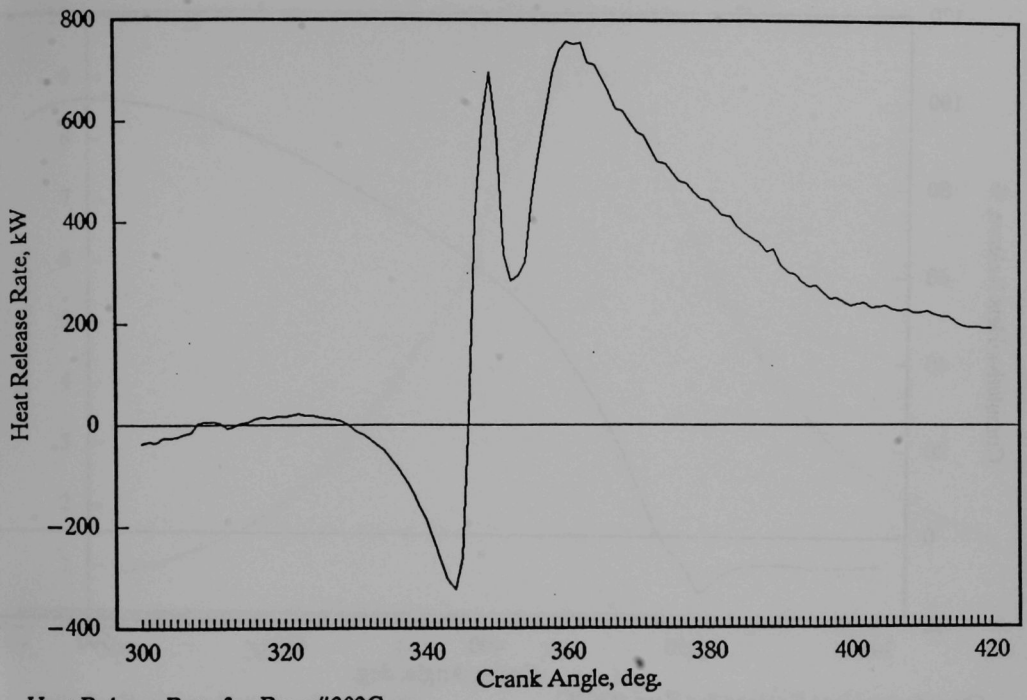
Cumulative Heat Release for Run #301C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



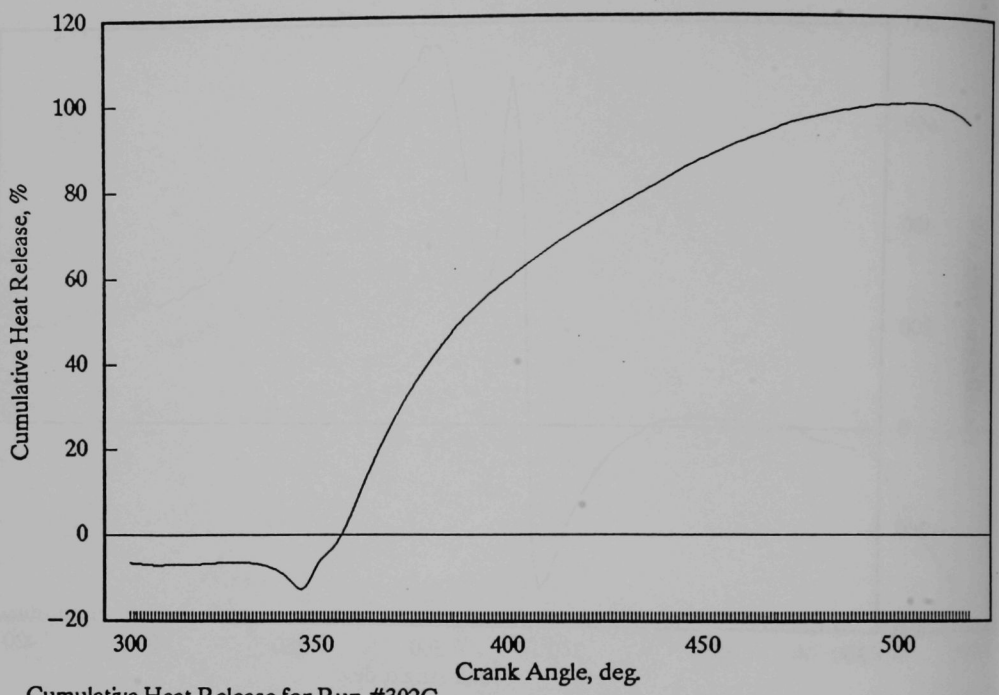
Cylinder Pressure Data for Run #302C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



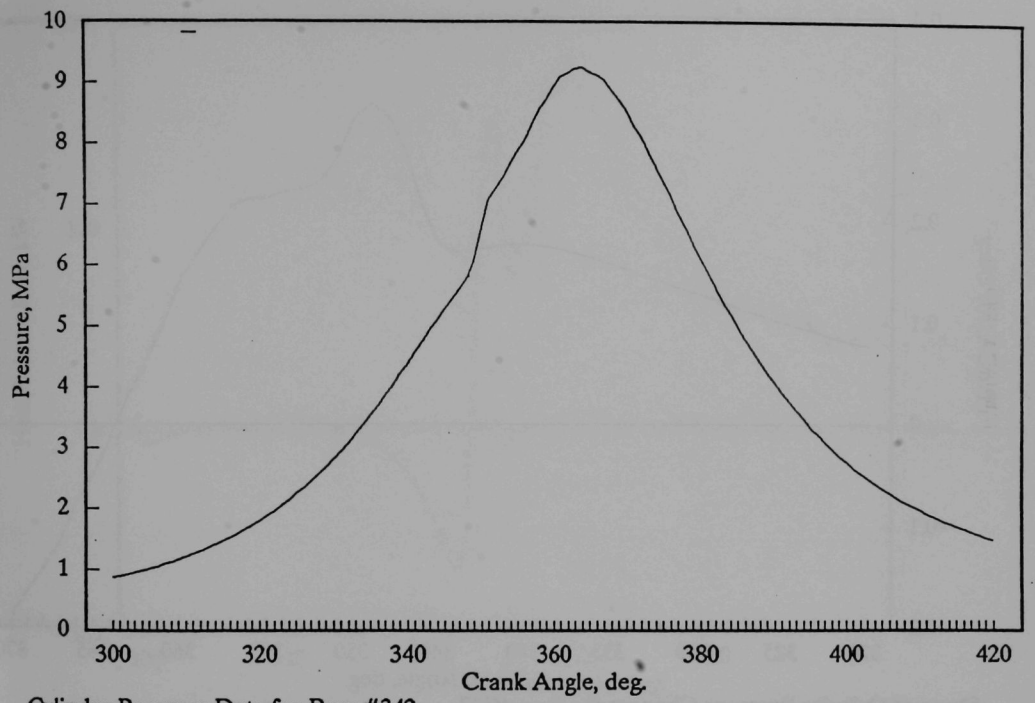
Slope of Cylinder Pressure Change for Run #302C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



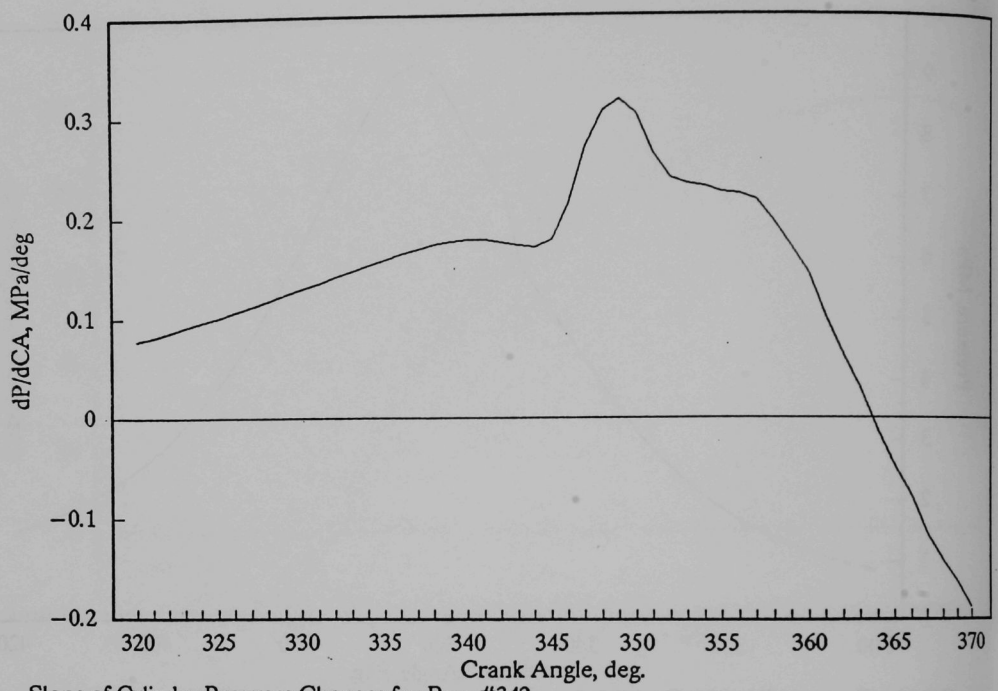
Heat Release Rate for Run #302C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



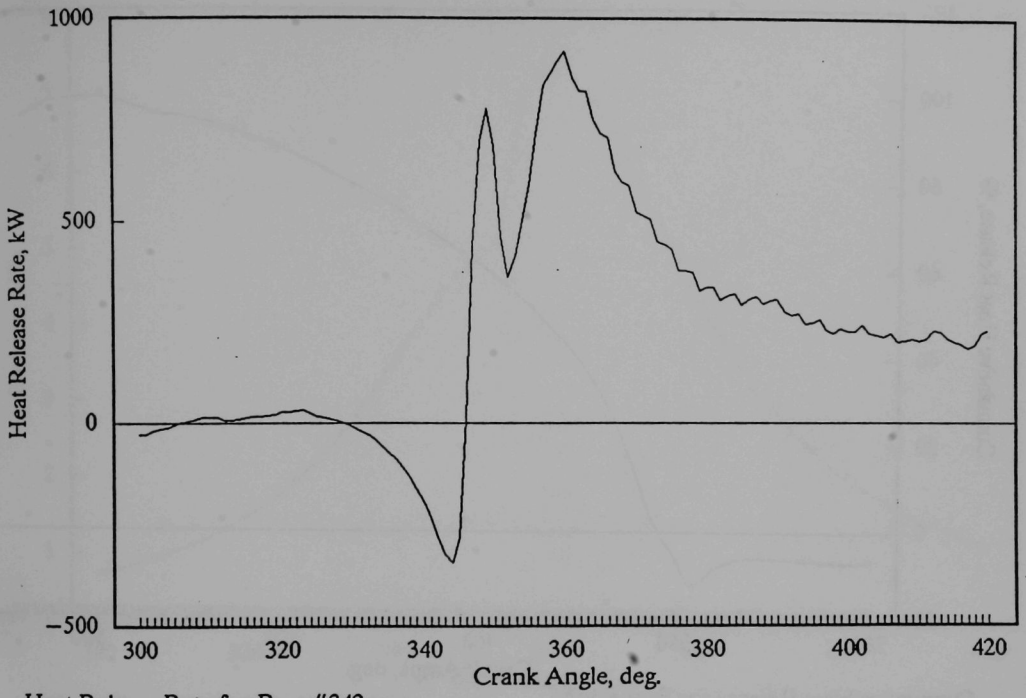
Cumulative Heat Release for Run #302C
(No.2 Fuel, Baseline, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



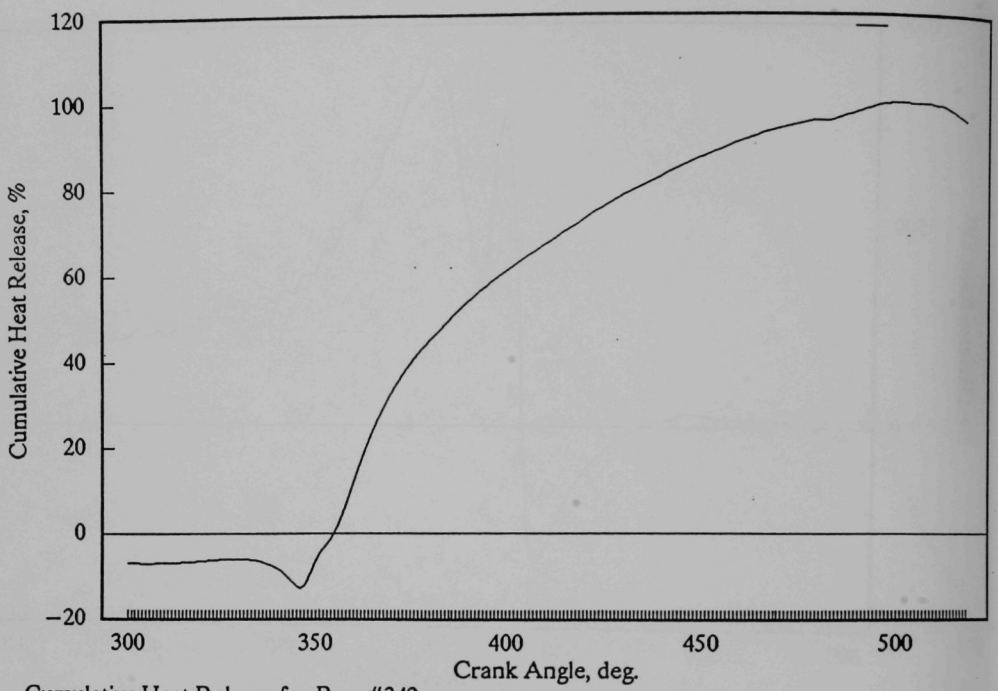
Cylinder Pressure Data for Run #342
(No.2 Fuel, A2, Const. Fuel Rate, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



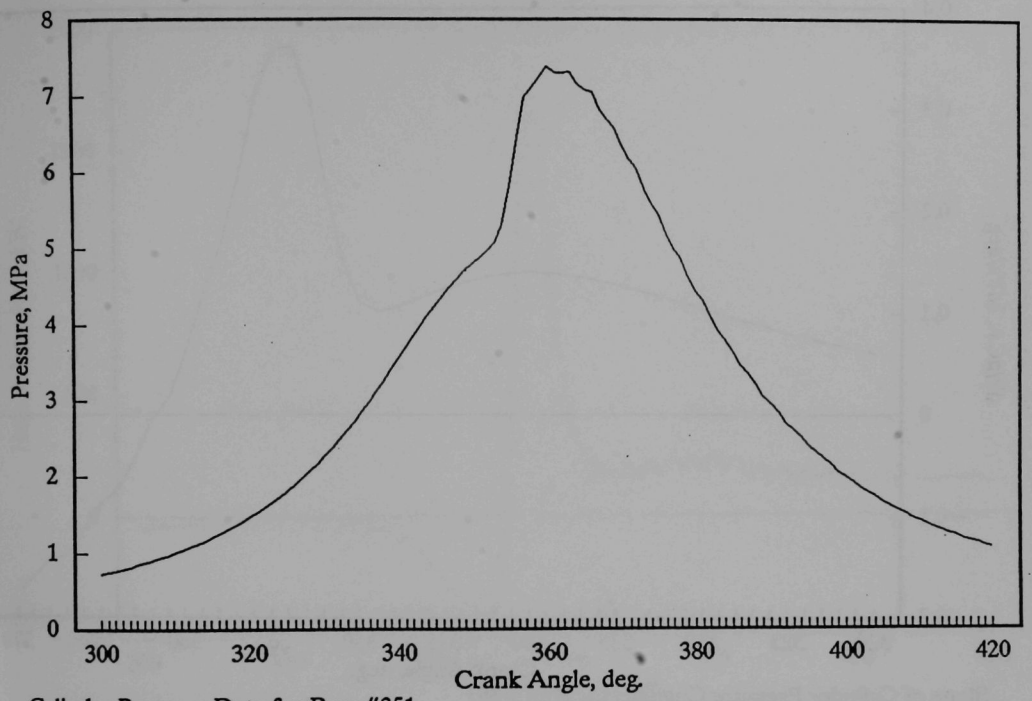
Slope of Cylinder Pressure Changes for Run #342
(No.2 Fuel, A2, Const. Fuel Rate, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



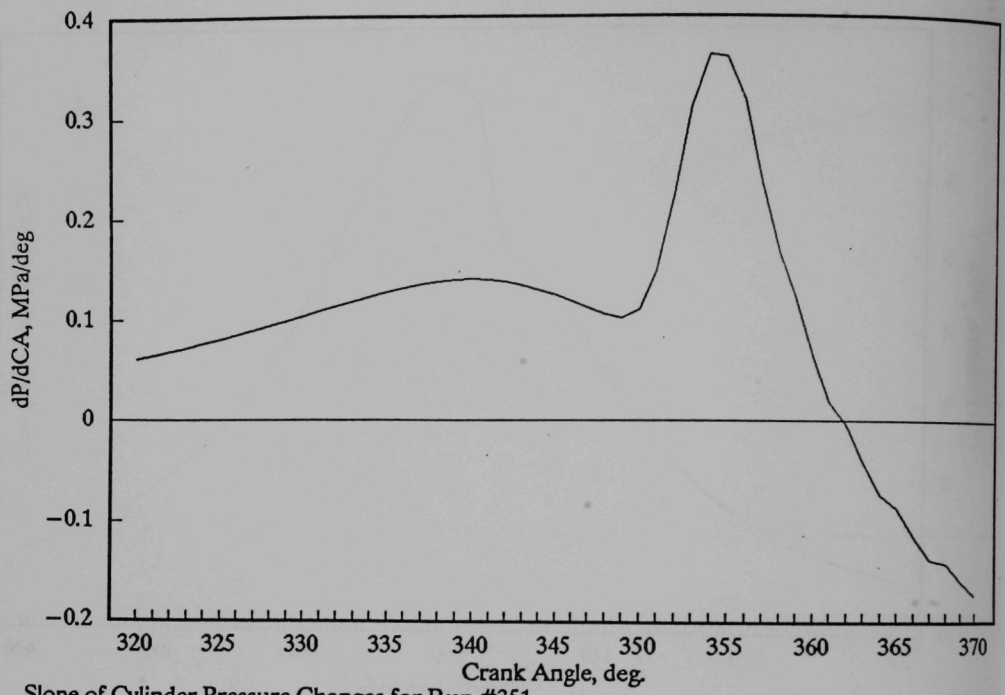
Heat Release Rate for Run #342
(No.2 Fuel, A2, Const. Fuel Rate, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



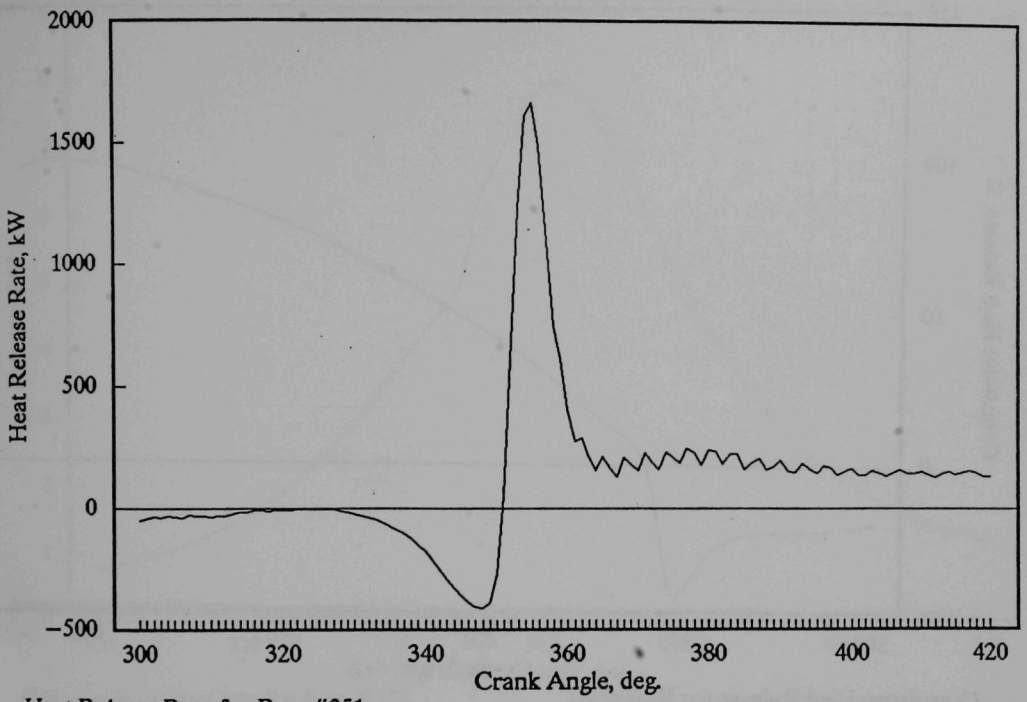
Cumulative Heat Release for Run #342
(No.2 Fuel, A2, Const. Fuel Rate, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



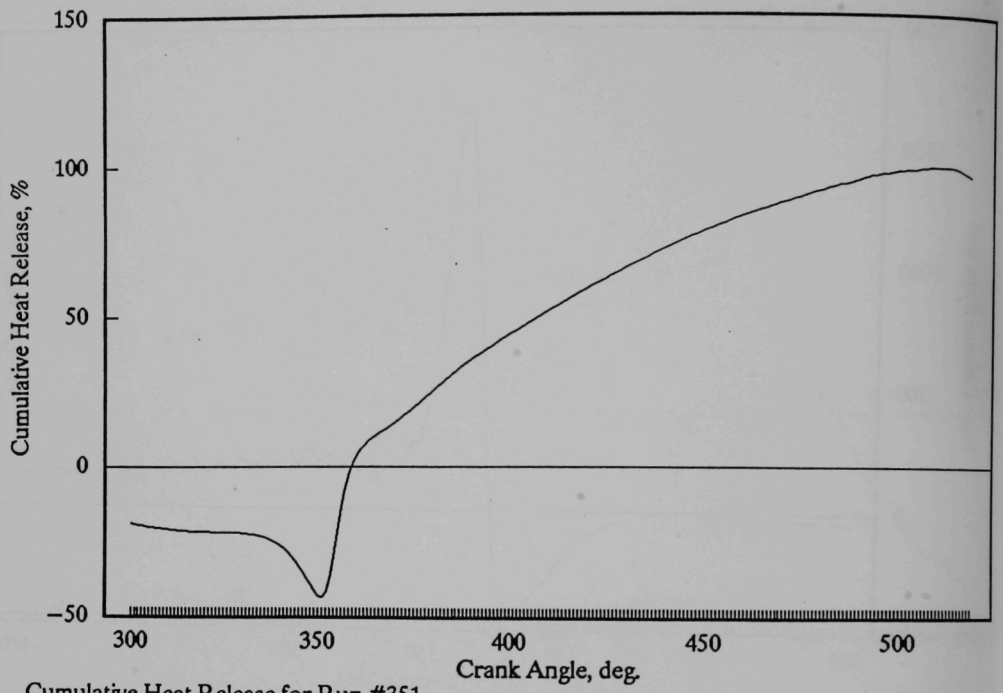
Cylinder Pressure Data for Run #351
(No.2 Fuel, B3, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 50% Load, 20% Water)



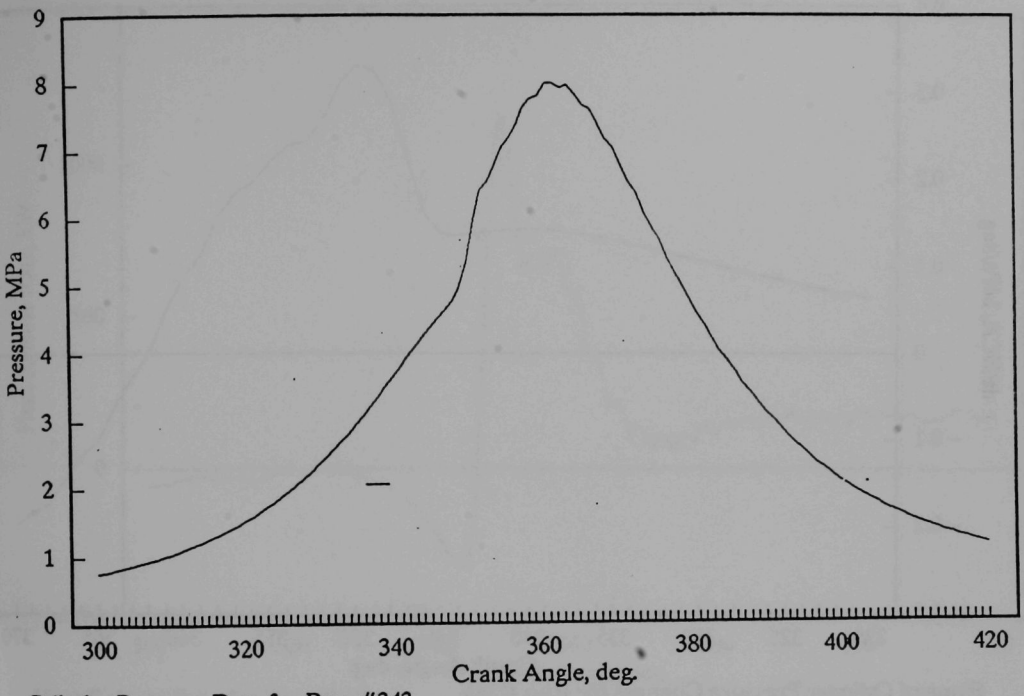
Slope of Cylinder Pressure Changes for Run #351
(No.2 Fuel, B3, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 50% Load, 20% Water)



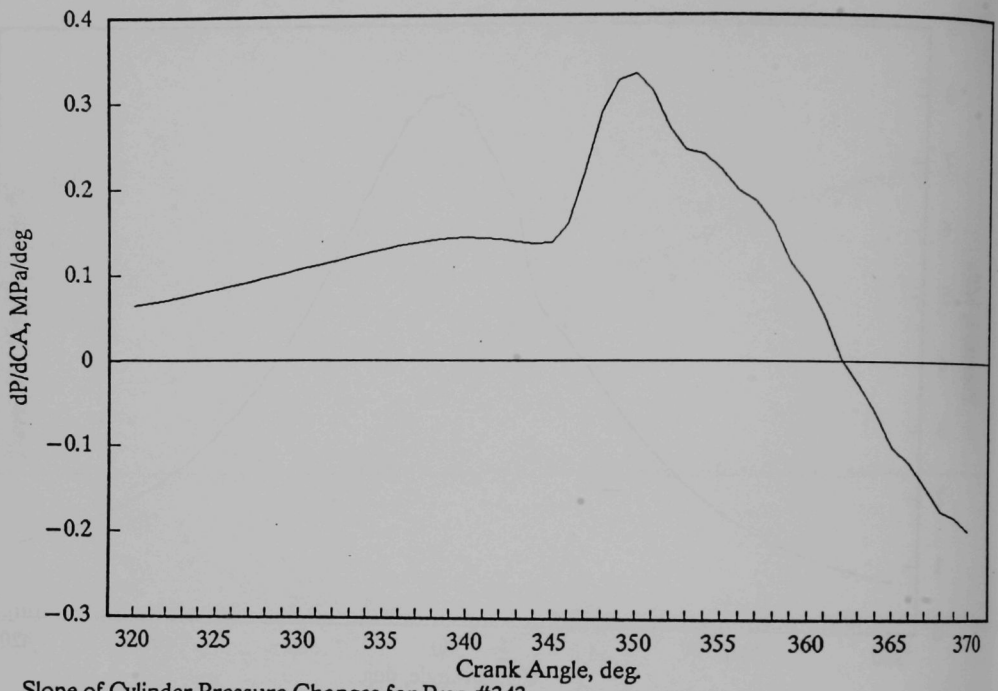
Heat Release Rate for Run #351
(No.2 Fuel, B3, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 50% Load, 20% Water)



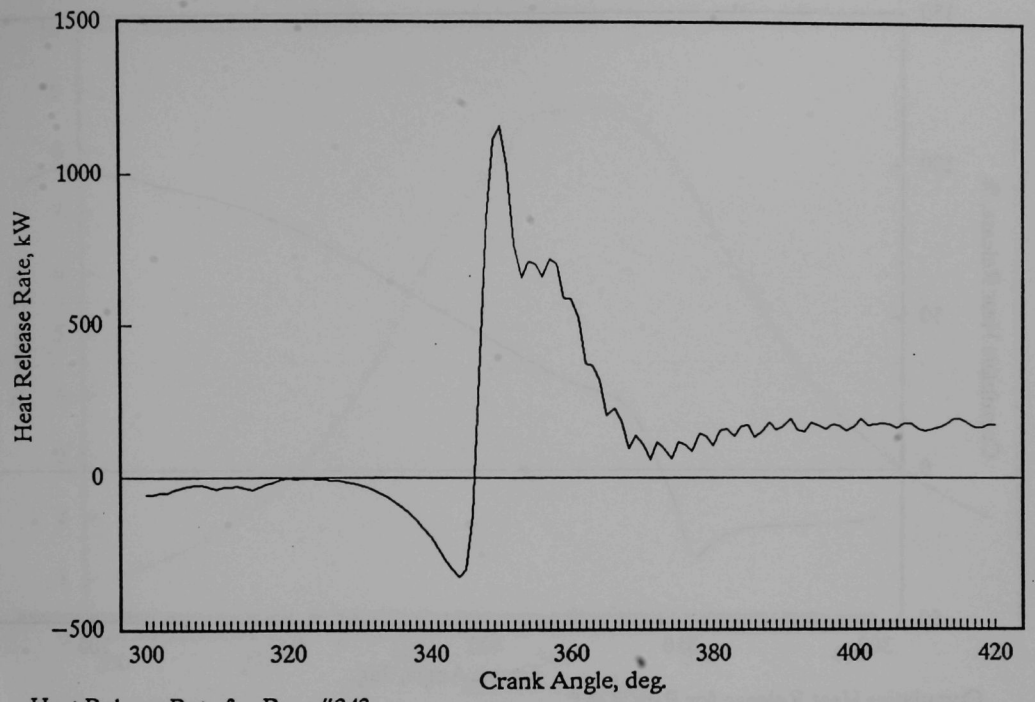
Cumulative Heat Release for Run #351
(No.2 Fuel, B3, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 50% Load, 20% Water)



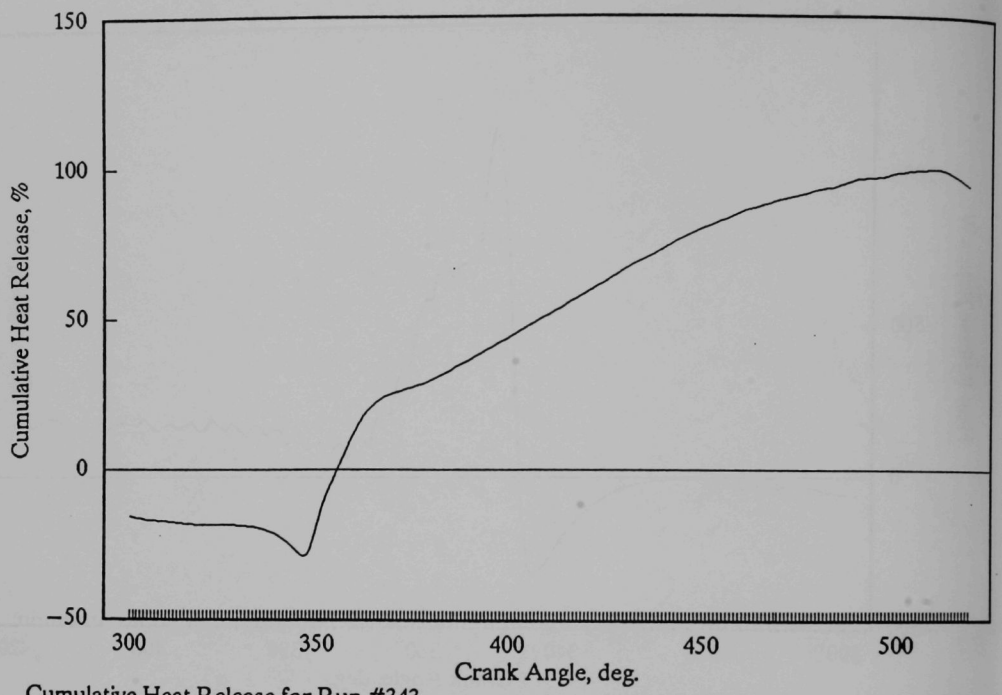
Cylinder Pressure Data for Run #343
(No.2 Fuel, A3, Const. Fuel Rate, 0 deg. Retard, 30% Oxygen, 50% Load, 20% Water)



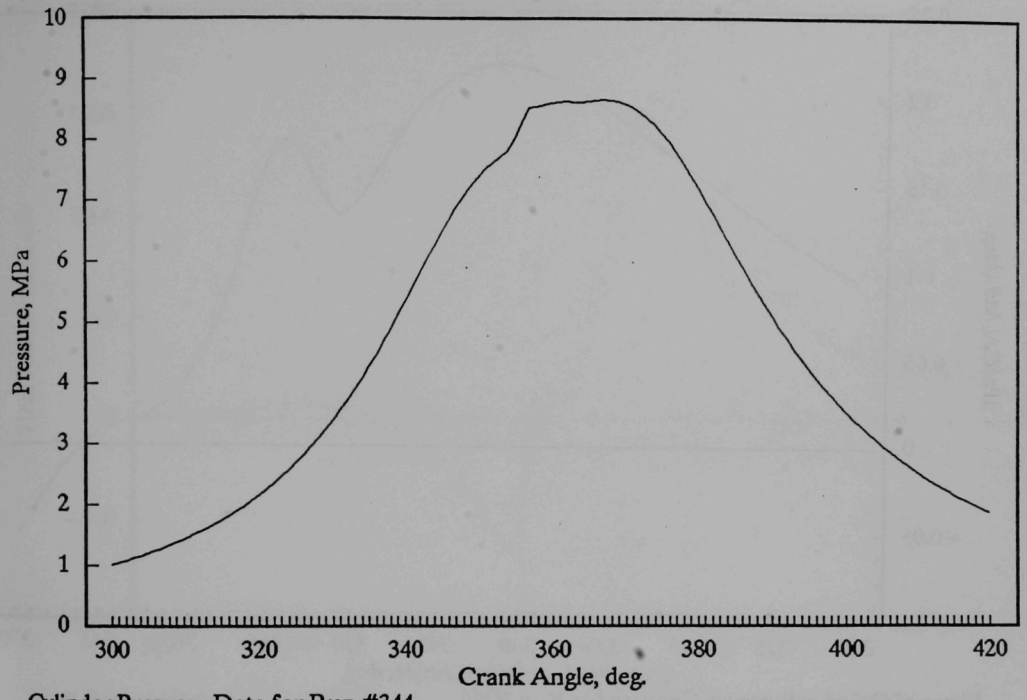
Slope of Cylinder Pressure Changes for Run #343
(No.2 Fuel, A3, Const. Fuel Rate, 0 deg. Retard, 30% Oxygen, 50% Load, 20% Water)



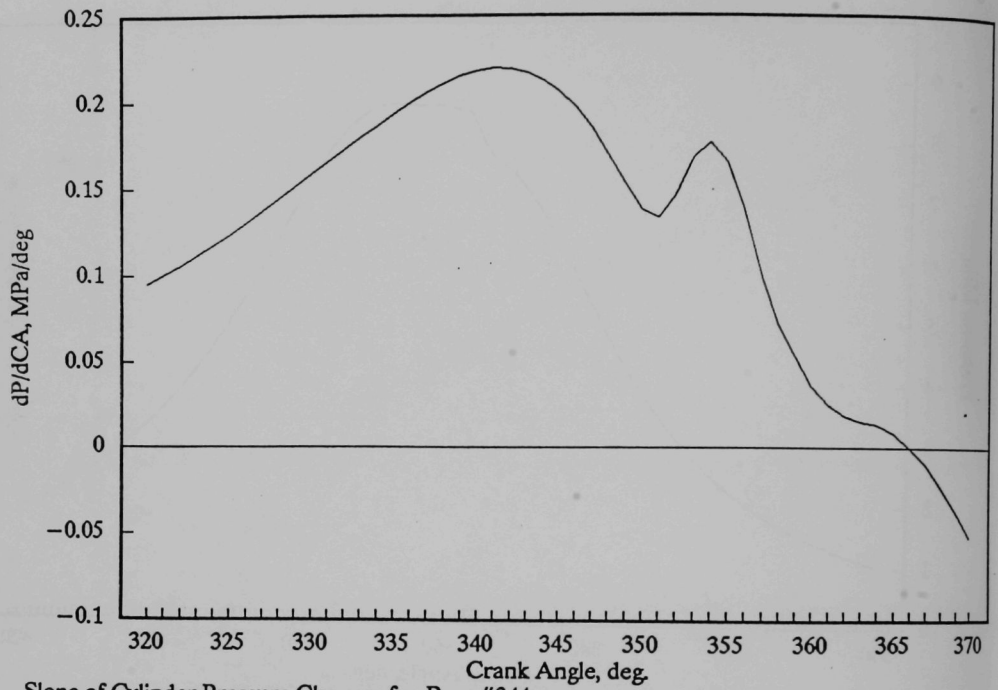
Heat Release Rate for Run #343
(No.2 Fuel, A3, Const. Fuel Rate, 0 deg. Retard, 30% Oxygen, 50% Load, 20% Water)



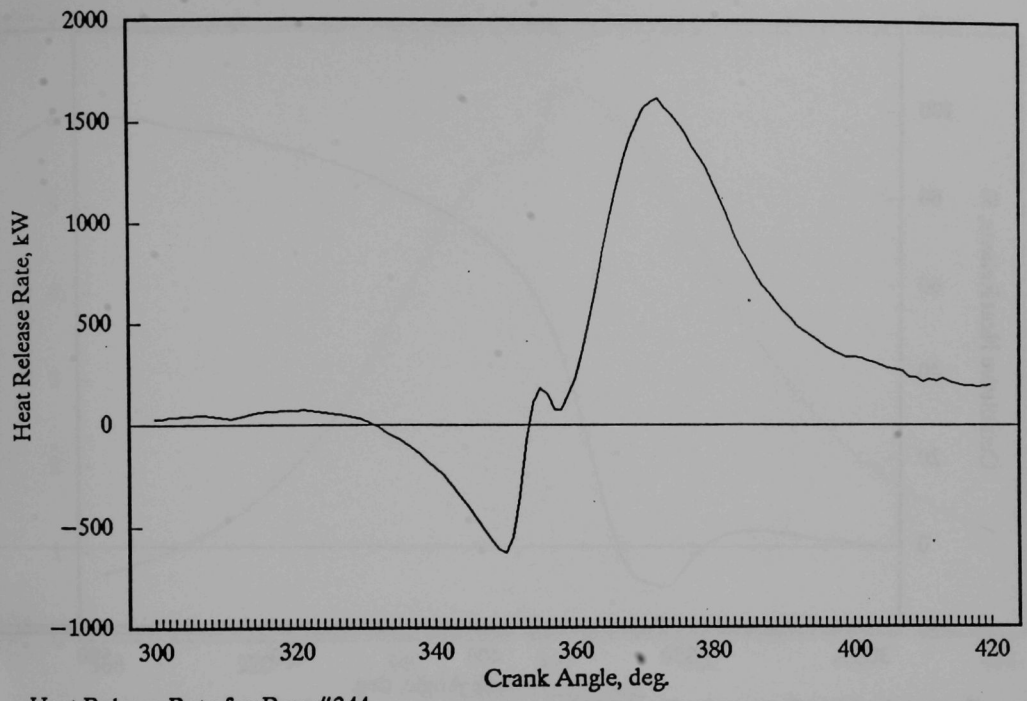
Cumulative Heat Release for Run #343
(No.2 Fuel, A3, Const. Fuel Rate, 0 deg. Retard, 30% Oxygen, 50% Load, 20% Water)



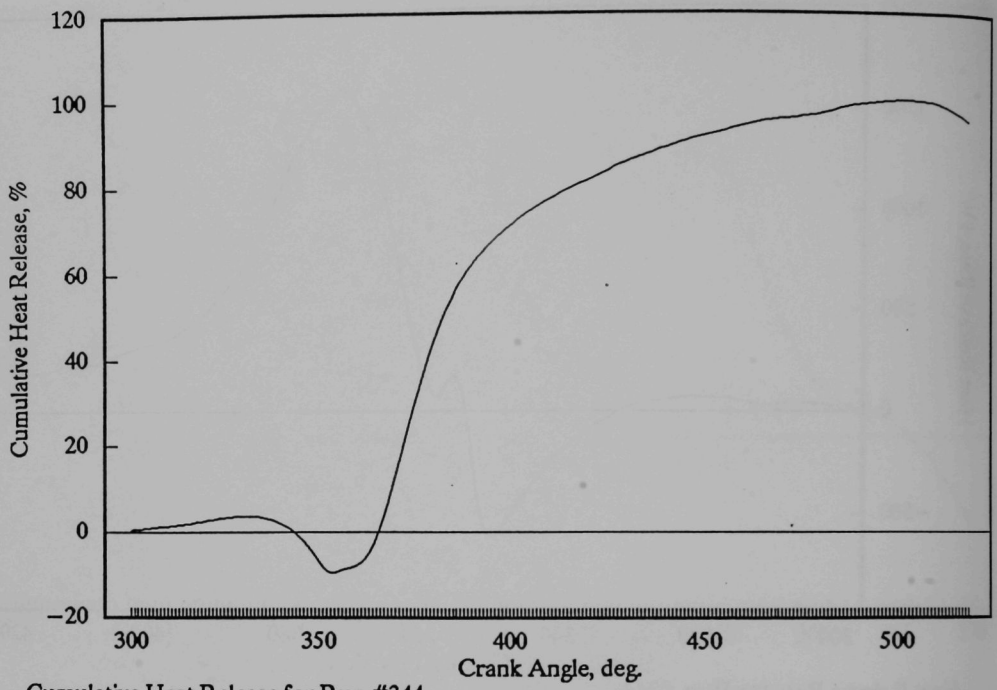
Cylinder Pressure Data for Run #344
(No.2 Fuel, A8, Const. Fuel Rate, 8 deg. Retard, 25.5% Oxygen, 100% Load, 20% Water)



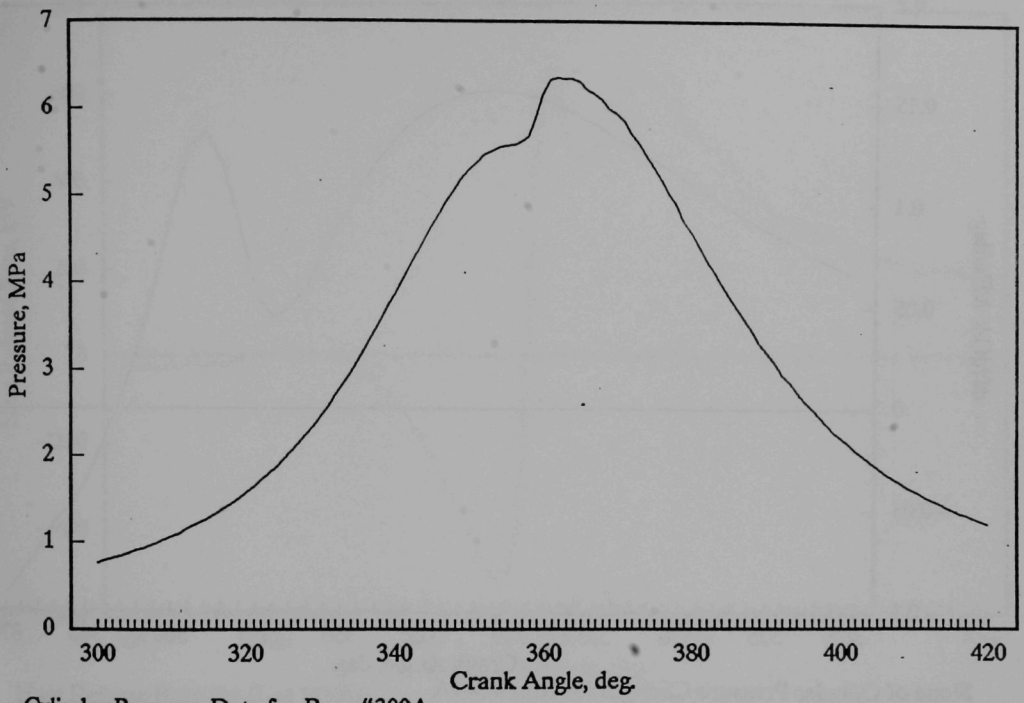
Slope of Cylinder Pressure Changes for Run #344
(No.2 Fuel, A8, Const. Fuel Rate, 8 deg. Retard, 25.5% Oxygen, 100% Load, 20% Water)



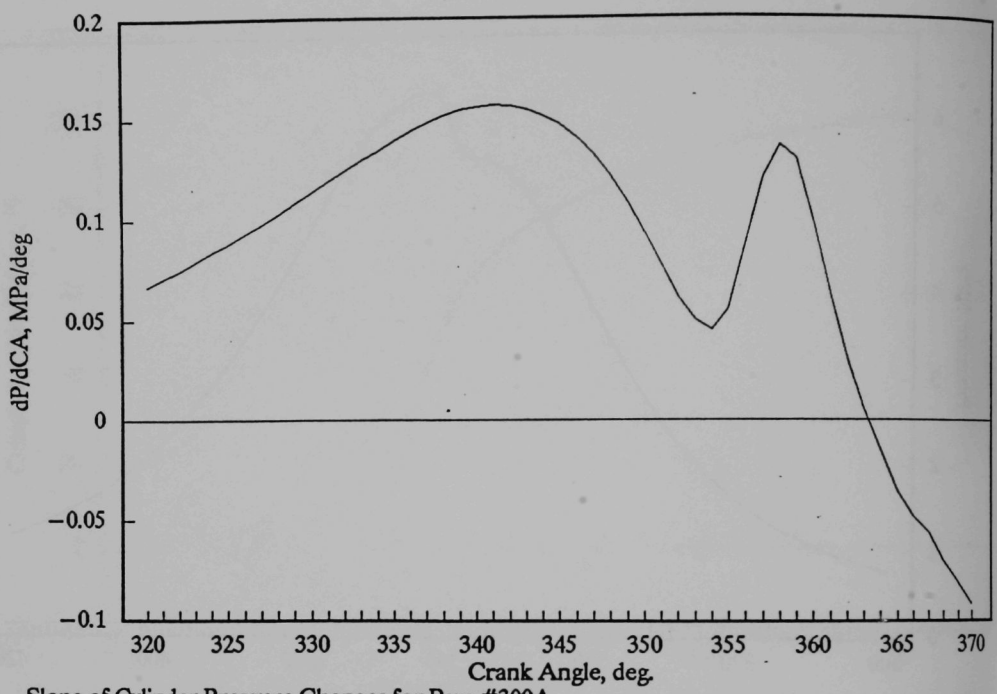
Heat Release Rate for Run #344
(No.2 Fuel, A8, Const. Fuel Rate, 8 deg. Retard, 25.5% Oxygen, 100% Load, 20% Water)



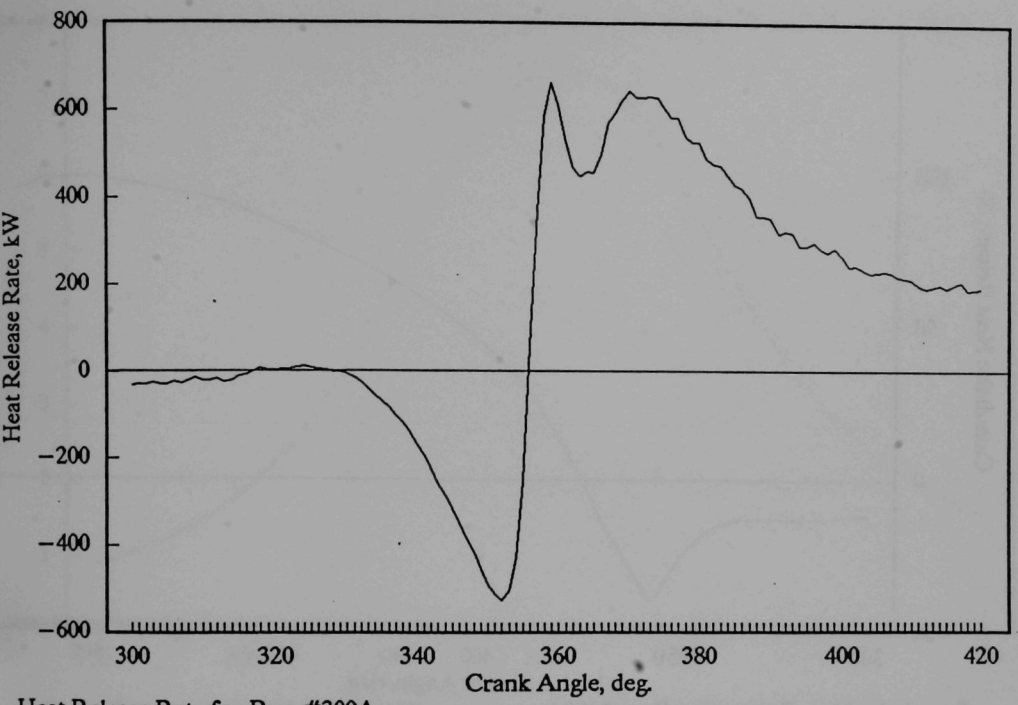
Cumulative Heat Release for Run #344
(No.2 Fuel, A8, Const. Fuel Rate, 8 deg. Retard, 25.5% Oxygen, 100% Load, 20% Water)



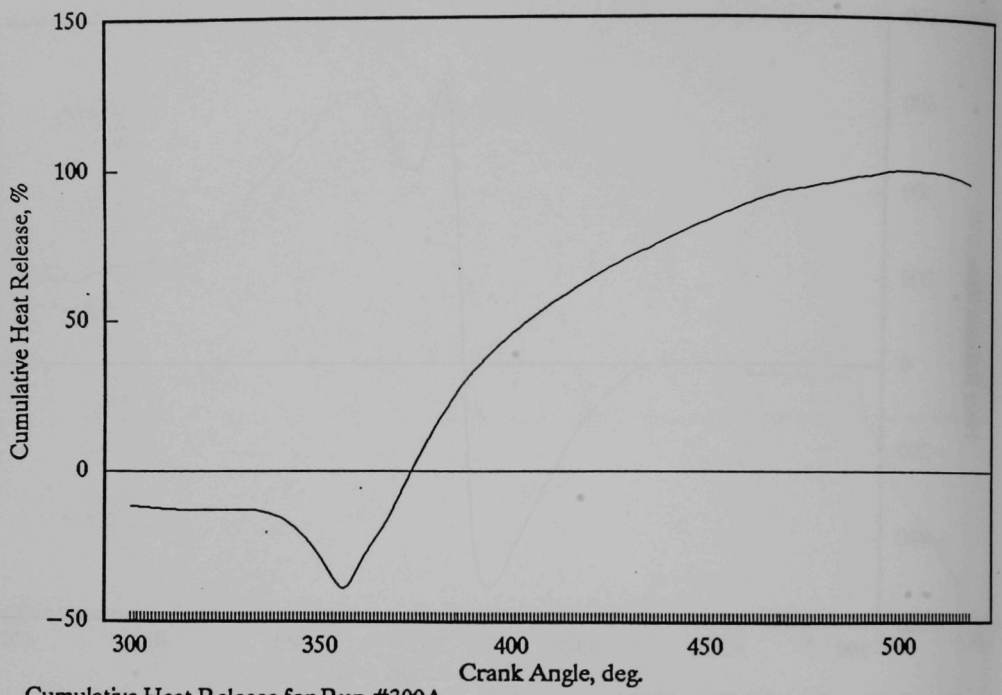
Cylinder Pressure Data for Run #309A
(No.2 Fuel, B7, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



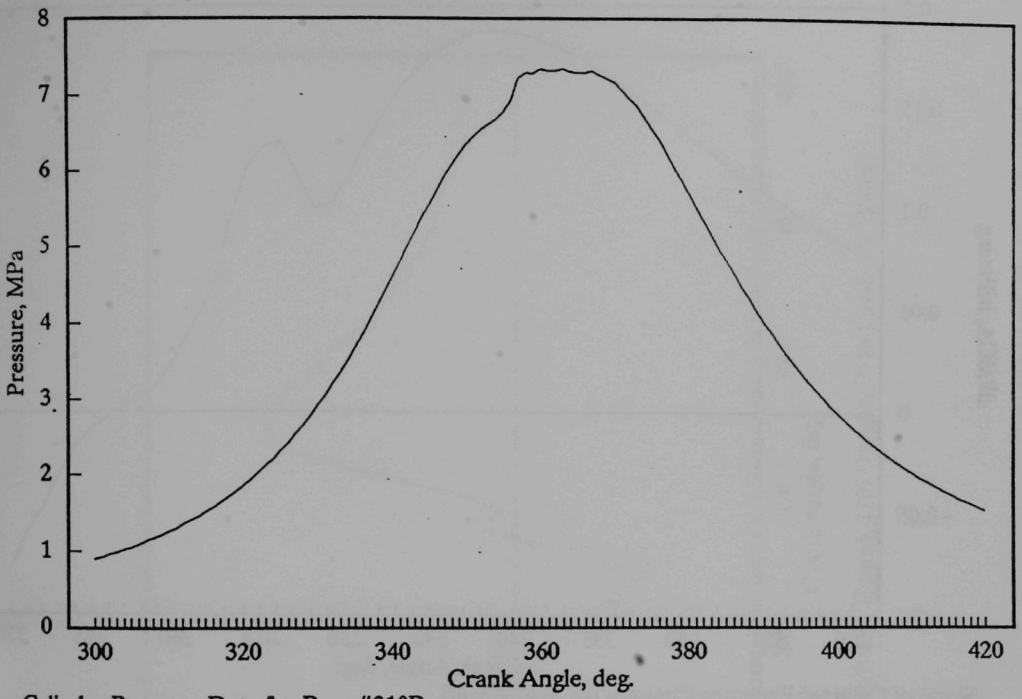
Slope of Cylinder Pressure Changes for Run #309A
(No.2 Fuel, B7, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



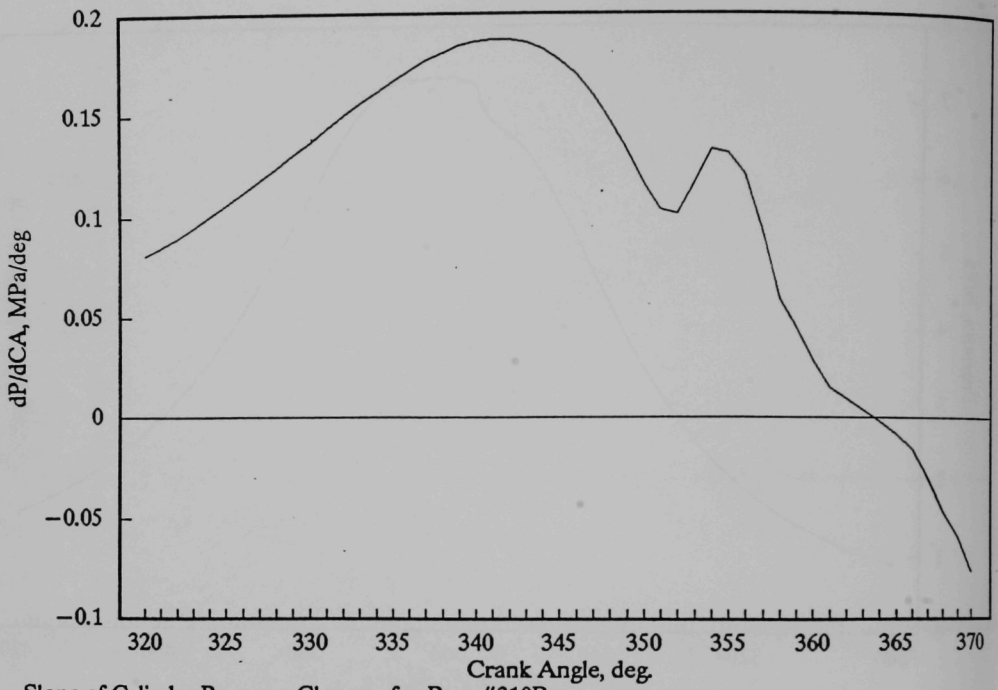
Heat Release Rate for Run #309A
(No.2 Fuel, B7, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



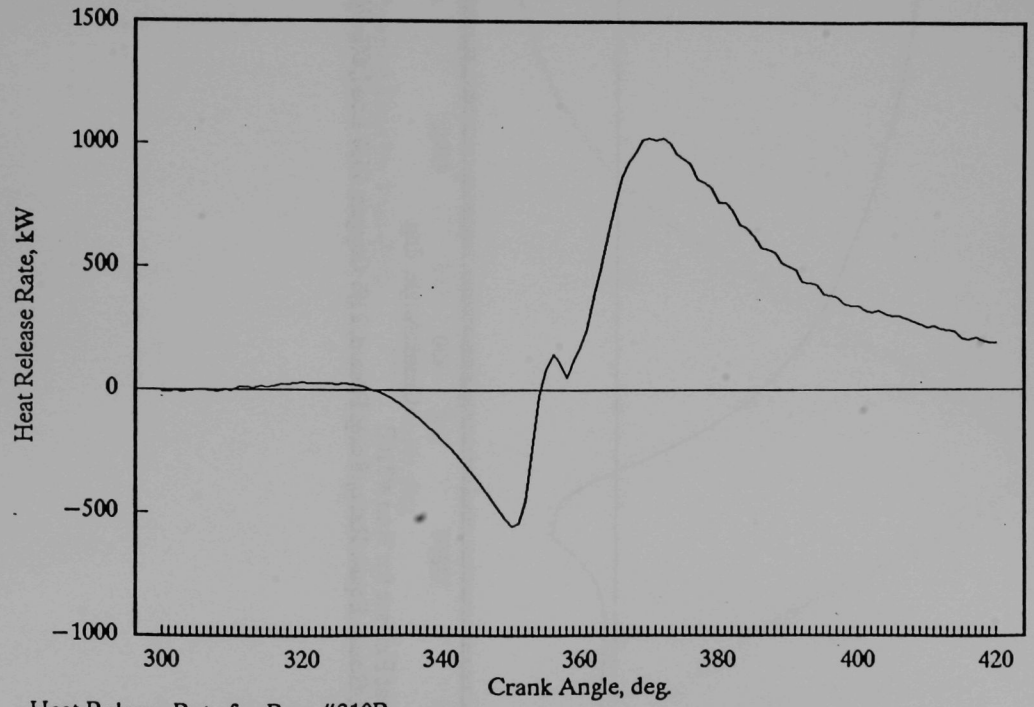
Cumulative Heat Release for Run #309A
(No.2 Fuel, B7, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



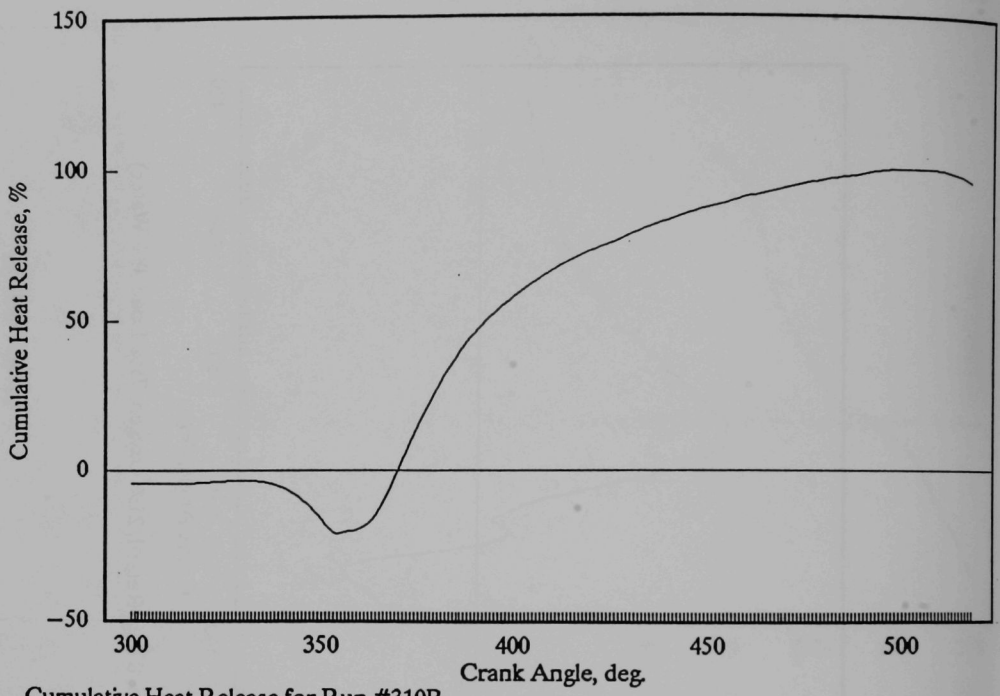
Cylinder Pressure Data for Run #310B
(No.2 Fuel, B9, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



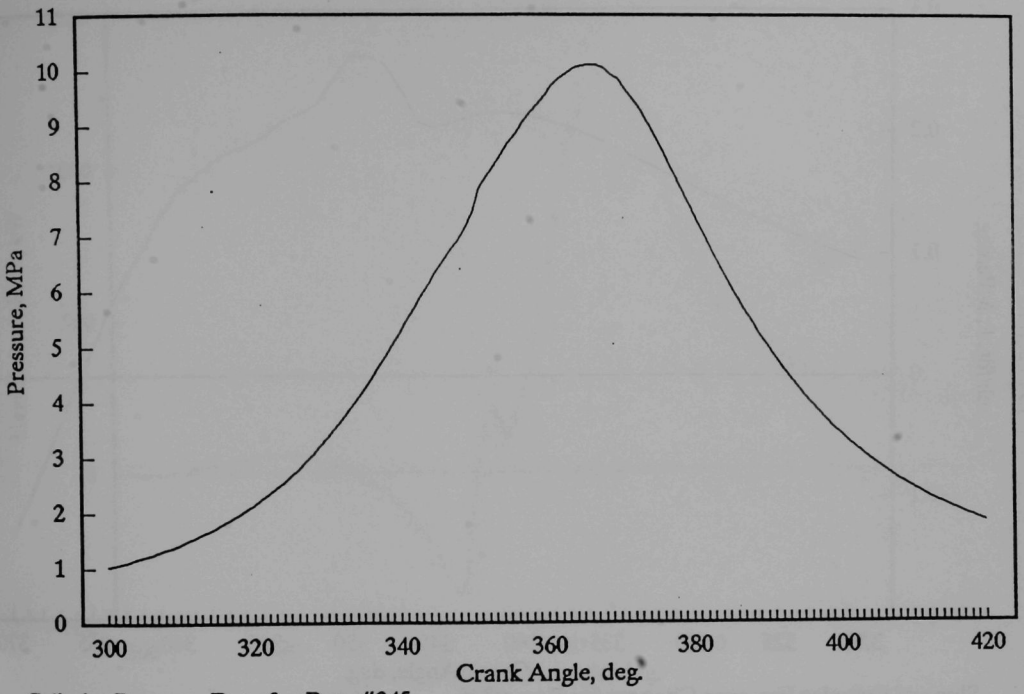
Slope of Cylinder Pressure Changes for Run #310B
(No.2 Fuel, B9, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



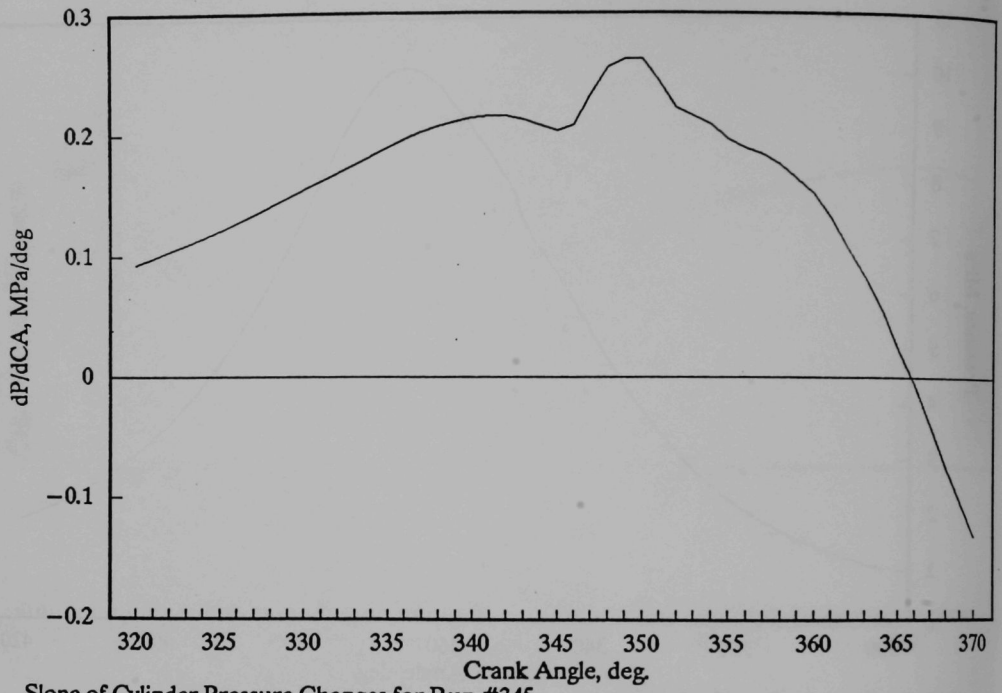
Heat Release Rate for Run #310B
(No.2 Fuel, B9, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



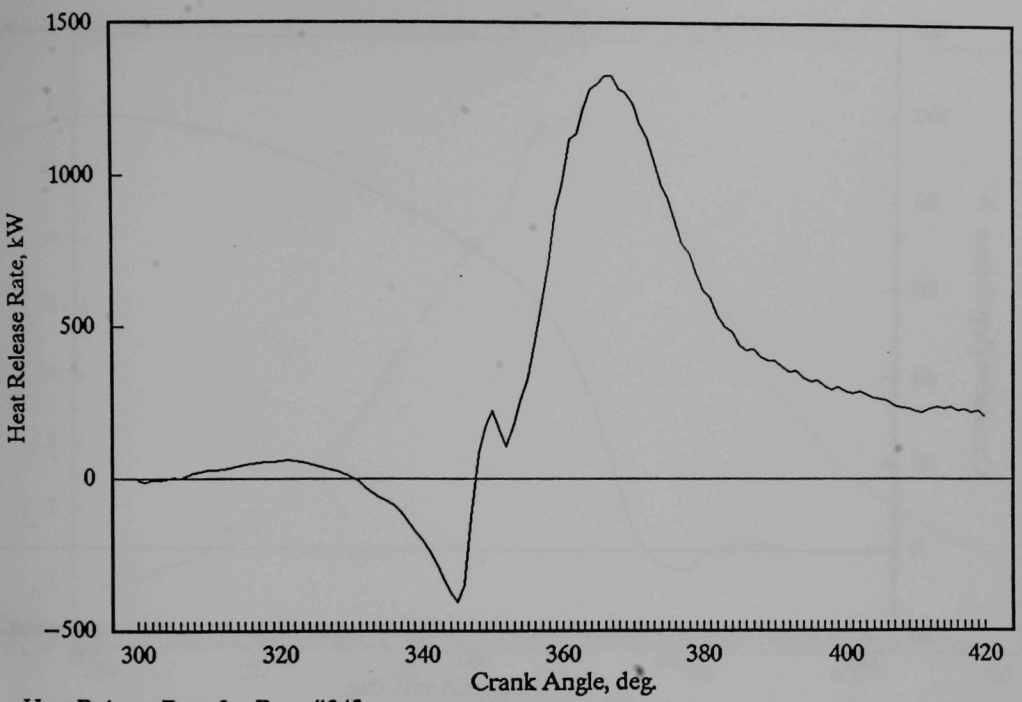
Cumulative Heat Release for Run #310B
(No.2 Fuel, B9, Const. Equiv. Ratio, 8 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



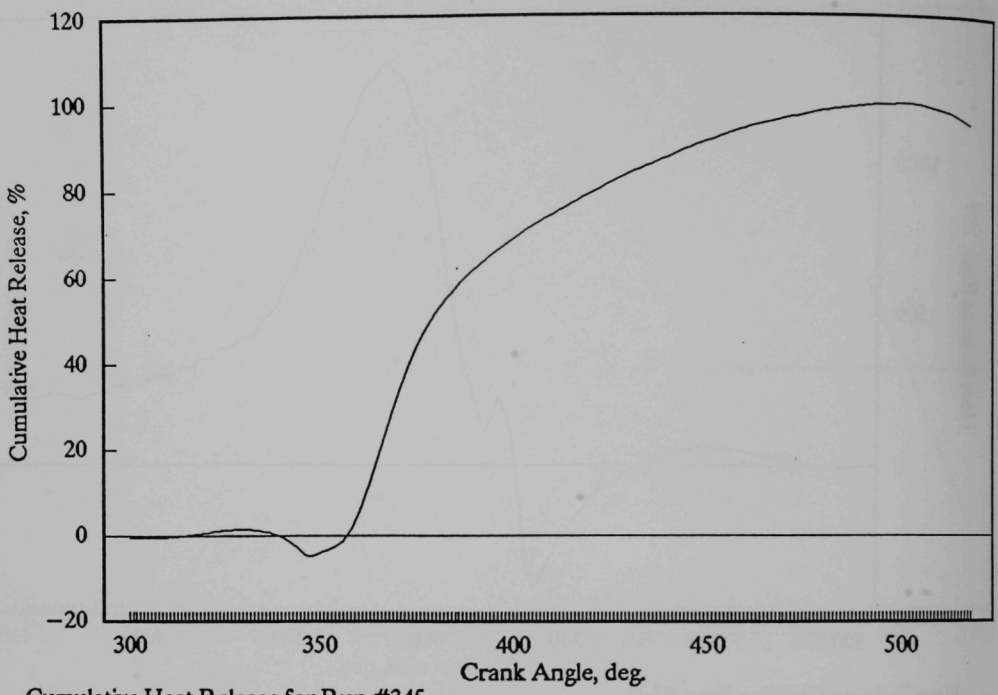
Cylinder Pressure Data for Run #345
(No.2 Fuel, A6, Const. Fuel Rate, 4 deg. Retard, 30% Oxygen, 100% Load, 10% Water)



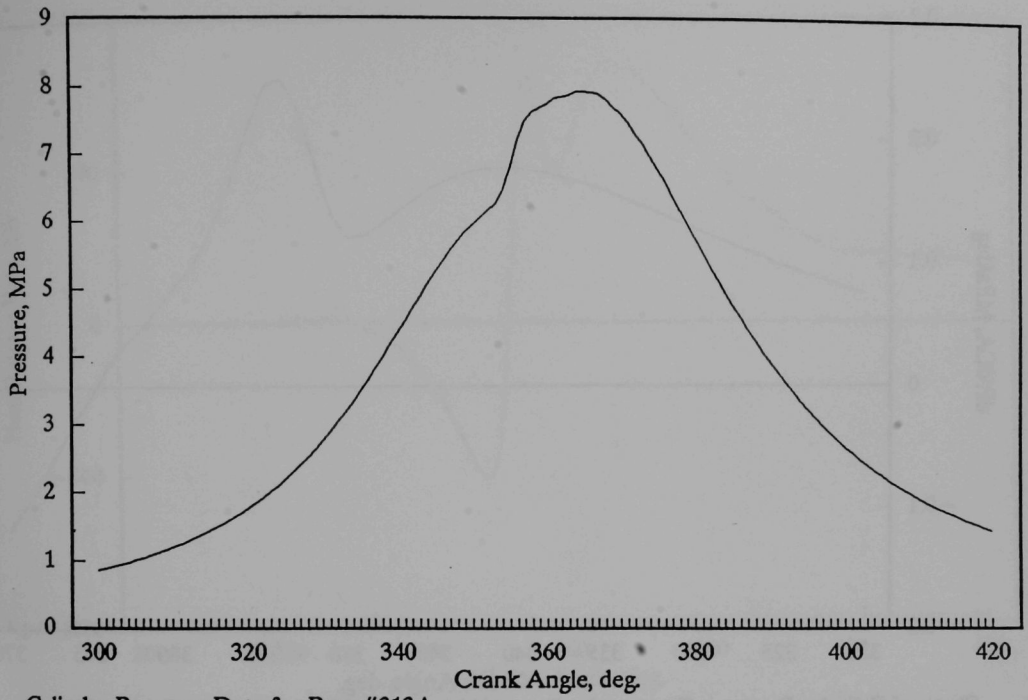
Slope of Cylinder Pressure Changes for Run #345
(No.2 Fuel, A6, Const. Fuel Rate, 4 deg. Retard, 30% Oxygen, 100% Load, 10% Water)



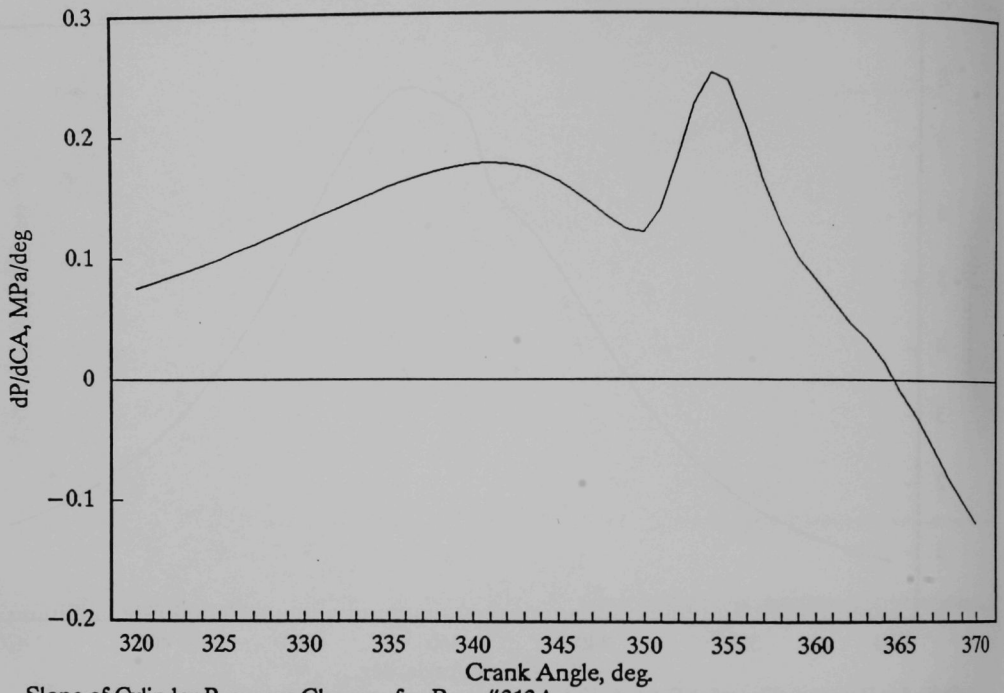
Heat Release Rate for Run #345
(No.2 Fuel, A6, Const. Fuel Rate, 4 deg. Retard, 30% Oxygen, 100% Load, 10% Water)



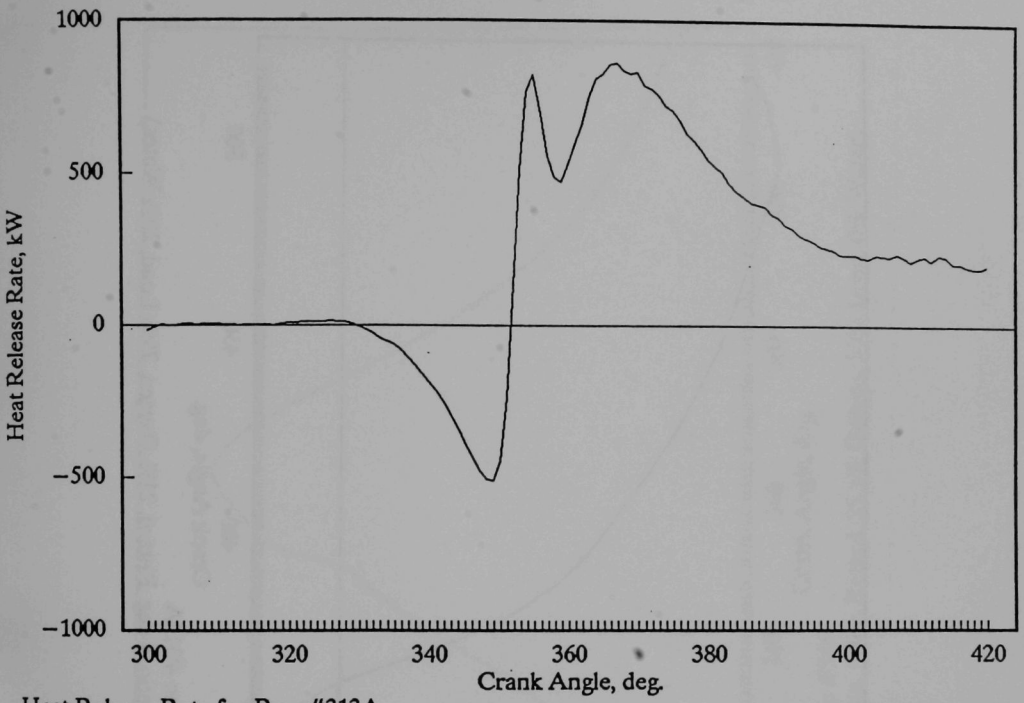
Cumulative Heat Release for Run #345
(No.2 Fuel, A6, Const. Fuel Rate, 4 deg. Retard, 30% Oxygen, 100% Load, 10% Water)



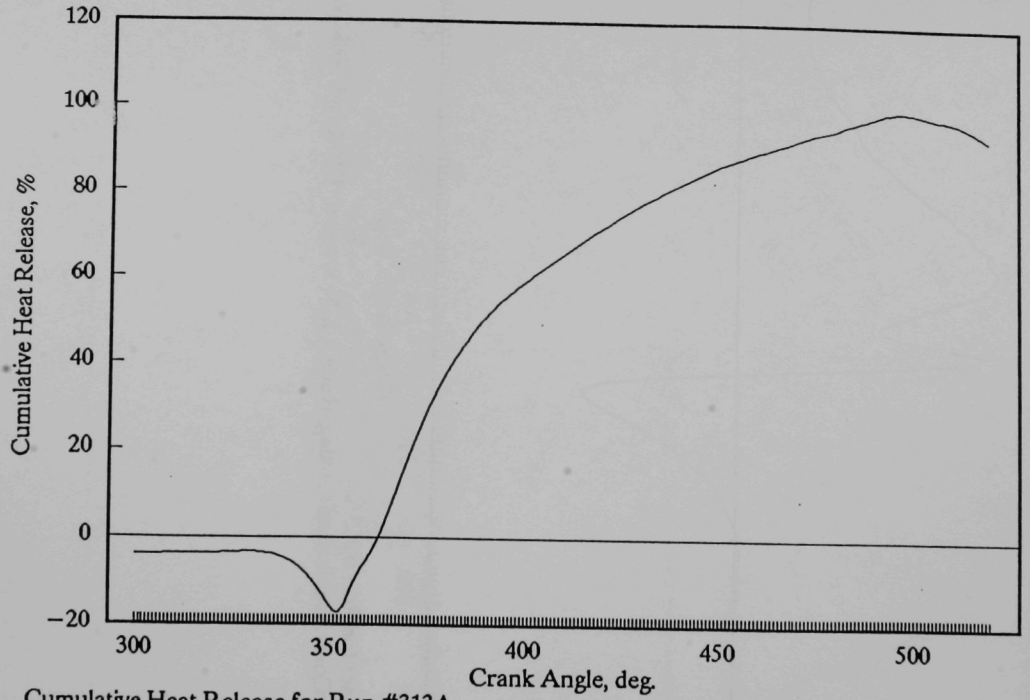
Cylinder Pressure Data for Run #313A
(No.2 Fuel, B4, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



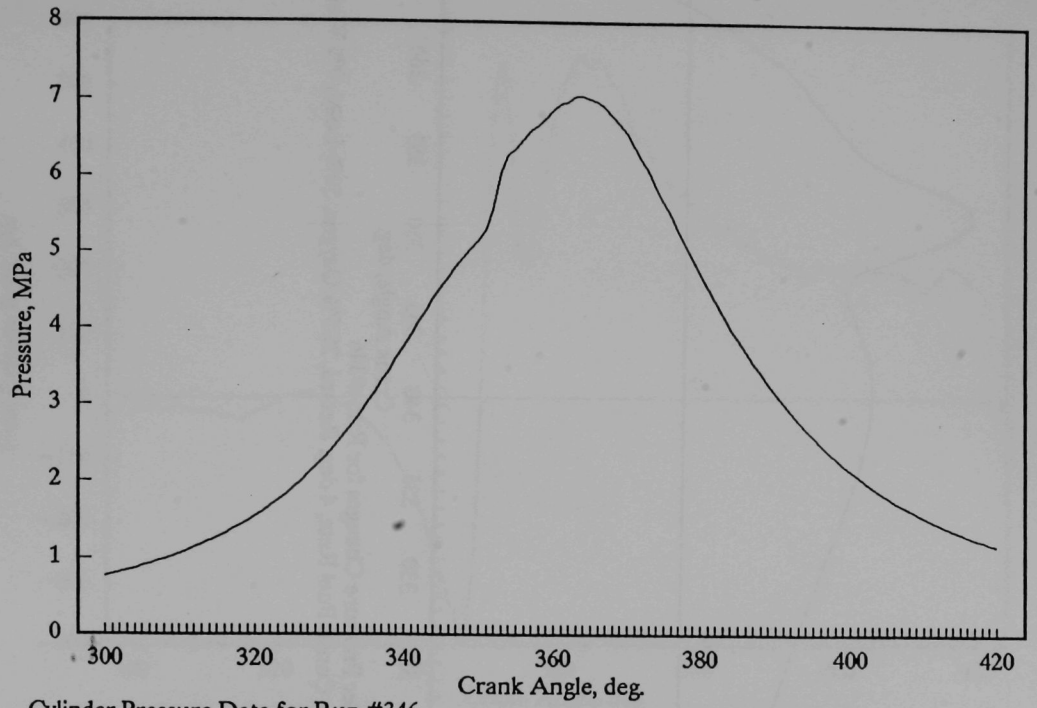
Slope of Cylinder Pressure Changes for Run #313A
(No.2 Fuel, B4, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



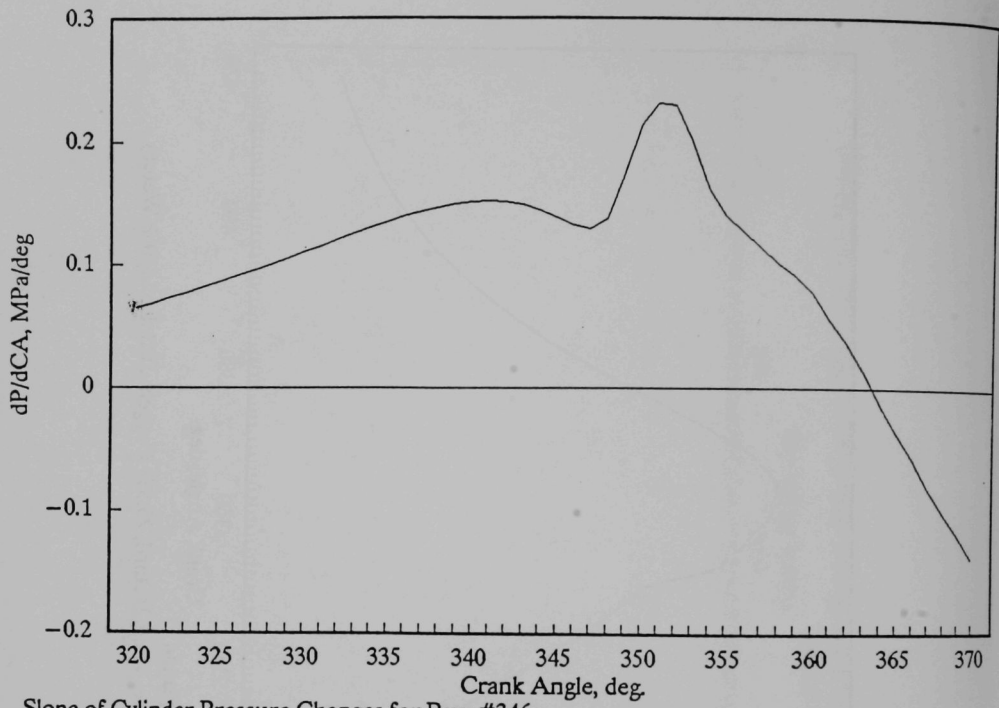
Heat Release Rate for Run #313A
(No.2 Fuel, B4, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



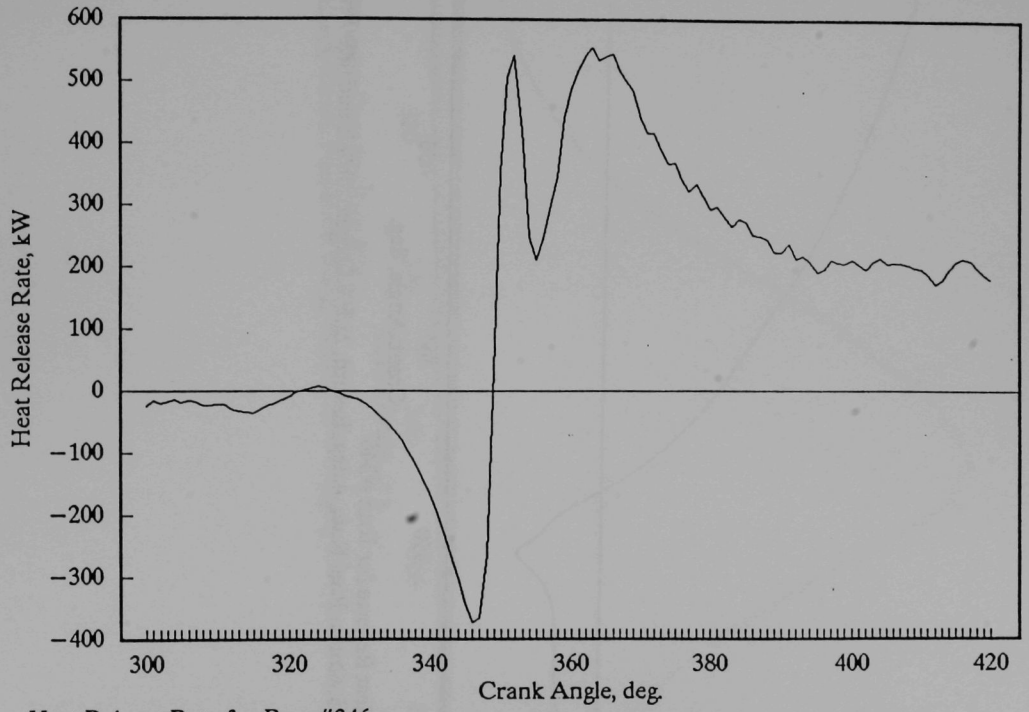
Cumulative Heat Release for Run #313A
(No.2 Fuel, B4, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



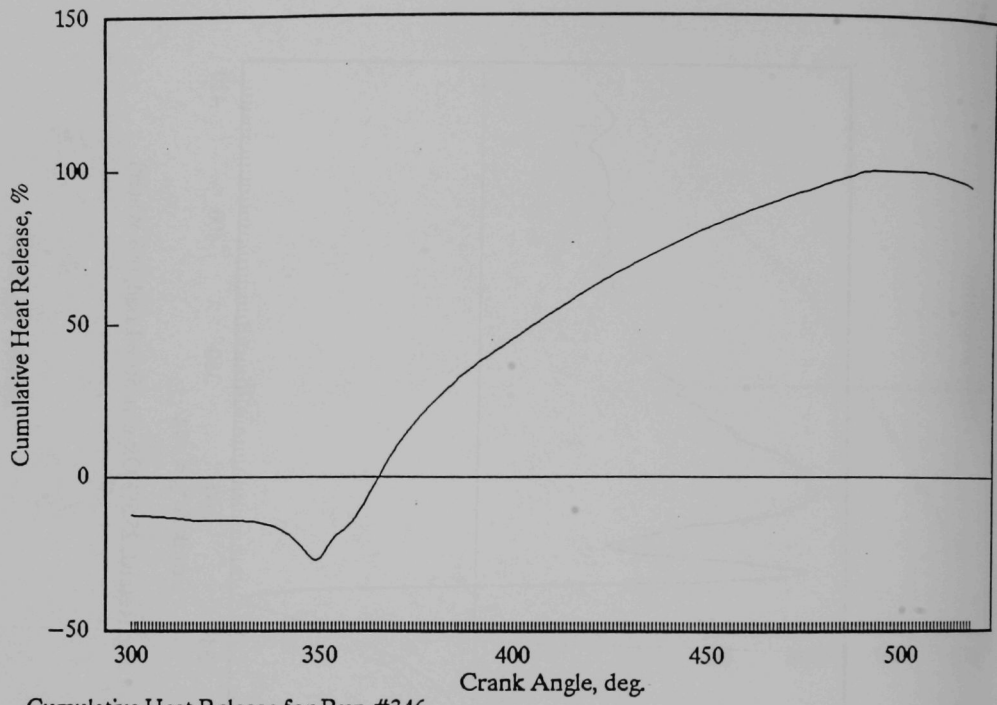
Cylinder Pressure Data for Run #346
(No.2 Fuel, A5, Const. Fuel Rate, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



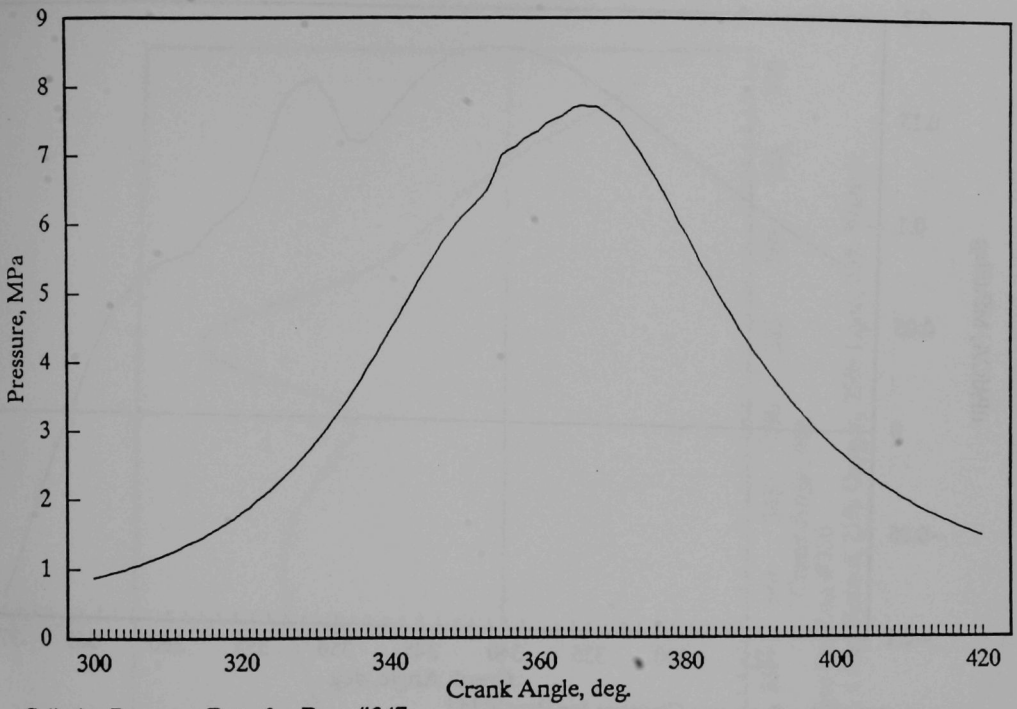
Slope of Cylinder Pressure Changes for Run #346
(No.2 Fuel, A5, Const. Fuel Rate, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



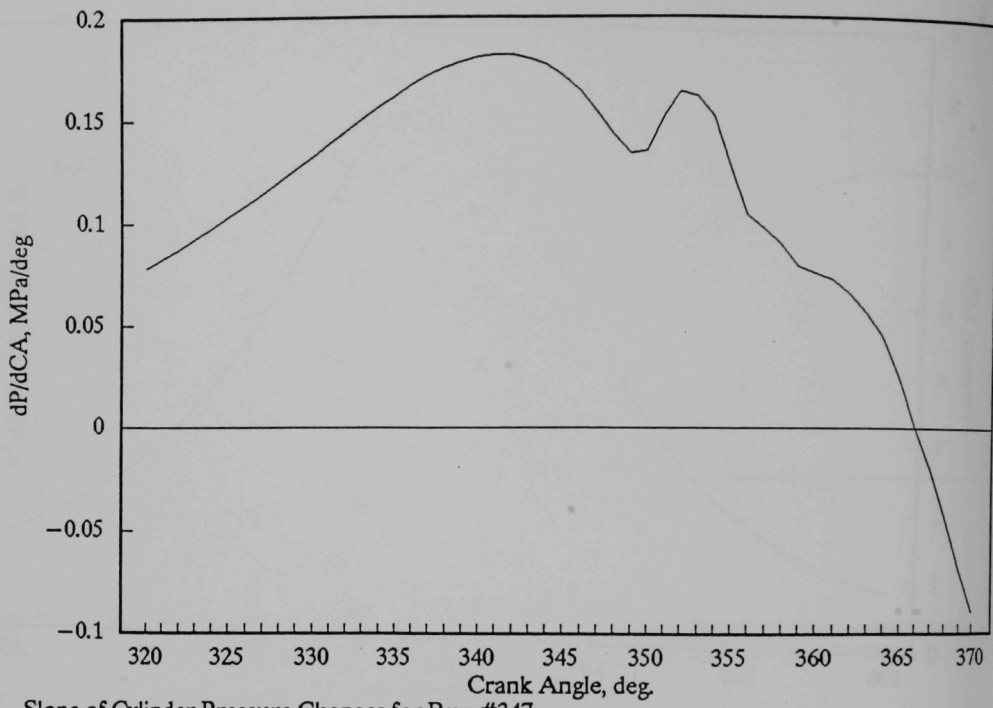
Heat Release Rate for Run #346
(No.2 Fuel, A5, Const. Fuel Rate, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



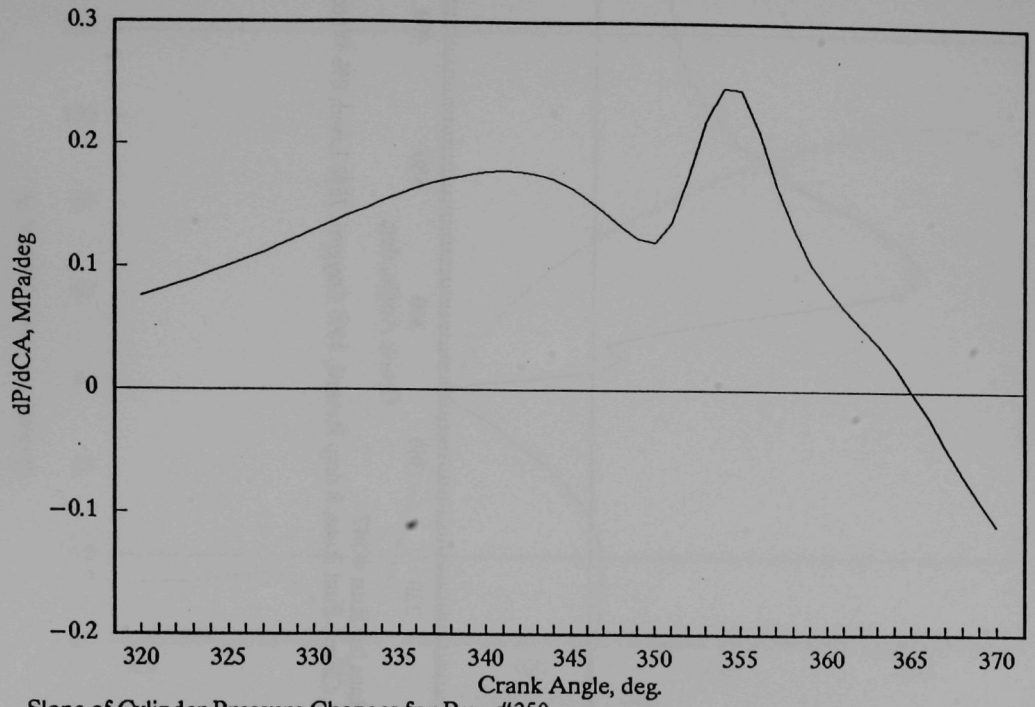
Cumulative Heat Release for Run #346
(No.2 Fuel, A5, Const. Fuel Rate, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



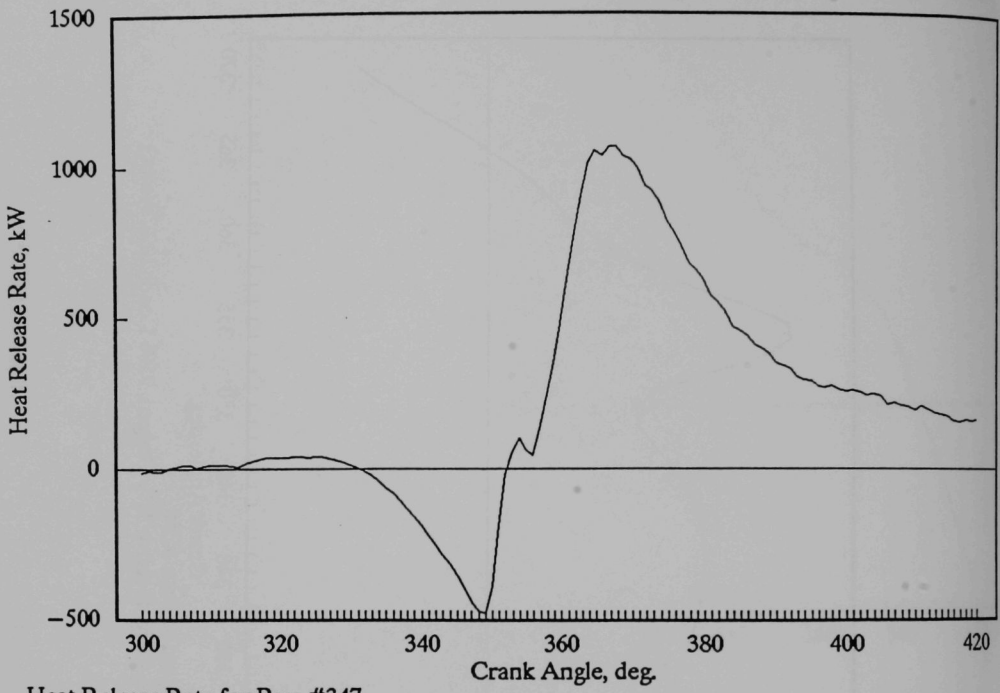
Cylinder Pressure Data for Run #347
(No.2 Fuel, A9, Const. Fuel Rate, 8 deg. Retard, 30% Oxygen, 75% Load, 0% Water)



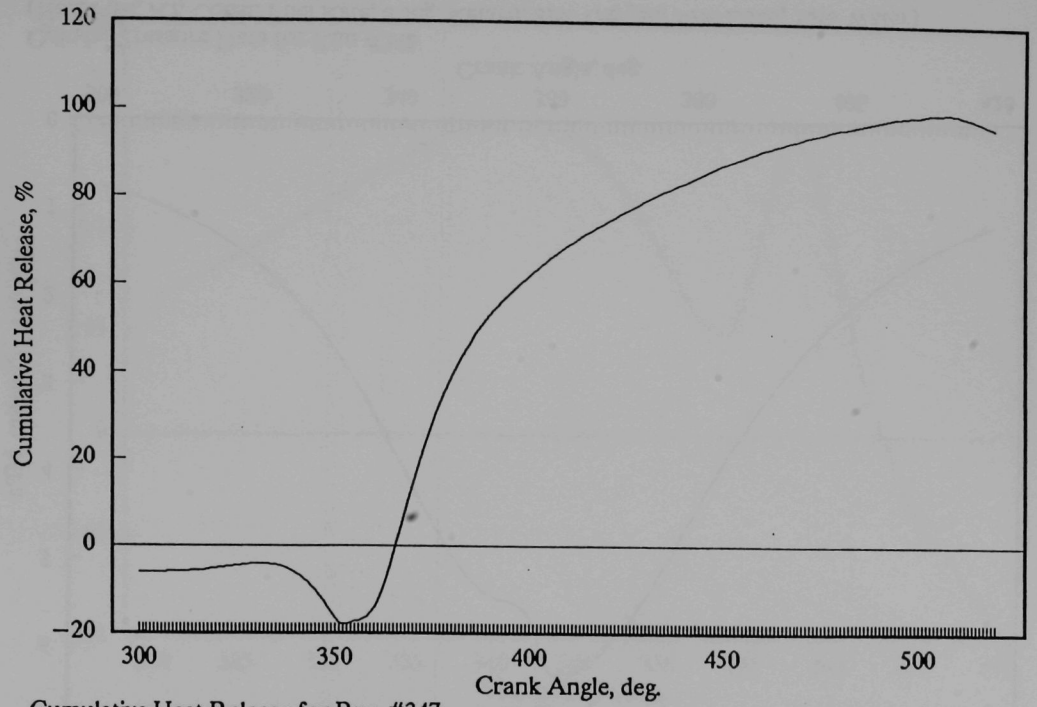
Slope of Cylinder Pressure Changes for Run #347
(No.2 Fuel, A9, Const. Fuel Rate, 8 deg. Retard, 30% Oxygen, 75% Load, 0% Water)



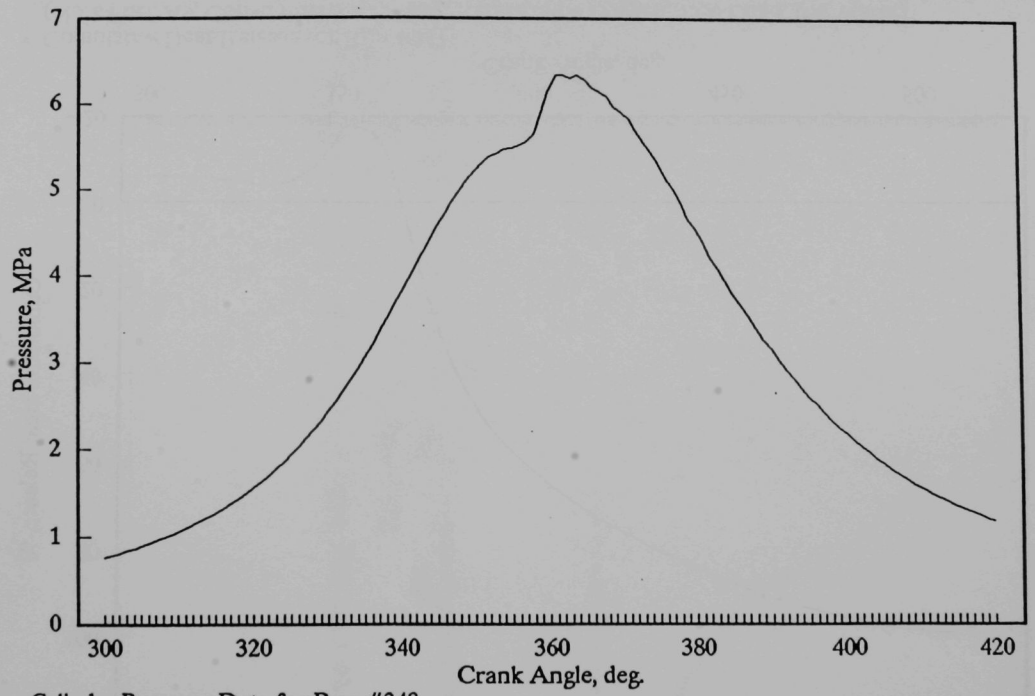
Slope of Cylinder Pressure Changes for Run #350
(No.2 Fuel, A4, Const. Fuel Rate, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



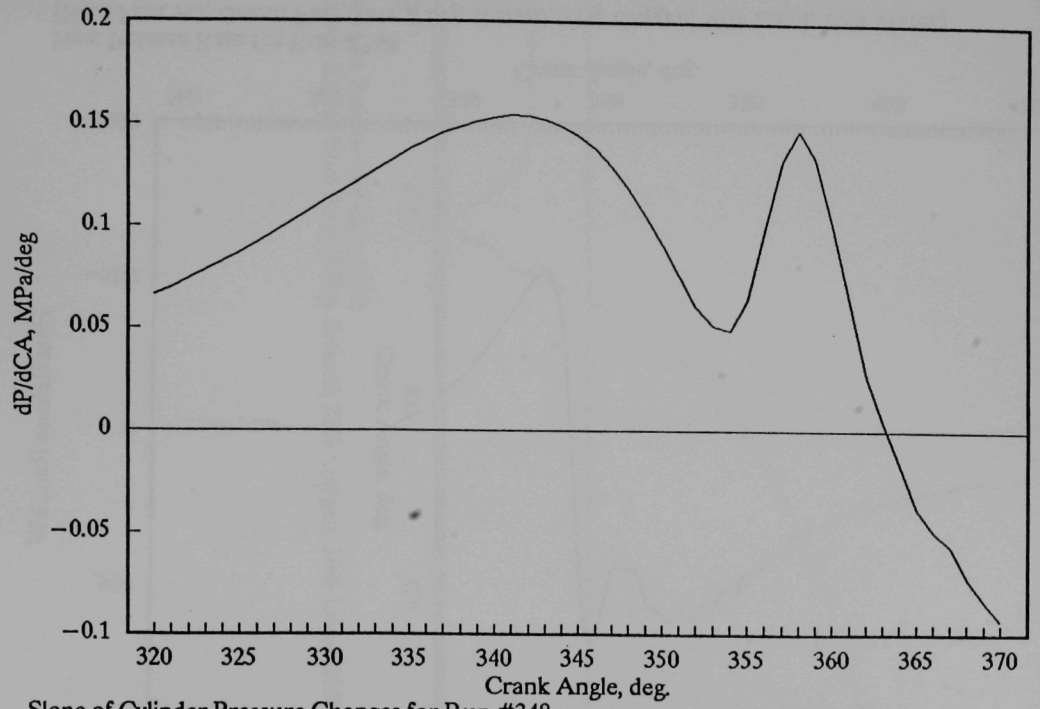
Heat Release Rate for Run #347
(No.2 Fuel, A9, Const. Fuel Rate, 8 deg. Retard, 30% Oxygen, 75% Load, 0% Water)



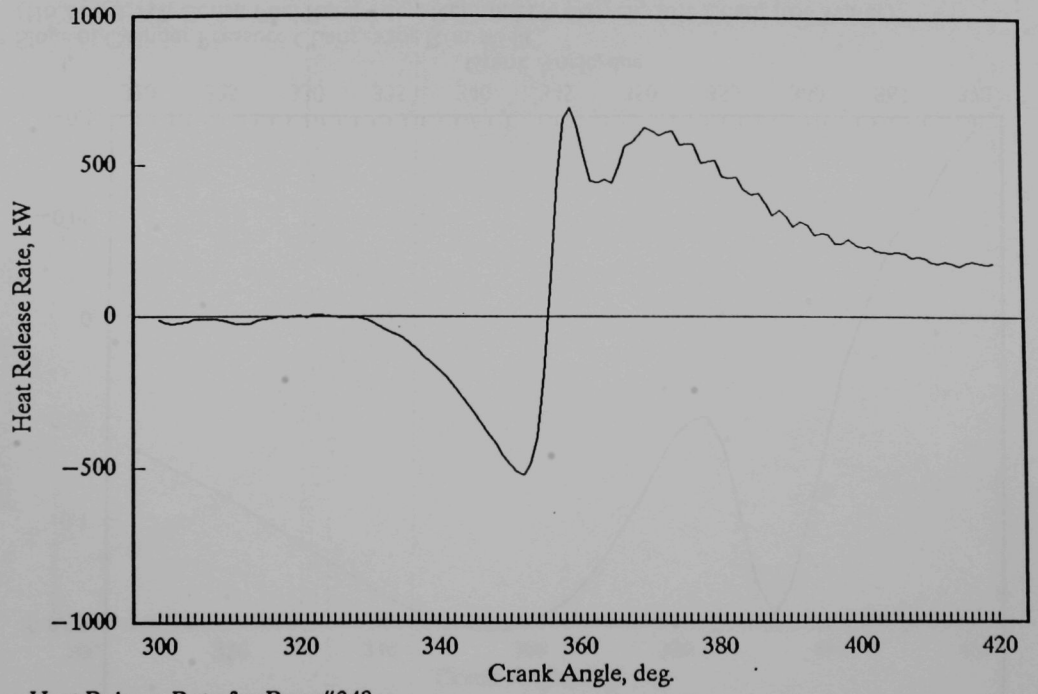
Cumulative Heat Release for Run #347
(No.2 Fuel, A9, Const. Fuel Rate, 8 deg. Retard, 30% Oxygen, 75% Load, 0% Water)



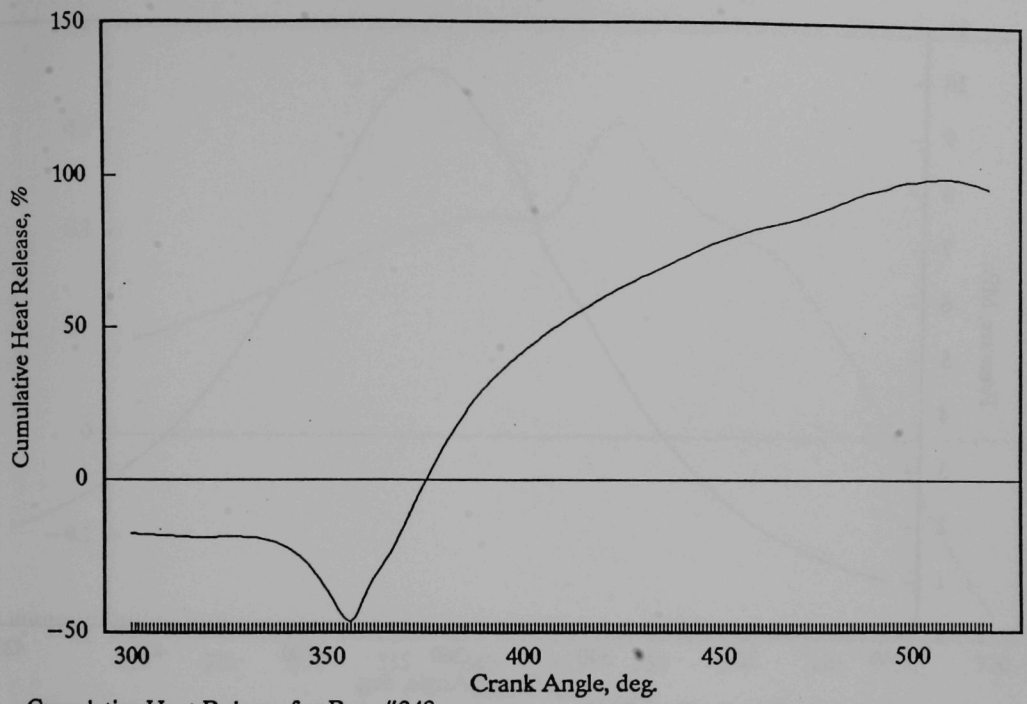
Cylinder Pressure Data for Run #348
(No.2 Fuel, A7, Const. Fuel Rate, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



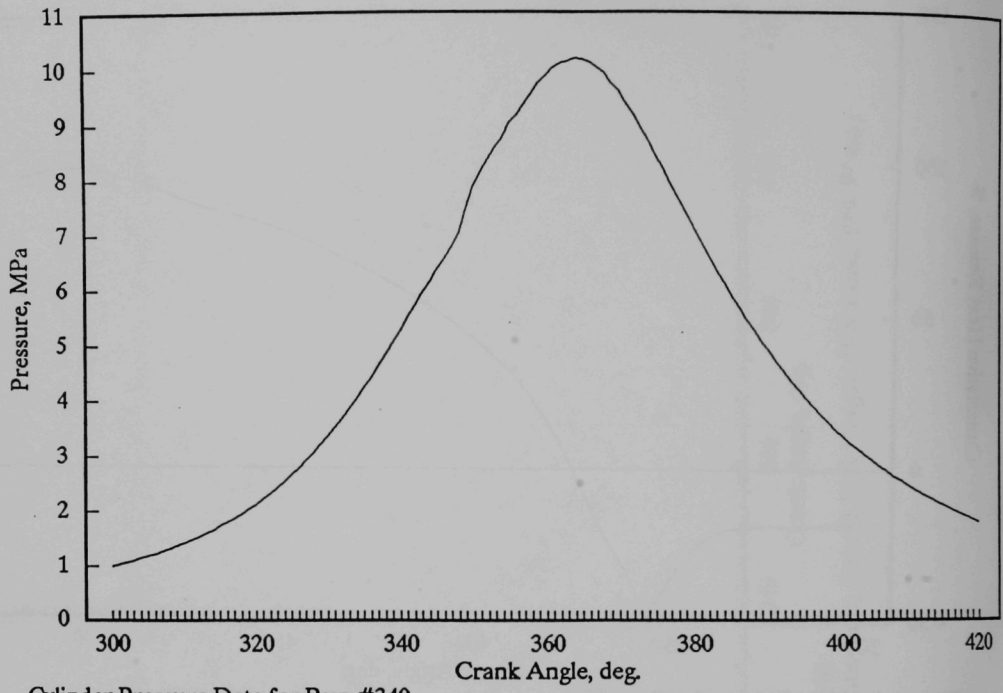
Slope of Cylinder Pressure Changes for Run #348
(No.2 Fuel, A7, Const. Fuel Rate, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



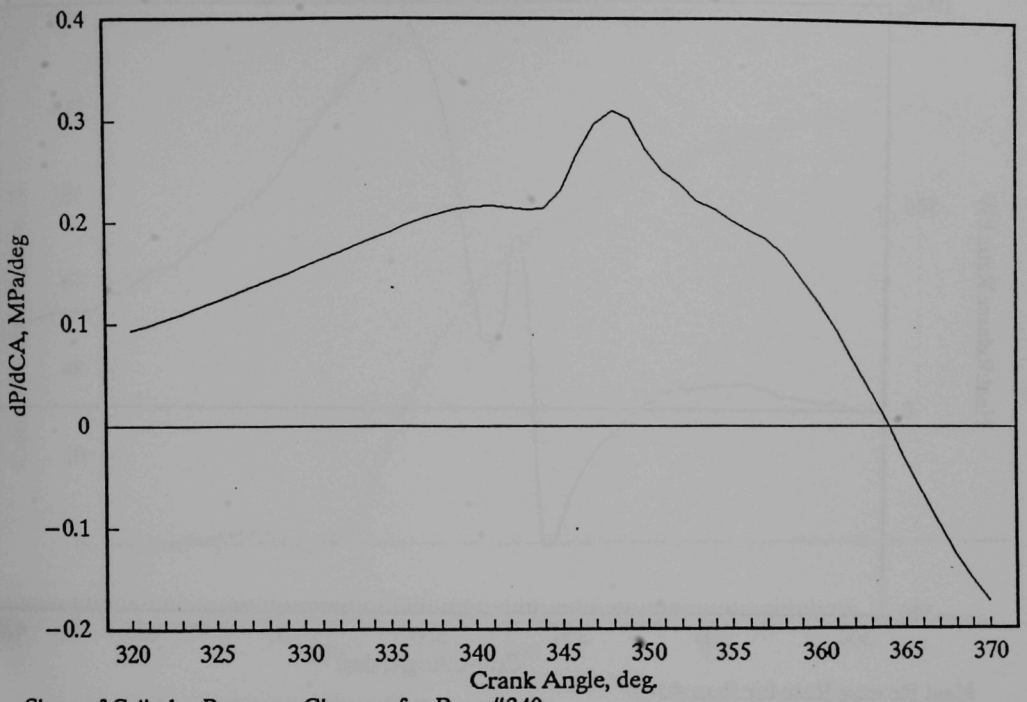
Heat Release Rate for Run #348
(No.2 Fuel, A7, Const. Fuel Rate, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



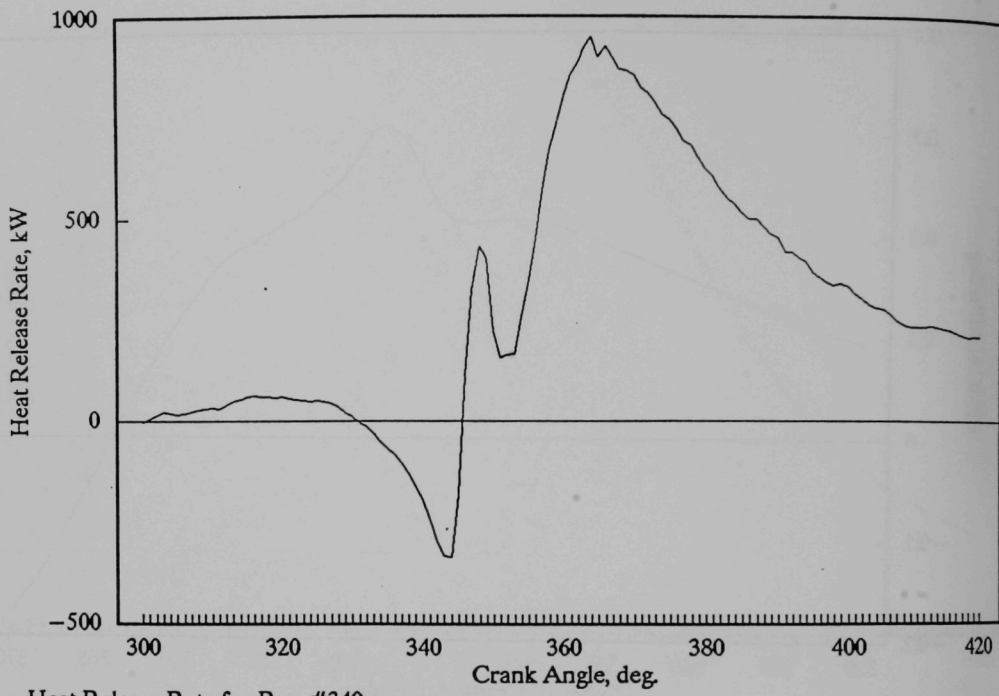
Cumulative Heat Release for Run #348
(No.2 Fuel, A7, Const. Fuel Rate, 8 deg. Retard, 21% Oxygen, 50% Load, 10% Water)



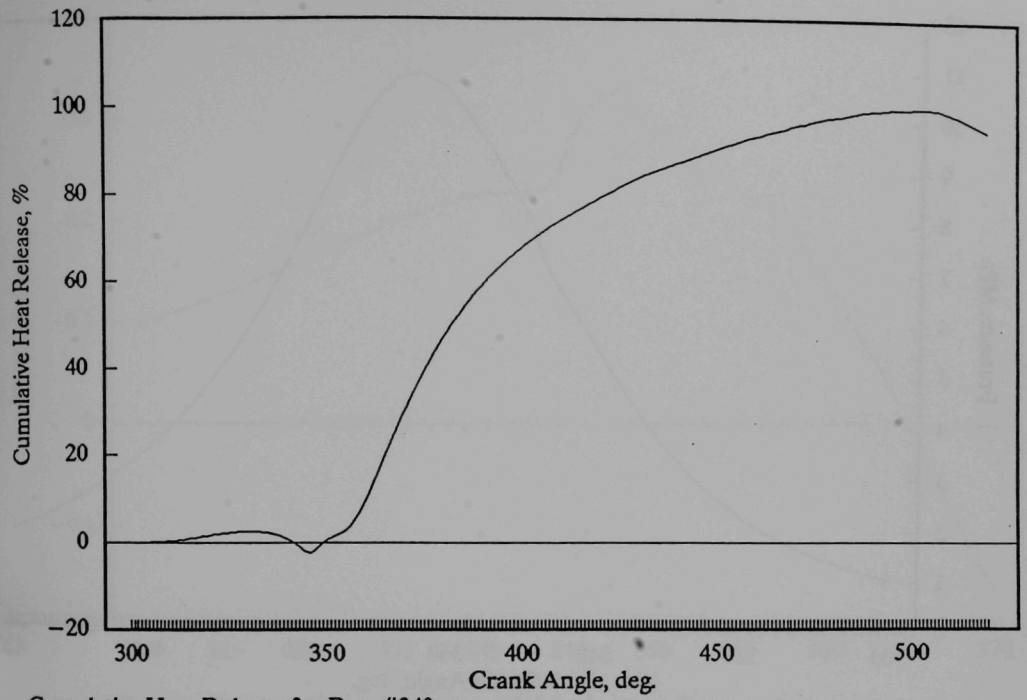
Cylinder Pressure Data for Run #349
(No.2 Fuel, A1, Const. Fuel Rate, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



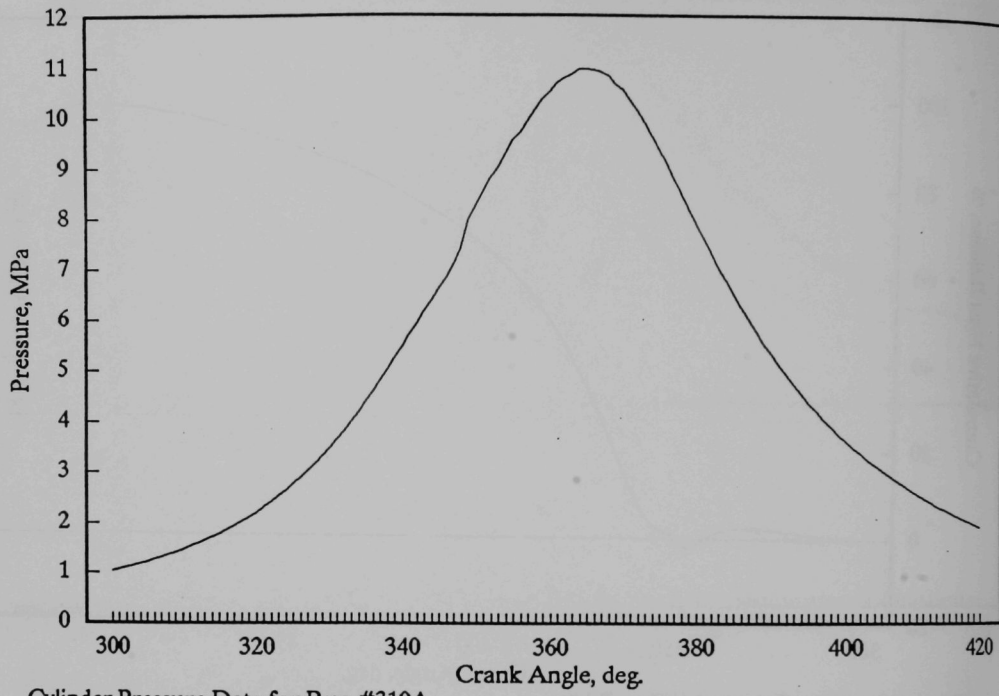
Slope of Cylinder Pressure Changes for Run #349
(No.2 Fuel, A1, Const. Fuel Rate, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



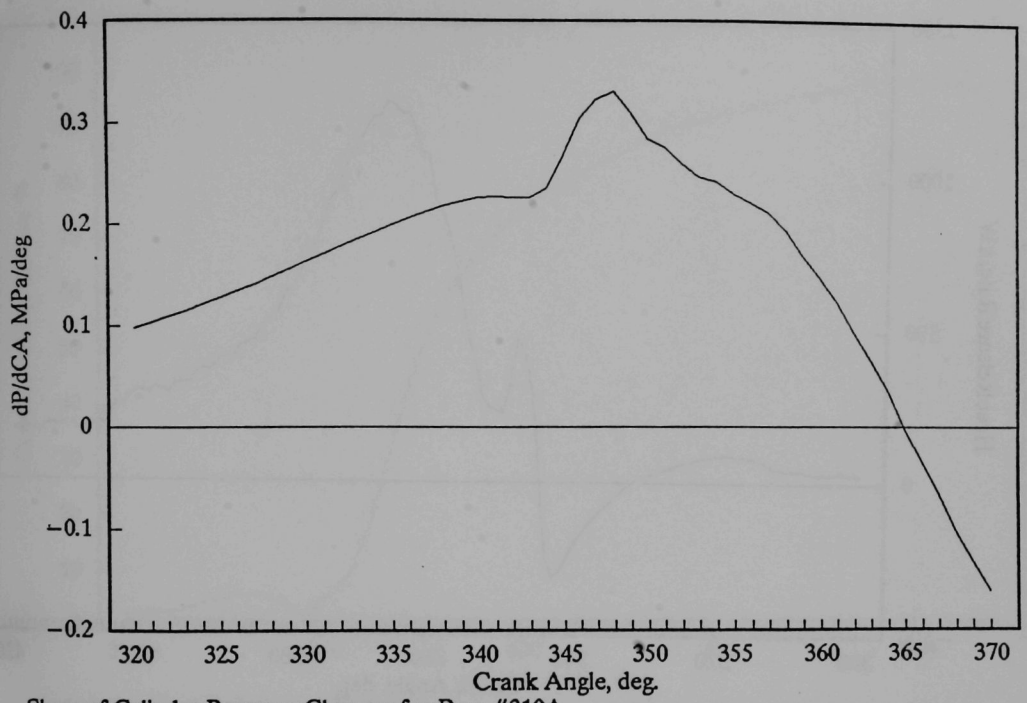
Heat Release Rate for Run #349
(No.2 Fuel, A1, Const. Fuel Rate, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



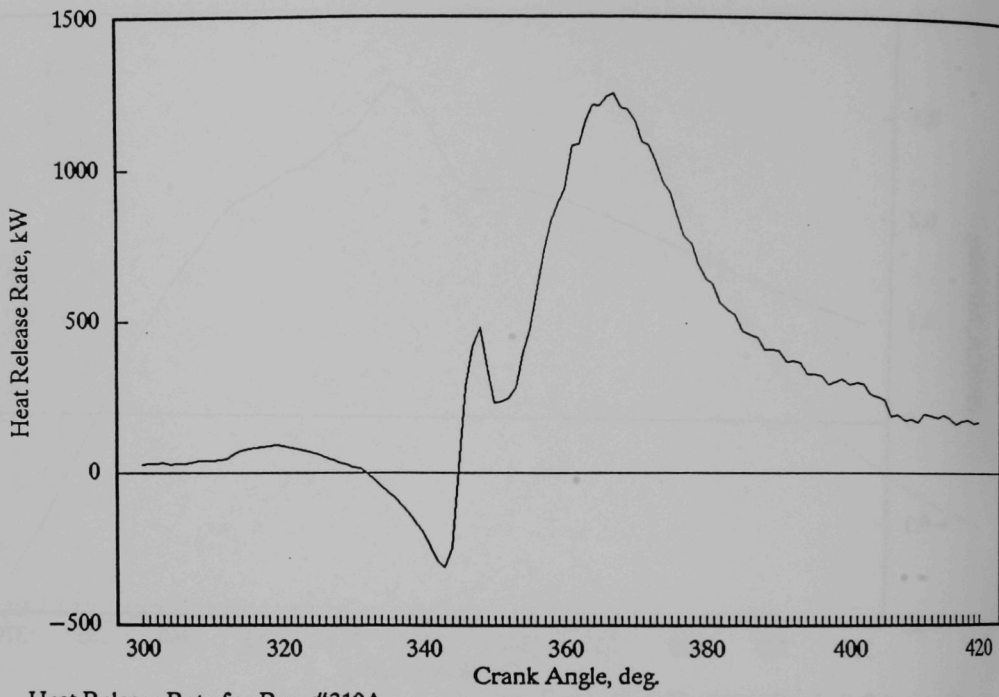
Cumulative Heat Release for Run #349
(No.2 Fuel, A1, Const. Fuel Rate, 0 deg. Retard, 21% Oxygen, 100% Load, 0% Water)



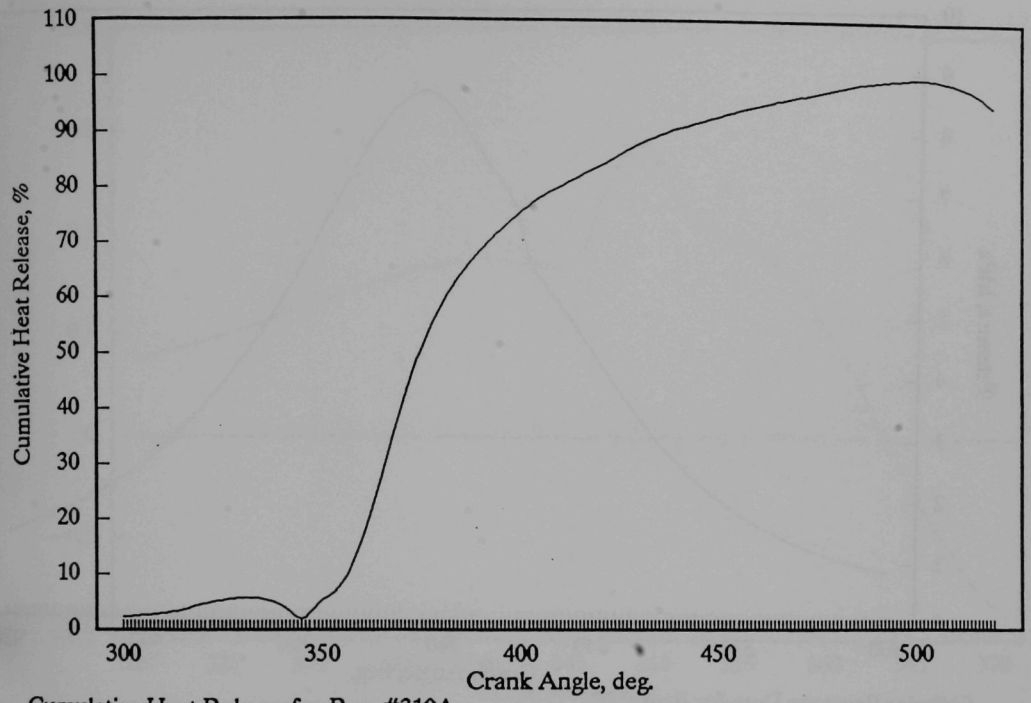
Cylinder Pressure Data for Run #319A
(No.2 Fuel, B2, Const. Equiv. Ratio, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



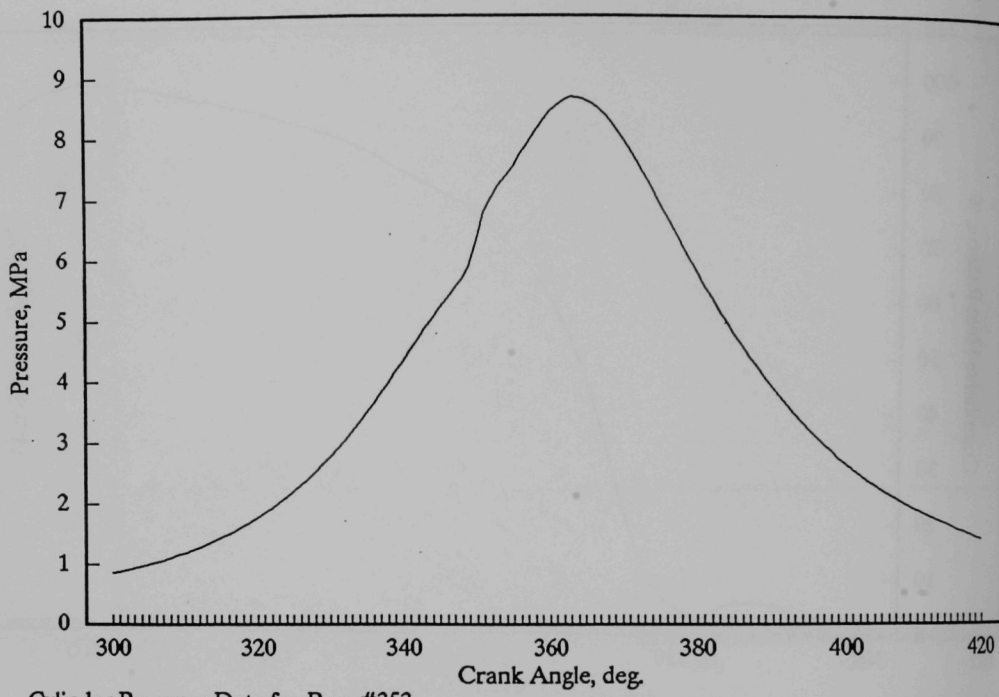
Slope of Cylinder Pressure Changes for Run #319A
(No.2 Fuel, B2, Const. Equiv. Ratio, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



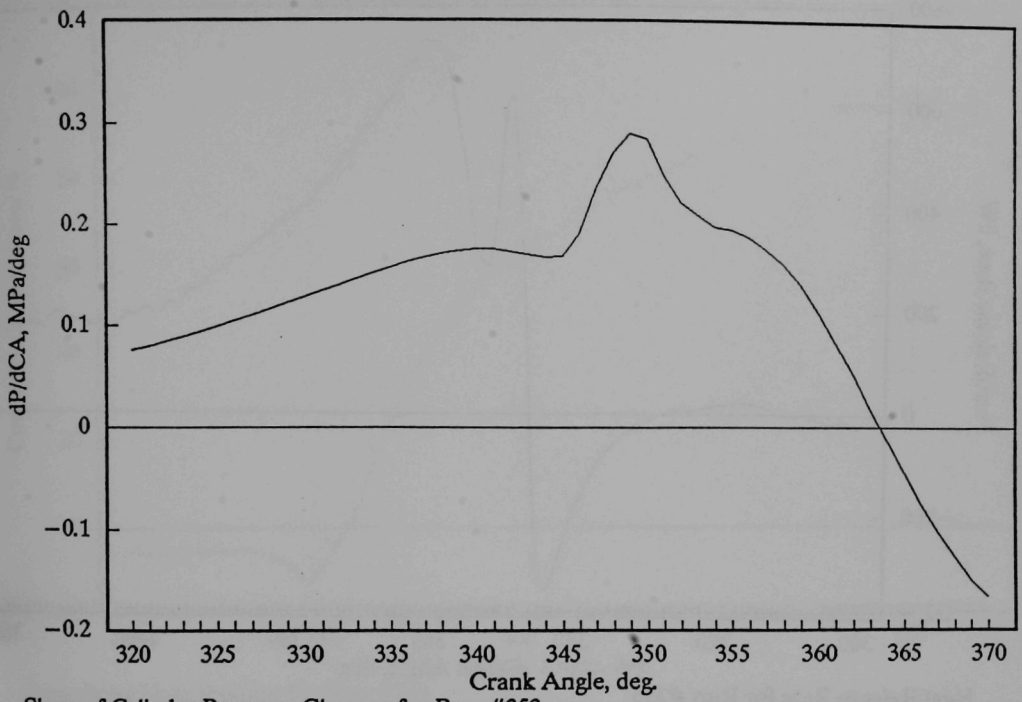
Heat Release Rate for Run #319A
(No.2 Fuel, B2, Const. Equiv. Ratio, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



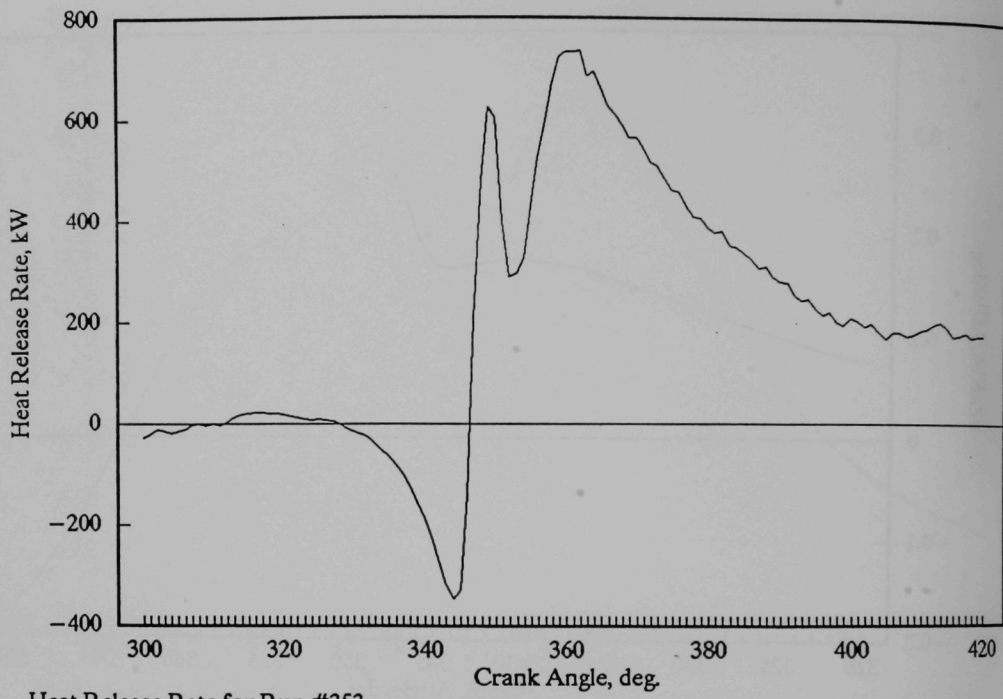
Cumulative Heat Release for Run #319A
(No.2 Fuel, B2, Const. Equiv. Ratio, 0 deg. Retard, 25.5% Oxygen, 75% Load, 10% Water)



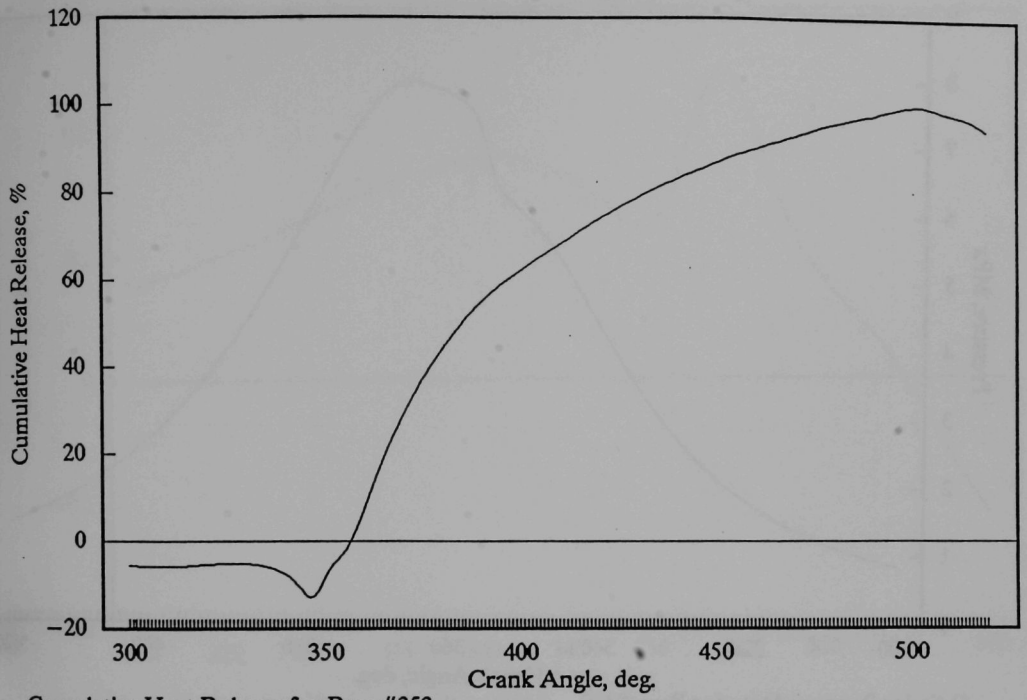
Cylinder Pressure Data for Run #353
(No.2 Fuel, B1, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



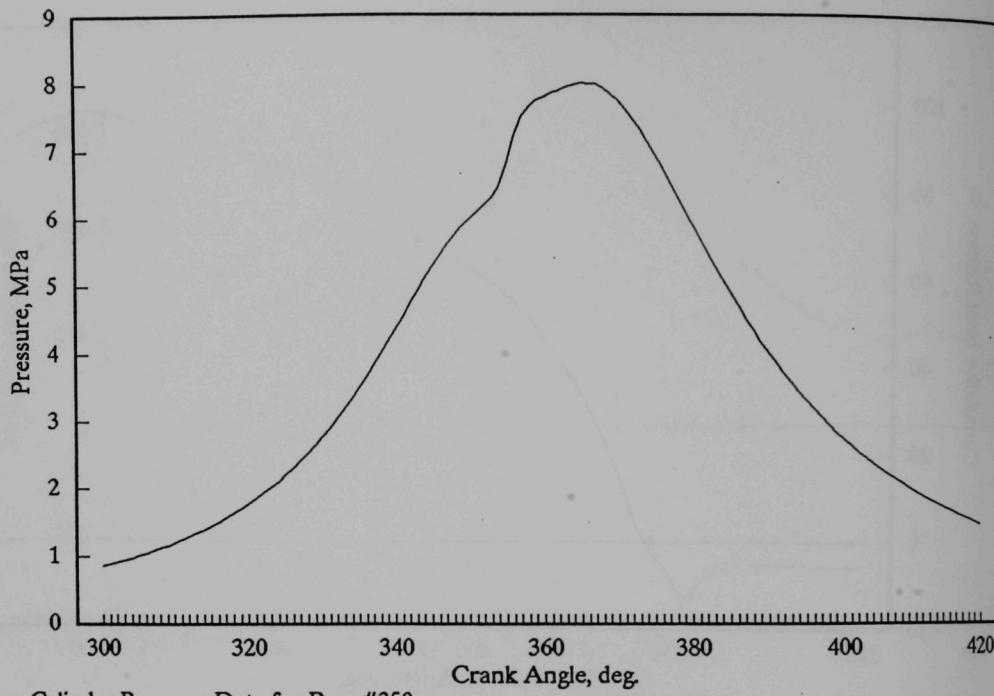
Slope of Cylinder Pressure Changes for Run #353
(No.2 Fuel, B1, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



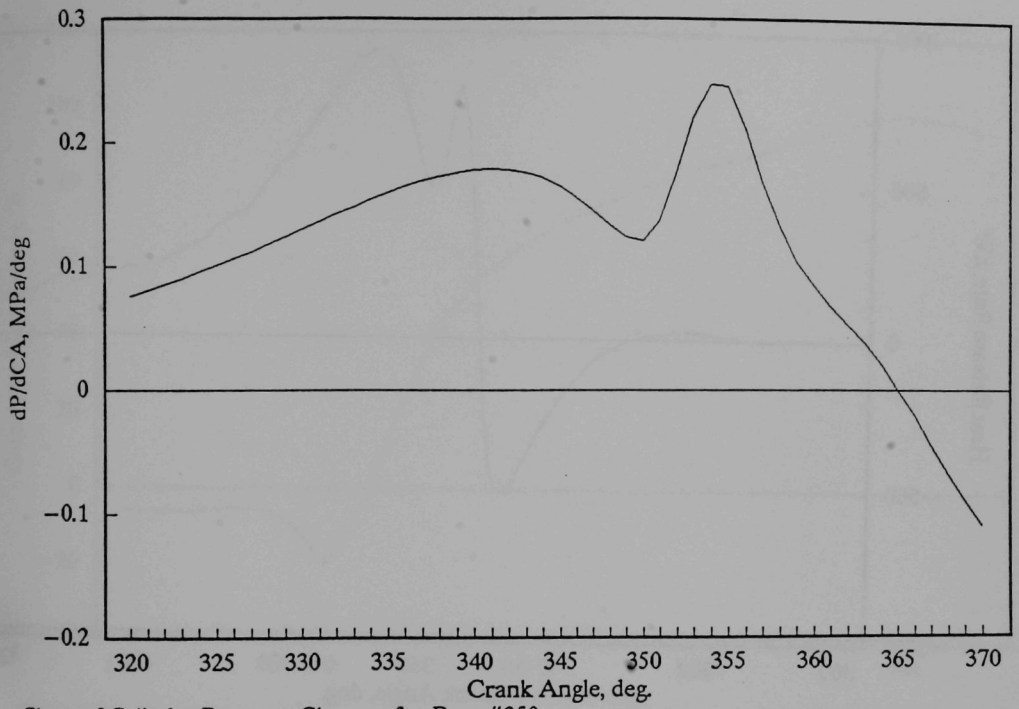
Heat Release Rate for Run #353
(No.2 Fuel, B1, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



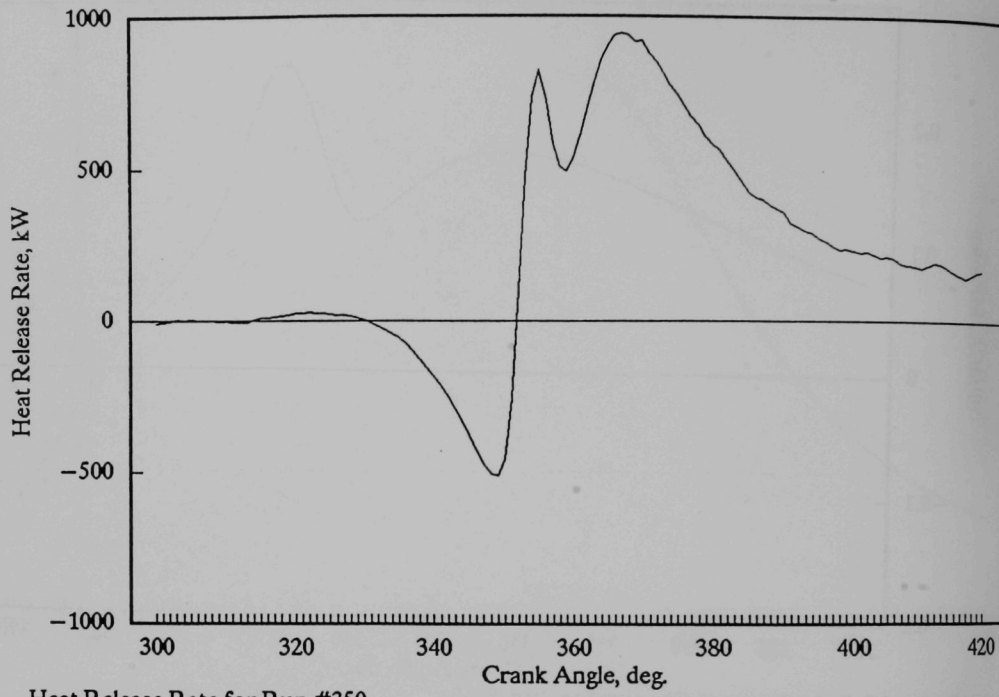
Cumulative Heat Release for Run #353
(No.2 Fuel, B1, Const. Equiv. Ratio, 0 deg. Retard, 21% Oxygen, 75% Load, 0% Water)



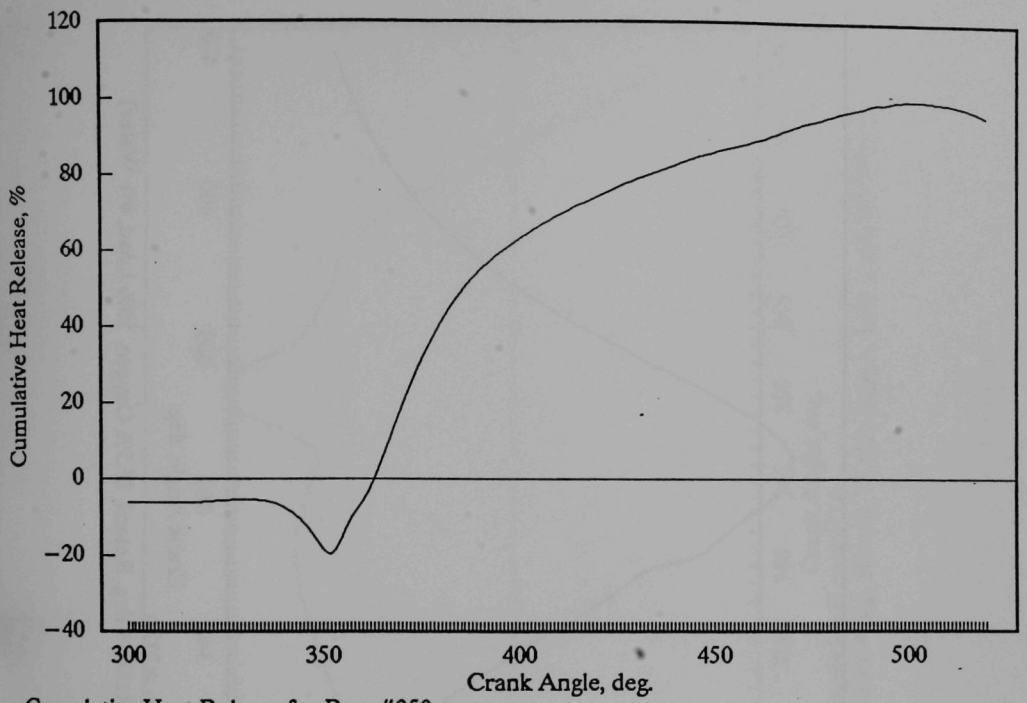
Cylinder Pressure Data for Run #350
(No.2 Fuel, A4, Const. Fuel Rate, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



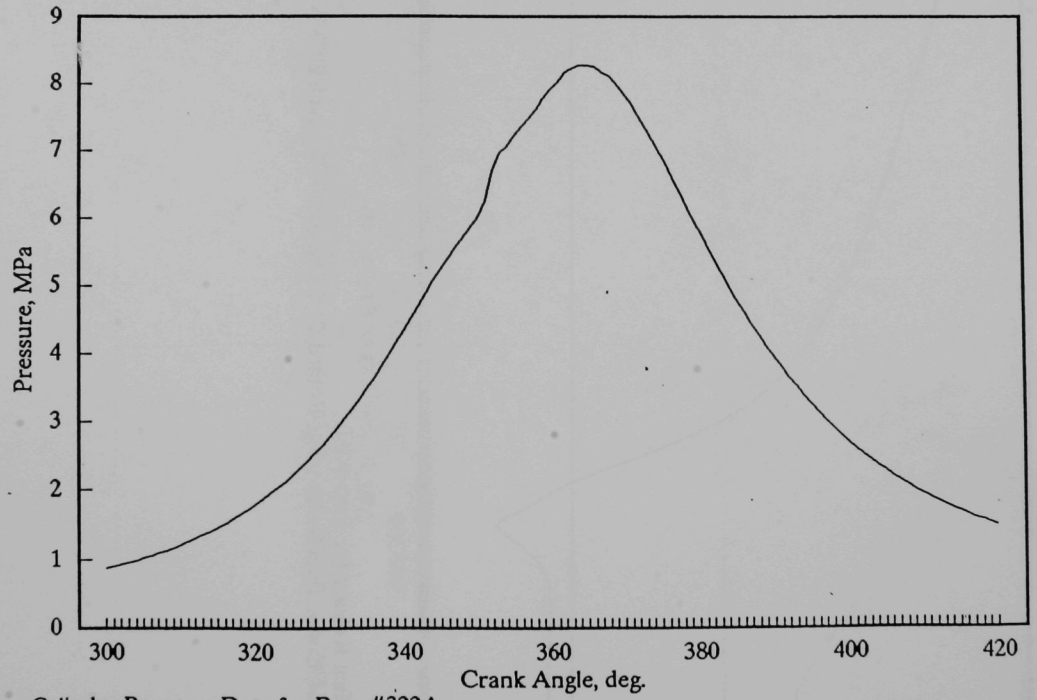
Slope of Cylinder Pressure Changes for Run #350
(No.2 Fuel, A4, Const. Fuel Rate, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



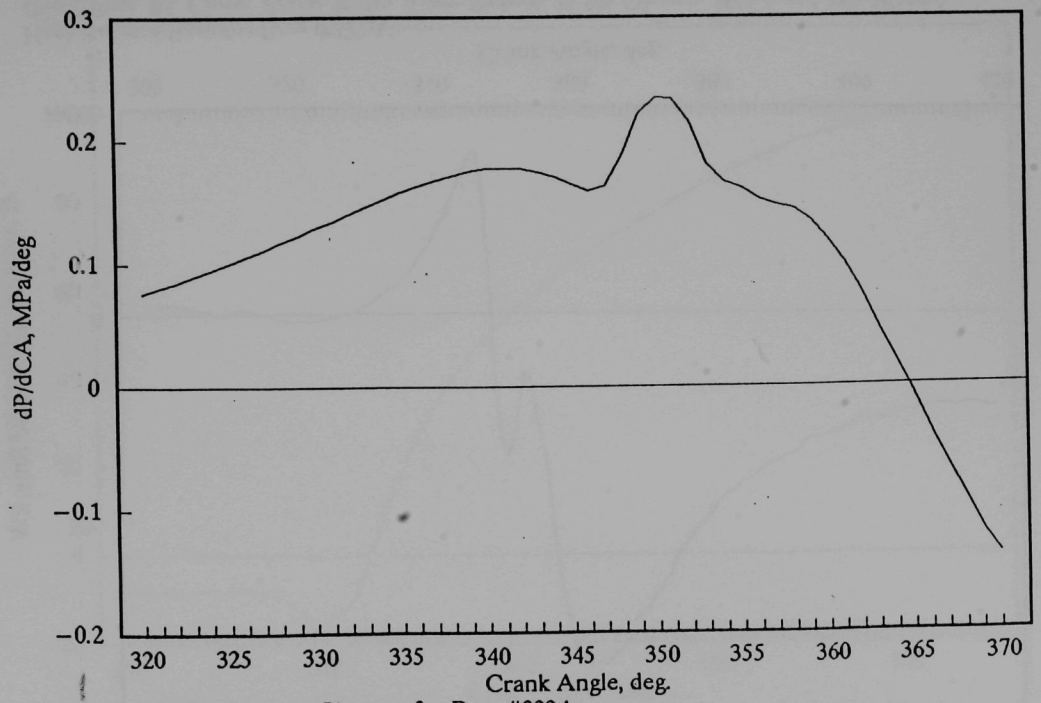
Heat Release Rate for Run #350
(No.2 Fuel, A4, Const. Fuel Rate, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



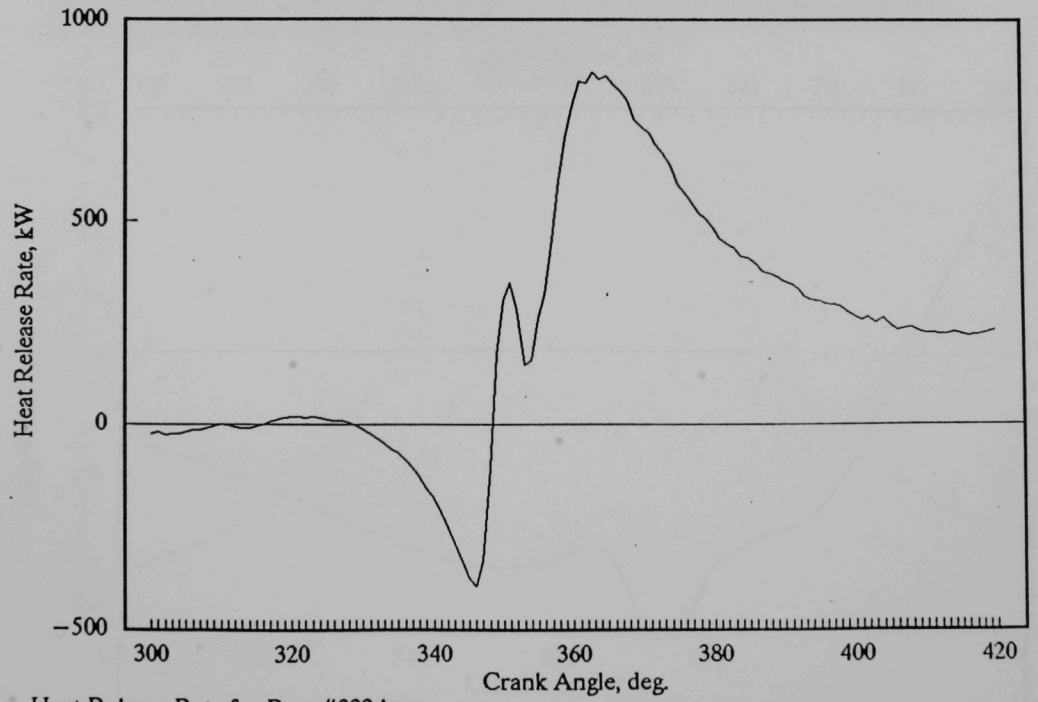
Cumulative Heat Release for Run #350
(No.2 Fuel, A4, Const. Fuel Rate, 4 deg. Retard, 21% Oxygen, 75% Load, 20% Water)



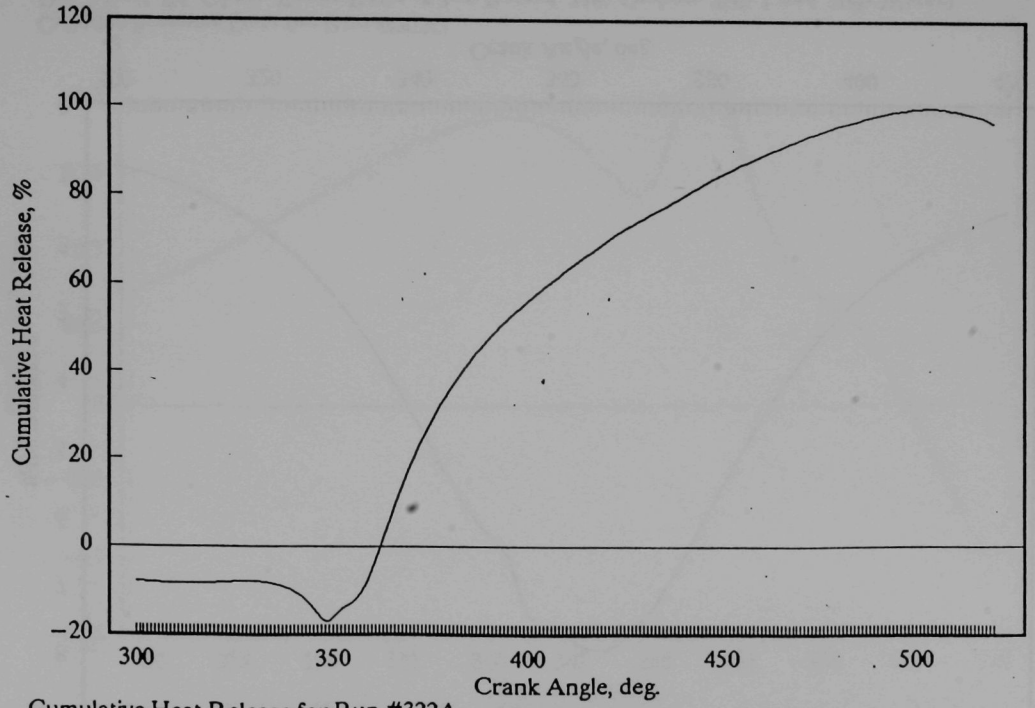
Cylinder Pressure Data for Run #322A
(No.2 Fuel, B5, Const. Equiv. Ratio, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



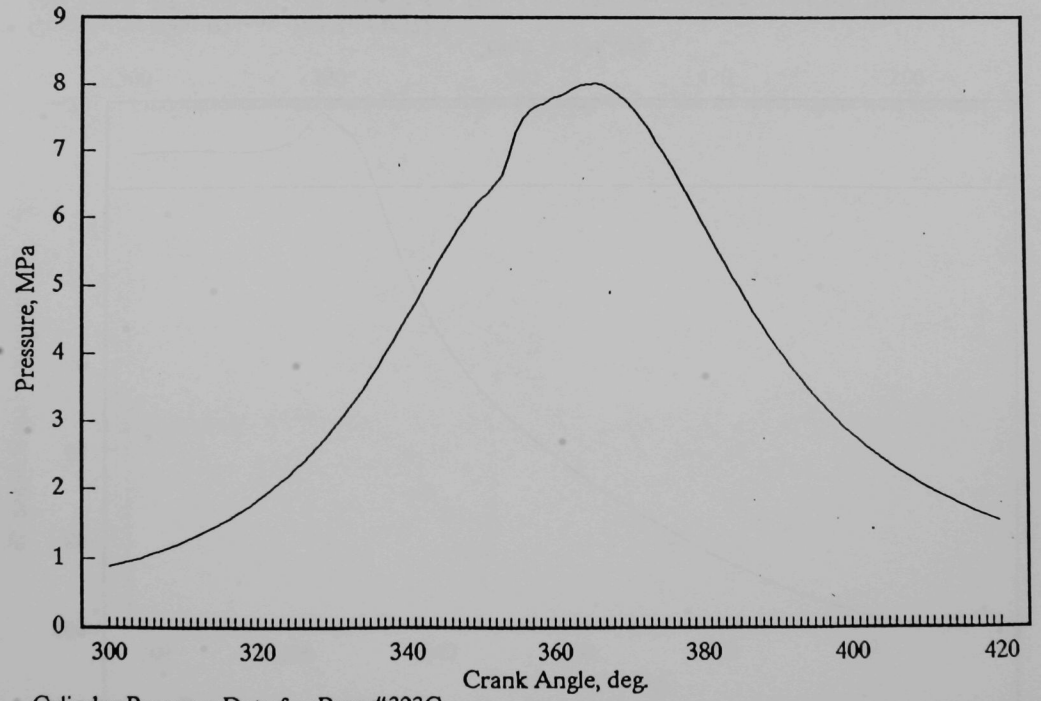
Slope of Cylinder Pressure Changes for Run #322A
(No.2 Fuel, B5, Const. Equiv. Ratio, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



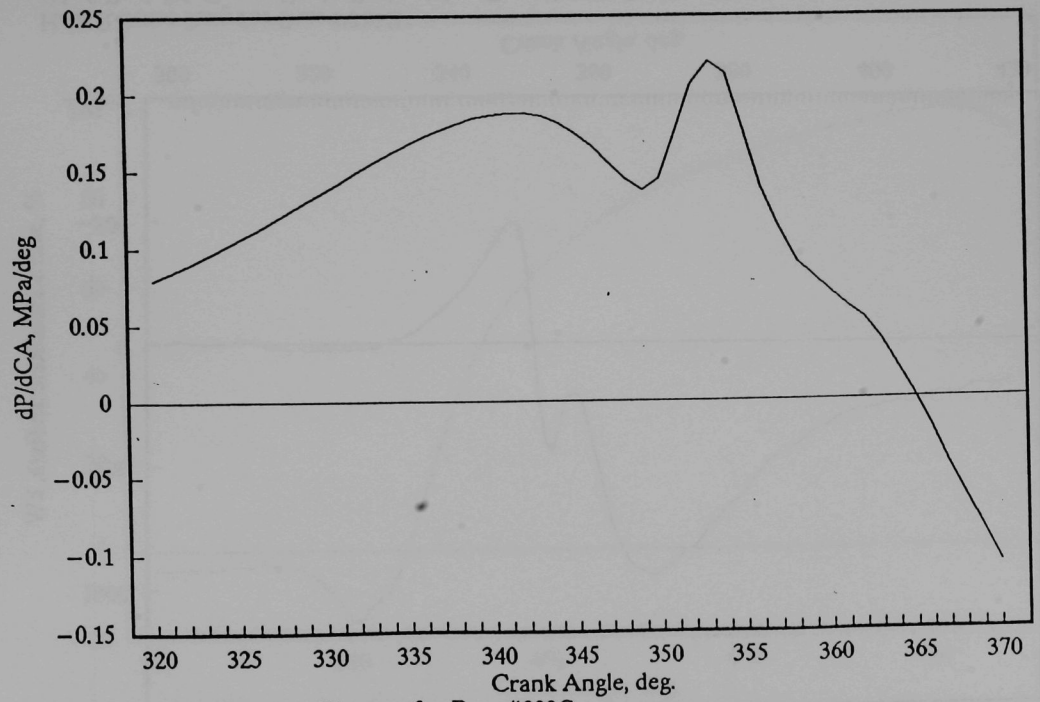
Heat Release Rate for Run #322A
(No.2 Fuel, B5, Const. Equiv. Ratio, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



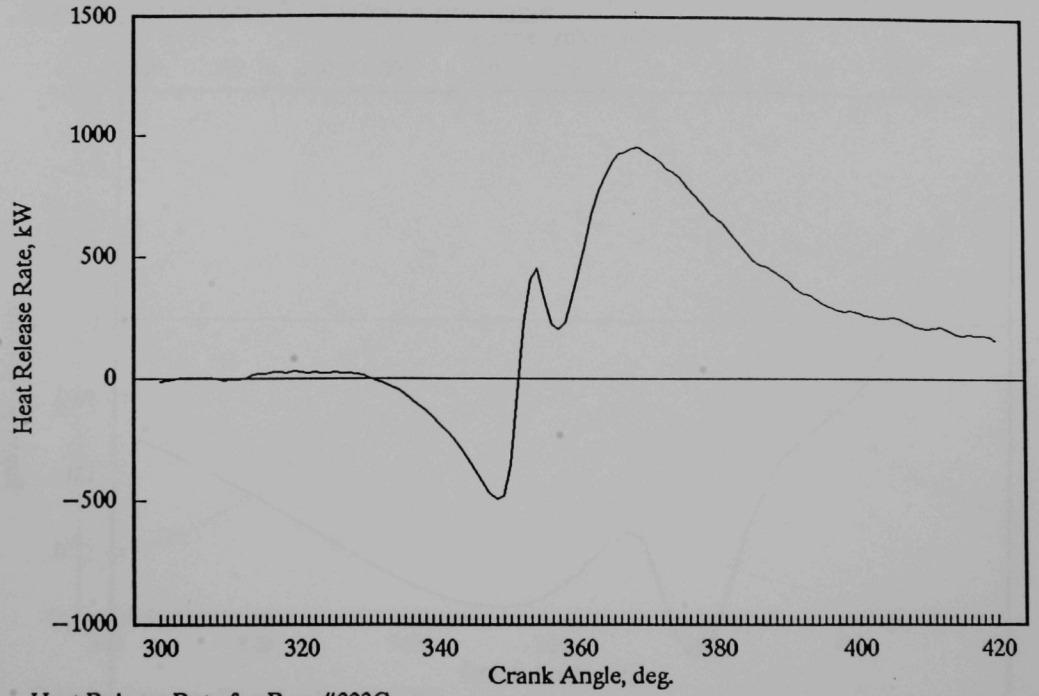
Cumulative Heat Release for Run #322A
(No.2 Fuel, B5, Const. Equiv. Ratio, 4 deg. Retard, 25.5% Oxygen, 50% Load, 0% Water)



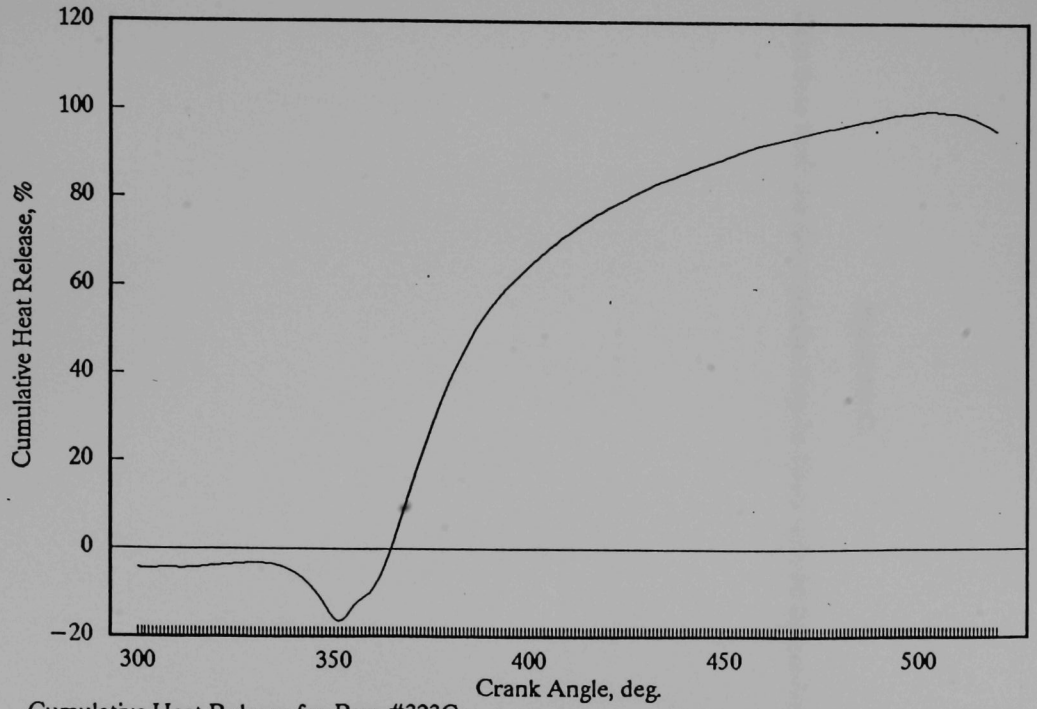
Cylinder Pressure Data for Run #323C
(No.2 Fuel, B6, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 10% Water)



Slope of Cylinder Pressure Changes for Run #323C
(No.2 Fuel, B6, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 10% Water)



Heat Release Rate for Run #323C
(No.2 Fuel, B6, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 10% Water)



Cumulative Heat Release for Run #323C
(No.2 Fuel, B6, Const. Equiv. Ratio, 4 deg. Retard, 21% Oxygen, 75% Load, 10% Water)

Appendix C:

Data Sets from the Six-Cylinder Engine Tests with #6 Diesel Fuel

MULTI-CYLINDER ENGINE TEST
NO. 6 FUEL

Table 1. Matrix A
Engine Load Characterized by Fuel Rate

	Injection Retard, deg.	Oxygen Content, %	Engine Load, %	Water Content, %
Level 1	0	21	100	0
2	4	25.5	75	10
3	8	30	50	20

Table 2. Matrix B
Engine Load Characterized by Equivalence Ratio

	Injection Retard, deg.	Oxygen Content, %	Engine Load, %	Water Content, %
Level 1	0	21	75	0
2	4	23	62.5	5
3	8	25	50	10

Table 3. Taguchi L9 Orthogonal Table

	Injection Retard	Oxygen Content	Engine Load	Water Content
Test #1	1	1	1	1
#2	1	2	2	2
#3	1	3	3	3
#4	2	1	2	3
#5	2	2	3	1
#6	2	3	1	2
#7	3	1	3	2
#8	3	2	1	3
#9	3	3	2	1

ARGONNE 6-CYLINDER ENGINE TEST MATRIX

SEQUENCE #3 (#6 FUEL)

ALI TEST #	ANL CODE	FUEL RATE OR EQU. RATIO	INJ. RETARD	OXYGEN %	LOAD %	WATER %
359	WE	FUEL(#2)	0	30	***	0
360	WE	FUEL(#2)	0	30	***	20
361C	B.L.,A1	FUEL*	0	21	100	0
362B	B.L.	-	0	21	75	0
363B	B.L.	-	0	21	62.5	0
364B	B.L.	-	0	21	50	0
365A	B2	EQ.R.**	0	23	62.5	5
366A	B1	EQ.R.	0	21	75	0
367A	A2	FUEL	0	25.5	75	10
368A	B3	EQ.R.	0	25	50	10
369A	A3	FUEL	0	30	50	20
370	A9	FUEL	8	30	75	0
371	B8	EQ.R.	8	23	75	10
372	A7	FUEL	8	21	50	10
373	A8	FUEL	8	25.5	100	20
374	B7	EQ.R.	8	21	50	5
375	B9	EQ.R.	8	25	62.5	0
376	A6	FUEL	4	30	100	10
377	B4	EQ.R.	4	21	62.5	10
378	A5	FUEL	4	25.5	50	0
379	B6	EQ.R.	4	25	75	5
380	B5	EQ.R.	4	23	50	0
381	A4	FUEL	4	21	75	20

* Maintain baseline fuel rate measured at corresponding engine load.

** Maintain baseline equivalence ratio measured at corresponding engine load.

*** Tests #359 and #360 are designed to check out the effects of water on emissions with the **No. 2 fuel**. These tests are not part of the Taguchi matrix. For these tests, the engine load should be maintained at **400 hp** if possible.

ARGONNE 6-CYLINDER ENGINE TEST MATRIX

SEQUENCE #4 (#6 FUEL)

ALI TEST #	ANL CODE	FUEL RATE OR EQUI. RATIO	INJ. RETARD	OXYGEN %	LOAD %	WATER %
382	A7	FUEL*	8	21	50	10
383	B8	EQ.R.**	8	23	75	10
384	A9	FUEL	8	30	75	0
385	A8	FUEL	8	25.5	100	20
386A	B7	EQ.R.	8	21	50	5
387A	B9	EQ.R.	8	25	62.5	0
388	A5	FUEL	4	25.5	50	0
389	B6	EQ.R.	4	25	75	5
390	A4	FUEL	4	21	75	20
391	A6	FUEL	4	30	100	10
392	B4	EQ.R.	4	21	62.5	10
393	B5	EQ.R.	4	23	50	0
395	B2	EQ.R.	0	23	62.5	5
396	A3	FUEL	0	30	50	20
397	A2	FUEL	0	25.5	75	10
398	B1	EQ.R.	0	21	75	0
399	B3	EQ.R.	0	25	50	10
400	A1	FUEL	0	21	100	0
401	WE	FUEL(#6)	0	21	100	10
402	WE	FUEL(#6)	0	21	100	20

* Maintain baseline fuel rate measured at corresponding engine load.

** Maintain baseline equivalence ratio measured at corresponding engine load.

*** Tests #401 and #402 are designed to check out the effects of water on emissions with the **No. 6 fuel**. These tests are not part of the Taguchi matrix.

No. 6 Fuel, Matrix A
0 Degree Retard, 21% Oxygen, 100% Load, 0% Water

Run #	361C	394
Test Matrix Data Point #	A1	A1
Date	07/04/92	08/07/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	20.99	20.99
O2 in Exhaust Air (Vol-%)	11.1	11.2
Intake Air Flow (kg/min)	26.60	26.96
O2 Flow from Air (kg/min)	6.17	6.26
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	6.17	6.26
Engine Load Level (%)	100	100
Power (kW)	223.9	221.1
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.980	0.974
Fuel-to-O2 Ratio	0.1587	0.1557
BSFC (kg/kW-hr)	0.263	0.264
Turbo Speed (rpm)	70300	71000
Intake Manifold Pressure (MPa)	0.21	0.21
Peak Cylinder Pressure (MPa)	9.61	8.20
Exhaust Temperature (K)	834.3	854.8
Thermal Efficiency (%)	32.2	31.9
Smoke (%)	9	16
Particulates (g/kWh)	1.691	2.779
NOx (g/kWh)	5.17	5.57
Ignition Delay (deg)	15.7	16.5

No. 6 Fuel, Matrix A
0 Degree Retard, 25.5% Oxygen, 75% Load, 10% Water

Run #	367A	397
Test Matrix Data Point #	A2	A2
Date	07/07/92	08/08/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	16.1	16.1
Intake Air Flow (kg/min)	21.91	22.70
O2 Flow from Air (kg/min)	4.76	4.94
O2 Flow from Bottle (kg/min)	1.37	1.42
Total O2 Flow (kg/min)	6.14	6.36
Engine Load Level (%)	75	75
Power (kW)	177.6	187.8
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	10.1
Net Fuel Rate (kg/min)	0.797	0.797
Fuel-to-O2 Ratio	0.1298	0.1254
BSFC (kg/kW-hr)	0.269	0.255
Turbo Speed (rpm)	58500	61200
Intake Manifold Pressure (MPa)	0.17	0.18
Peak Cylinder Pressure (MPa)	8.35	8.97
Exhaust Temperature (K)	779.3	794.3
Thermal Efficiency (%)	31.4	33.1
Smoke (%)	1	1
Particulates (g/kWh)	1.055	1.163
NOx (g/kWh)	16.95	16.97
Ignition Delay (deg)	16.3	15.2

No. 6 Fuel, Matrix A
0 Degree Retard, 30% Oxygen, 50% Load, 20% Water

Run #	369A	396
Test Matrix Data Point #	A3	A3
Date	07/07/92	08/08/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	30	30
O2 in Exhaust Air (Vol-%)	21.8	21.9
Intake Air Flow (kg/min)	18.38	18.40
O2 Flow from Air (kg/min)	3.73	3.74
O2 Flow from Bottle (kg/min)	2.29	2.29
Total O2 Flow (kg/min)	6.02	6.03
Engine Load Level (%)	50	50
Power (kW)	118.8	125.2
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	19.9	20.3
Net Fuel Rate (kg/min)	0.584	0.586
Fuel-to-O2 Ratio	0.0970	0.0972
BSFC (kg/kW-hr)	0.295	0.281
Turbo Speed (rpm)	47500	48800
Intake Manifold Pressure (MPa)	0.14	0.14
Peak Cylinder Pressure (MPa)	7.44	7.39
Exhaust Temperature (K)	700.4	713.2
Thermal Efficiency (%)	28.6	30.1
Smoke (%)	0	0
Particulates (g/kWh)	1.390	1.522
NOx (g/kWh)	27.65	27.99
Ignition Delay (deg)	17.6	14.8

No. 6 Fuel, Matrix A
4 Degree Retard, 21% Oxygen, 75% Load, 20% Water

Run #	381	390
Test Matrix Data Point #	A4	A4
Date	07/21/92	07/29/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	20.99	20.99
O2 in Exhaust Air (Vol-%)	11.6	11.5
Intake Air Flow (kg/min)	23.64	23.39
O2 Flow from Air (kg/min)	5.48	5.43
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	5.48	5.43
Engine Load Level (%)	75	75
Power (kW)	172.5	172.5
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	20.4	19.5
Net Fuel Rate (kg/min)	0.791	0.797
Fuel-to-O2 Ratio	0.1441	0.1470
BSFC (kg/kW-hr)	0.275	0.277
Turbo Speed (rpm)	62500	63200
Intake Manifold Pressure (MPa)	0.18	0.18
Peak Cylinder Pressure (MPa)	7.99	8.08
Exhaust Temperature (K)	805.4	821.5
Thermal Efficiency (%)	30.7	30.4
Smoke (%)	7	9
Particulates (g/kWh)	1.820	1.920
NOx (g/kWh)	2.90	2.72
Ignition Delay (deg)	17.9	16.3

No. 6 Fuel, Matrix A
4 Degree Retard, 25.5% Oxygen, 50% Load, 0% Water

Run #	378	388
Test Matrix Data Point #	A5	A5
Date	07/20/92	07/29/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	17.1	17.4
Intake Air Flow (kg/min)	19.65	20.23
O2 Flow from Air (kg/min)	4.27	4.40
O2 Flow from Bottle (kg/min)	1.23	1.27
Total O2 Flow (kg/min)	5.50	5.66
Engine Load Level (%)	50	50
Power (kW)	124.0	115.0
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.586	0.581
Fuel-to-O2 Ratio	0.1065	0.1025
BSFC (kg/kW-hr)	0.284	0.303
Turbo Speed (rpm)	51700	53300
Intake Manifold Pressure (MPa)	0.14	0.15
Peak Cylinder Pressure (MPa)	6.90	6.65
Exhaust Temperature (K)	756.5	762.6
Thermal Efficiency (%)	29.8	27.9
Smoke (%)	4	6
Particulates (g/kWh)	1.843	3.285
NOx (g/kWh)	12.00	10.11
Ignition Delay (deg)	14.5	16.2

No. 6 Fuel, Matrix A
4 Degree Retard, 30% Oxygen, 100% Load, 10% Water

Run #	376	391
Test Matrix Data Point #	A6	A6
Date	07/19/92	07/31/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	30	30
O2 in Exhaust Air (Vol-%)	19.3	19.7
Intake Air Flow (kg/min)	27.58	26.80
O2 Flow from Air (kg/min)	5.60	5.44
O2 Flow from Bottle (kg/min)	3.43	3.33
Total O2 Flow (kg/min)	9.04	8.78
Engine Load Level (%)	100	100
Power (kW)	253.0	237.7
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	9.8	10.4
Net Fuel Rate (kg/min)	0.990	0.989
Fuel-to-O2 Ratio	0.1096	0.1127
BSFC (kg/kW-hr)	0.235	0.250
Turbo Speed (rpm)	72000	69700
Intake Manifold Pressure (MPa)	0.22	0.21
Peak Cylinder Pressure (MPa)	9.93	9.58
Exhaust Temperature (K)	866.5	839.3
Thermal Efficiency (%)	36.0	33.8
Smoke (%)	1	0
Particulates (g/kWh)	1.269	1.419
NOx (g/kWh)	26.43	27.71
Ignition Delay (deg)	13.3	9

No. 6 Fuel, Matrix A
8 Degree Retard, 21% Oxygen, 50% Load, 10% Water

Run #	372	382
Test Matrix Data Point #	A7	A7
Date	07/08/92	07/26/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	20.99	20.99
O2 in Exhaust Air (Vol-%)	13.2	13.3
Intake Air Flow (kg/min)	19.23	19.49
O2 Flow from Air (kg/min)	4.46	4.52
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	4.46	4.52
Engine Load Level (%)	50	50
Power (kW)	94.6	102.2
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10.2	9.8
Net Fuel Rate (kg/min)	0.590	0.591
Fuel-to-O2 Ratio	0.1322	0.1307
BSFC (kg/kW-hr)	0.374	0.347
Turbo Speed (rpm)	51700	53500
Intake Manifold Pressure (MPa)	0.13	0.15
Peak Cylinder Pressure (MPa)	5.80	6.29
Exhaust Temperature (K)	747.6	768.7
Thermal Efficiency (%)	22.6	24.3
Smoke (%)	19	22
Particulates (g/kWh)	5.889	6.204
NOx (g/kWh)	2.39	2.56
Ignition Delay (deg)	19	18

No. 6 Fuel, Matrix A
8 Degree Retard, 25.5% Oxygen, 100% Load, 20% Water

Run #	373	385
Test Matrix Data Point #	A8	A8
Date	07/09/92	07/27/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	25.5	25.5
O2 in Exhaust Air (Vol-%)	15.6	15.5
Intake Air Flow (kg/min)	26.12	27.36
O2 Flow from Air (kg/min)	5.68	5.95
O2 Flow from Bottle (kg/min)	1.64	1.71
Total O2 Flow (kg/min)	7.32	7.66
Engine Load Level (%)	100	100
Power (kW)	214.7	230.0
H2O in Fuel (Wt-%) -- Planned	20	20
H2O in Fuel (Wt-%) -- Actual	20.2	20.1
Net Fuel Rate (kg/min)	0.978	0.983
Fuel-to-O2 Ratio	0.1337	0.1282
BSFC (kg/kW-hr)	0.273	0.256
Turbo Speed (rpm)	69500	71300
Intake Manifold Pressure (MPa)	0.20	0.22
Peak Cylinder Pressure (MPa)	8.11	8.79
Exhaust Temperature (K)	843.2	863.2
Thermal Efficiency (%)	30.9	32.9
Smoke (%)	2	0
Particulates (g/kWh)	1.049	1.039
NOx (g/kWh)	11.32	12.06
Ignition Delay (deg)	12	6

No. 6 Fuel, Matrix A
8 Degree Retard, 30% Oxygen, 75% Load, 0% Water

Run #	370	384
Test Matrix Data Point #	A9	A9
Date	07/08/92	07/26/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	30	30
O2 in Exhaust Air (Vol-%)	20.7	20.9
Intake Air Flow (kg/min)	23.70	23.68
O2 Flow from Air (kg/min)	4.81	4.81
O2 Flow from Bottle (kg/min)	2.95	2.95
Total O2 Flow (kg/min)	7.76	7.76
Engine Load Level (%)	75	75
Power (kW)	170.0	176.3
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.794	0.798
Fuel-to-O2 Ratio	0.1023	0.1029
BSFC (kg/kW-hr)	0.280	0.272
Turbo Speed (rpm)	62900	63800
Intake Manifold Pressure (MPa)	0.18	0.19
Peak Cylinder Pressure (MPa)	7.17	7.82
Exhaust Temperature (K)	808.7	828.7
Thermal Efficiency (%)	30.1	31.1
Smoke (%)	1	1
Particulates (g/kWh)	1.318	1.443
NOx (g/kWh)	21.94	21.72
Ignition Delay (deg)	13.1	16.7

No. 6 Fuel, Matrix B
0 Degree Retard, 21% Oxygen, 75% Load, 0% Water

Run #	366A	398
Test Matrix Data Point #	B1	B1
Date	07/06/92	08/09/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	20.99	20.99
O2 in Exhaust Air (Vol-%)	12.2	11.8
Intake Air Flow (kg/min)	21.78	23.34
O2 Flow from Air (kg/min)	5.05	5.41
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	5.05	5.41
Engine Load Level (%)	75	75
Power (kW)	153.3	173.8
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.737	0.790
Fuel-to-O2 Ratio	0.1459	0.1459
BSFC (kg/kW-hr)	0.288	0.273
Turbo Speed (rpm)	58100	62500
Intake Manifold Pressure (MPa)	0.17	0.19
Peak Cylinder Pressure (MPa)	7.89	8.72
Exhaust Temperature (K)	780.9	822.6
Thermal Efficiency (%)	29.3	30.9
Smoke (%)	14	21
Particulates (g/kWh)	3.034	4.316
NOx (g/kWh)	4.66	4.30
Ignition Delay (deg)	16.9	14.8

No. 6 Fuel, Matrix B
0 Degree Retard, 23% Oxygen, 62.5% Load, 5% Water

Run #	365A	395
Test Matrix Data Point #	B2	B2
Date	07/06/92	08/08/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	23	23
O2 in Exhaust Air (Vol-%)	13.9	13.5
Intake Air Flow (kg/min)	22.64	24.47
O2 Flow from Air (kg/min)	5.10	5.52
O2 Flow from Bottle (kg/min)	0.64	0.68
Total O2 Flow (kg/min)	5.74	6.20
Engine Load Level (%)	62.5	62.5
Power (kW)	178.9	201.9
H2O in Fuel (Wt-%) -- Planned	5	5
H2O in Fuel (Wt-%) -- Actual	5	4.9
Net Fuel Rate (kg/min)	0.806	0.865
Fuel-to-O2 Ratio	0.1404	0.1395
BSFC (kg/kW-hr)	0.270	0.257
Turbo Speed (rpm)	60200	65900
Intake Manifold Pressure (MPa)	0.18	0.19
Peak Cylinder Pressure (MPa)	8.40	9.28
Exhaust Temperature (K)	782.0	818.7
Thermal Efficiency (%)	31.2	32.8
Smoke (%)	2	3
Particulates (g/kWh)	1.187	1.375
NOx (g/kWh)	9.51	10.15
Ignition Delay (deg)	17.2	13.1

No. 6 Fuel, Matrix B
0 Degree Retard, 25% Oxygen, 50% Load, 10% Water

Run #	368A	399
Test Matrix Data Point #	B3	B3
Date	07/07/92	08/09/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	0	0
O2 in Intake Air (Vol-%)	25	25
O2 in Exhaust Air (Vol-%)	15.7	15.2
Intake Air Flow (kg/min)	21.96	23.51
O2 Flow from Air (kg/min)	4.81	5.15
O2 Flow from Bottle (kg/min)	1.22	1.31
Total O2 Flow (kg/min)	6.04	6.46
Engine Load Level (%)	50	50
Power (kW)	176.3	199.3
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10	9.6
Net Fuel Rate (kg/min)	0.798	0.844
Fuel-to-O2 Ratio	0.1323	0.1306
BSFC (kg/kW-hr)	0.272	0.254
Turbo Speed (rpm)	58500	63300
Intake Manifold Pressure (MPa)	0.17	0.19
Peak Cylinder Pressure (MPa)	8.37	9.41
Exhaust Temperature (K)	777.0	812.0
Thermal Efficiency (%)	31.1	33.2
Smoke (%)	1	3
Particulates (g/kWh)	1.101	1.224
NOx (g/kWh)	15.55	14.88
Ignition Delay (deg)	16.1	13.7

No. 6 Fuel, Matrix B
4 Degree Retard, 21% Oxygen, 62.5% Load, 10% Water

Run #	377	392
Test Matrix Data Point #	B4	B4
Date	07/20/92	07/31/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	20.99	20.99
O2 in Exhaust Air (Vol-%)	11.9	12.2
Intake Air Flow (kg/min)	22.77	23.53
O2 Flow from Air (kg/min)	5.28	5.46
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	5.28	5.46
Engine Load Level (%)	62.5	62.5
Power (kW)	155.9	153.3
H2O in Fuel (Wt-%) -- Planned	10	10
H2O in Fuel (Wt-%) -- Actual	10.2	9.9
Net Fuel Rate (kg/min)	0.737	0.760
Fuel-to-O2 Ratio	0.1396	0.1392
BSFC (kg/kW-hr)	0.284	0.297
Turbo Speed (rpm)	61800	62600
Intake Manifold Pressure (MPa)	0.18	0.18
Peak Cylinder Pressure (MPa)	7.41	7.85
Exhaust Temperature (K)	813.7	807.6
Thermal Efficiency (%)	29.8	28.4
Smoke (%)	14	13
Particulates (g/kWh)	3.693	4.705
NOx (g/kWh)	2.69	3.12
Ignition Delay (deg)	18.2	15.4

No. 6 Fuel, Matrix B
4 Degree Retard, 23% Oxygen, 50% Load, 0% Water

Run #	380	393
Test Matrix Data Point #	B5	B5
Date	07/21/92	07/31/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	23	23
O2 in Exhaust Air (Vol-%)	13.9	14.2
Intake Air Flow (kg/min)	25.20	25.05
O2 Flow from Air (kg/min)	5.68	5.65
O2 Flow from Bottle (kg/min)	0.71	0.70
Total O2 Flow (kg/min)	6.39	6.35
Engine Load Level (%)	50	50
Power (kW)	178.9	173.8
H2O in Fuel (Wt-%) -- Planned	0	0
H2O in Fuel (Wt-%) -- Actual	0	0
Net Fuel Rate (kg/min)	0.843	0.831
Fuel-to-O2 Ratio	0.1319	0.1309
BSFC (kg/kW-hr)	0.283	0.287
Turbo Speed (rpm)	65700	65000
Intake Manifold Pressure (MPa)	0.19	0.19
Peak Cylinder Pressure (MPa)	8.46	8.60
Exhaust Temperature (K)	827.6	820.9
Thermal Efficiency (%)	29.9	29.4
Smoke (%)	14	13
Particulates (g/kWh)	2.703	3.019
NOx (g/kWh)	7.18	7.42
Ignition Delay (deg)	24.4	14

No. 6 Fuel, Matrix B
4 Degree Retard, 25% Oxygen, 75% Load, 5% Water

Run #	379	389
Test Matrix Data Point #	B6	B6
Date	07/20/92	07/29/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	4	4
O2 in Intake Air (Vol-%)	25	25
O2 in Exhaust Air (Vol-%)	13.5	13.7
Intake Air Flow (kg/min)	31.63	31.15
O2 Flow from Air (kg/min)	6.93	6.82
O2 Flow from Bottle (kg/min)	1.76	1.74
Total O2 Flow (kg/min)	8.69	8.56
Engine Load Level (%)	75	75
Power (kW)	302.9	296.5
H2O in Fuel (Wt-%) -- Planned	5	5
H2O in Fuel (Wt-%) -- Actual	5	5.3
Net Fuel Rate (kg/min)	1.259	1.222
Fuel-to-O2 Ratio	0.1448	0.1427
BSFC (kg/kW-hr)	0.249	0.247
Turbo Speed (rpm)	81600	80600
Intake Manifold Pressure (MPa)	0.26	0.26
Peak Cylinder Pressure (MPa)	11.26	11.23
Exhaust Temperature (K)	937.0	930.4
Thermal Efficiency (%)	33.9	34.1
Smoke (%)	0	1
Particulates (g/kWh)	1.157	1.320
NOx (g/kWh)	13.87	13.61
Ignition Delay (deg)	21	14.1

No. 6 Fuel, Matrix B
8 Degree Retard, 21% Oxygen, 50% Load, 5% Water

Run #	374	386A
Test Matrix Data Point #	B7	B7
Date	07/09/92	07/28/92
Fuel Type (#)	6	6
Injection Retard (deg./btdc)	8	8
O2 in Intake Air (Vol-%)	20.99	20.99
O2 in Exhaust Air (Vol-%)	13.2	12.7
Intake Air Flow (kg/min)	20.86	22.83
O2 Flow from Air (kg/min)	4.84	5.30
O2 Flow from Bottle (kg/min)	0.00	0.00
Total O2 Flow (kg/min)	4.84	5.30
Engine Load Level (%)	50	50
Power (kW)	101.0	125.2
H2O in Fuel (Wt-%) -- Planned	5	5
H2O in Fuel (Wt-%) -- Actual	5	4.8
Net Fuel Rate (kg/min)	0.631	0.692
Fuel-to-O2 Ratio	0.1305	0.1306
BSFC (kg/kW-hr)	0.375	0.331
Turbo Speed (rpm)	56400	61100
Intake Manifold Pressure (MPa)	0.16	0.17
Peak Cylinder Pressure (MPa)	6.26	6.97
Exhaust Temperature (K)	780.4	808.2
Thermal Efficiency (%)	22.5	25.5
Smoke (%)	30	22
Particulates (g/kWh)	8.982	7.358
NOx (g/kWh)	2.64	2.49
Ignition Delay (deg)	19.5	14.4

No. 6 Fuel
Comparison of Baseline Data At Different Engine Load Levels

Run #	361C	362B	363B	364B
Test Matrix Data Point #	BL	BL	BL	BL
Date	07/04/92	07/04/92	07/04/92	07/04/92
Fuel Type (#)	6	6	6	6
Injection Retard (deg./btdc)	0	0	0	0
O2 in Intake Air (Vol-%)	20.99	20.99	20.99	20.99
O2 in Exhaust Air (Vol-%)	11.1	12	12.4	13
Intake Air Flow (kg/min)	26.60	23.61	21.17	19.24
O2 Flow from Air (kg/min)	6.17	5.48	4.91	4.46
O2 Flow from Bottle (kg/min)	0.00	0.00	0.00	0.00
Total O2 Flow (kg/min)	6.17	5.48	4.91	4.46
Engine Load Level (%)	100	75	62.5	50
Power (kW)	223.9	167.7	139.8	111.9
H2O in Fuel (Wt-%) -- Planned	0	0	0	0
H2O in Fuel (Wt-%) -- Actual	0	0	0	0
Net Fuel Rate (kg/min)	0.980	0.796	0.684	0.587
Fuel-to-O2 Ratio	0.1587	0.1453	0.1393	0.1314
BSFC (kg/kW-hr)	0.263	0.285	0.294	0.314
Turbo Speed (rpm)	70300	62600	56500	50900
Intake Manifold Pressure (MPa)	0.21	0.18	0.16	0.15
Peak Cylinder Pressure (MPa)	9.61	8.42	7.80	7.12
Exhaust Temperature (K)	834.3	801.5	767.6	730.9
Thermal Efficiency (%)	32.2	29.6	28.8	26.9
Smoke (%)	9	17	19	22
Particulates (g/kWh)	1.691	4.204	4.315	5.298
NOx (g/kWh)	5.17	4.33	4.48	4.53
Ignition Delay (deg)	15.7	7.3	8.1	9.6

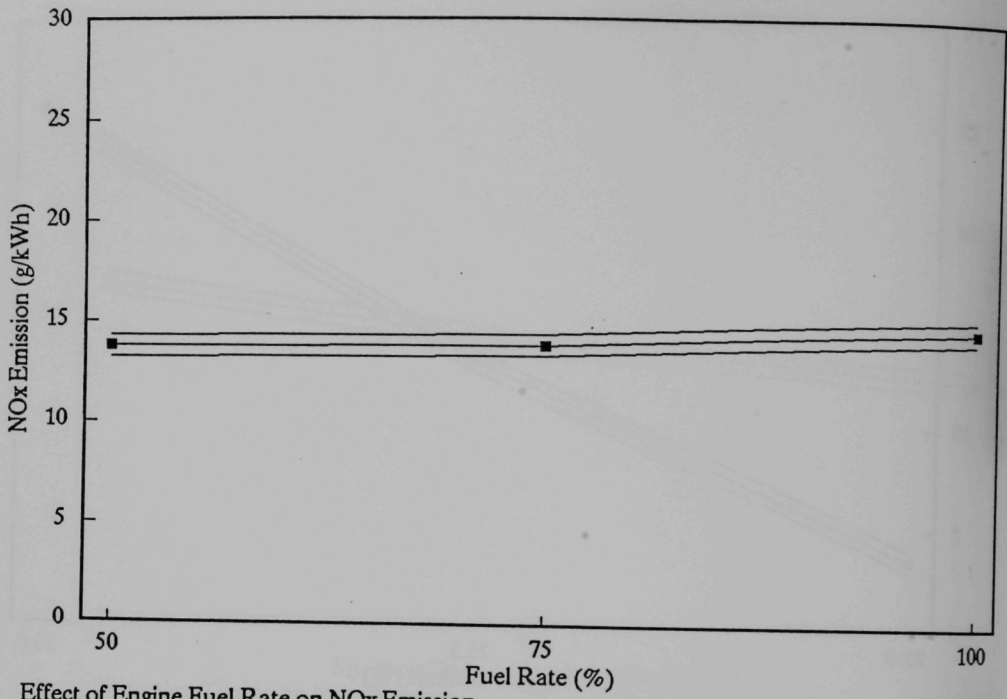
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel #6 Matrix A

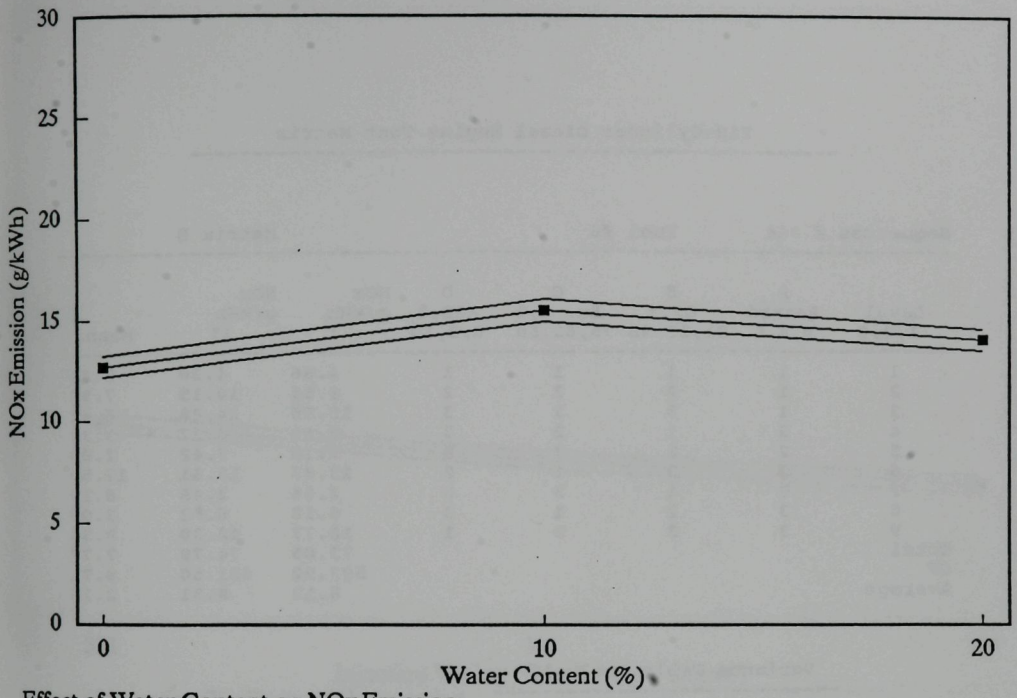
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	NOx g/kWh I	NOx g/kWh II	Mean
1	1	1	1	1	5.17	5.37	16.68
2	1	2	2	2	16.95	16.97	13.65
3	1	3	3	3	27.65	27.99	12.00
4	2	1	2	3	2.90	2.72	3.52
5	2	2	3	1	12.00	10.11	13.24
6	2	3	1	2	26.43	27.71	25.57
7	3	1	3	2	2.39	2.56	14.68
8	3	2	1	3	11.32	12.06	13.87
9	3	3	2	1	21.94	21.72	13.78
Total					126.75	127.21	12.72
CF					1785.06	1798.04	15.50
Average					14.08	14.13	14.11

Variance Table Analysis

Source	f	S	V	F	S'	% contr.
Timing	2	67.78	33.89	90.37	67.03	4.29
Oxygen	2	1466.14	733.07	1954.76	1465.39	93.75
Fuel	2	2.92	1.46	3.90	2.17	0.14
Water	2	23.24	11.62	30.99	22.49	1.44
Replicat.	1	0.01	0.01	0.03	0.00	0.00
e	8	3.00	0.38			0.38
Pooled e	9	3.01	0.33			
T	17	1563.10				100.00



Effect of Engine Fuel Rate on NOx Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on NOx Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)

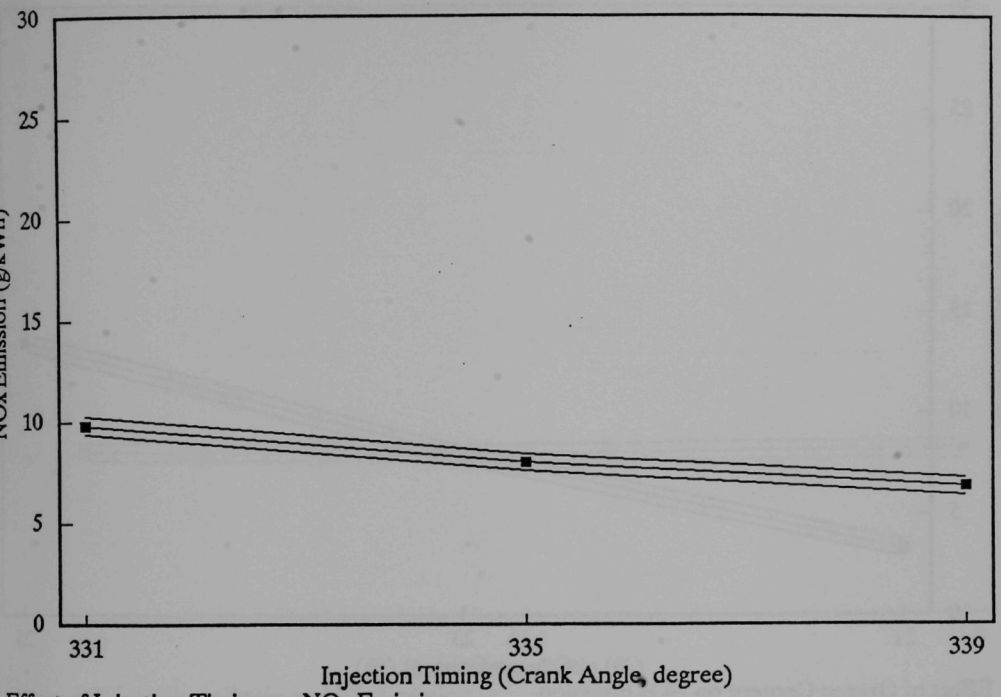
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel #6 Matrix B

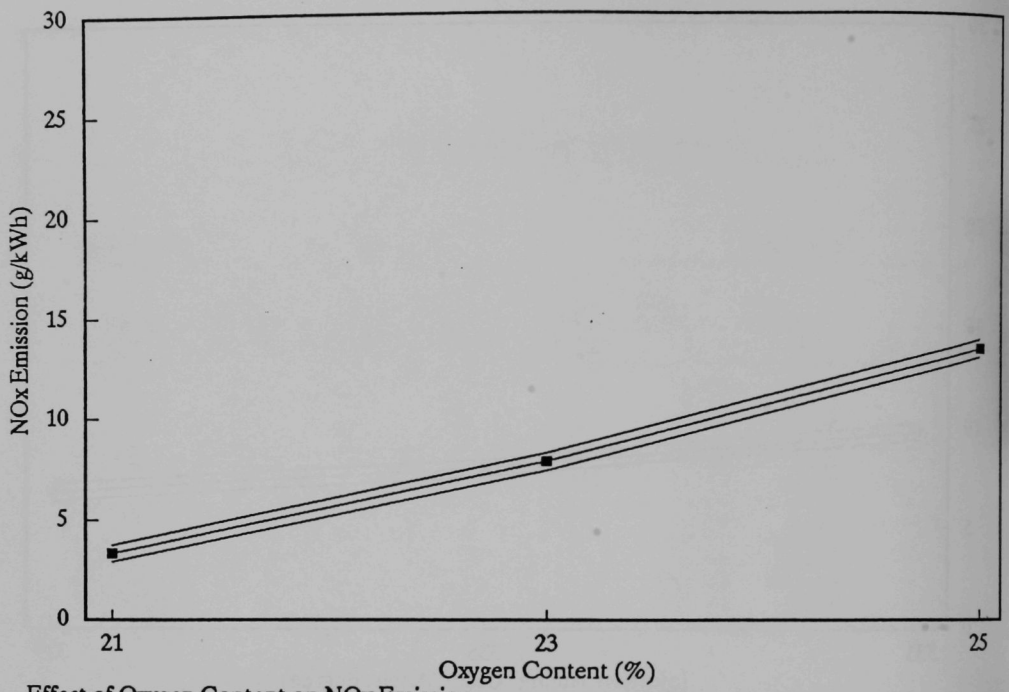
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	NOx g/kWh I	NOx g/kWh II	Mean
1	1	1	1	1	4.66	4.30	9.84
2	1	2	2	2	9.51	10.15	7.98
3	1	3	3	3	15.55	14.88	6.82
4	2	1	2	3	2.69	3.12	3.32
5	2	2	3	1	7.18	7.42	7.83
6	2	3	1	2	13.87	13.61	13.50
7	3	1	3	2	2.64	2.49	8.19
8	3	2	1	3	6.18	6.52	8.09
9	3	3	2	1	10.77	12.30	8.36
Total					73.05	74.79	7.77
CF					592.92	621.50	8.71
Average					8.12	8.31	8.16

Variance Table Analysis

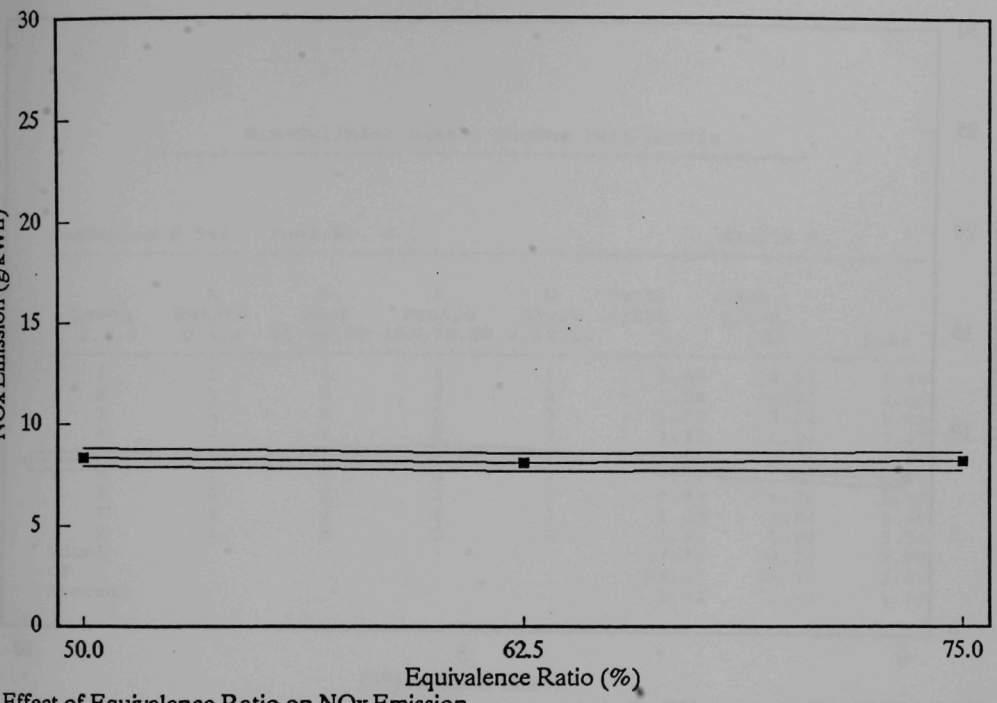
Source	f	S	V	F	S'	% contr.
Timing	2	27.93	13.97	64.95	27.50	7.97
Oxygen	2	312.24	156.12	725.98	311.81	90.39
Eq. R	2	0.22	0.11	0.52	-0.21	0.00
Water	2	2.68	1.34	6.23	2.25	0.65
Replicat.	1	0.17	0.17	0.78	0.00	0.00
e	8	1.72	0.22			0.99
Pooled e	9	1.89	0.21			
T	17	344.97				100.00



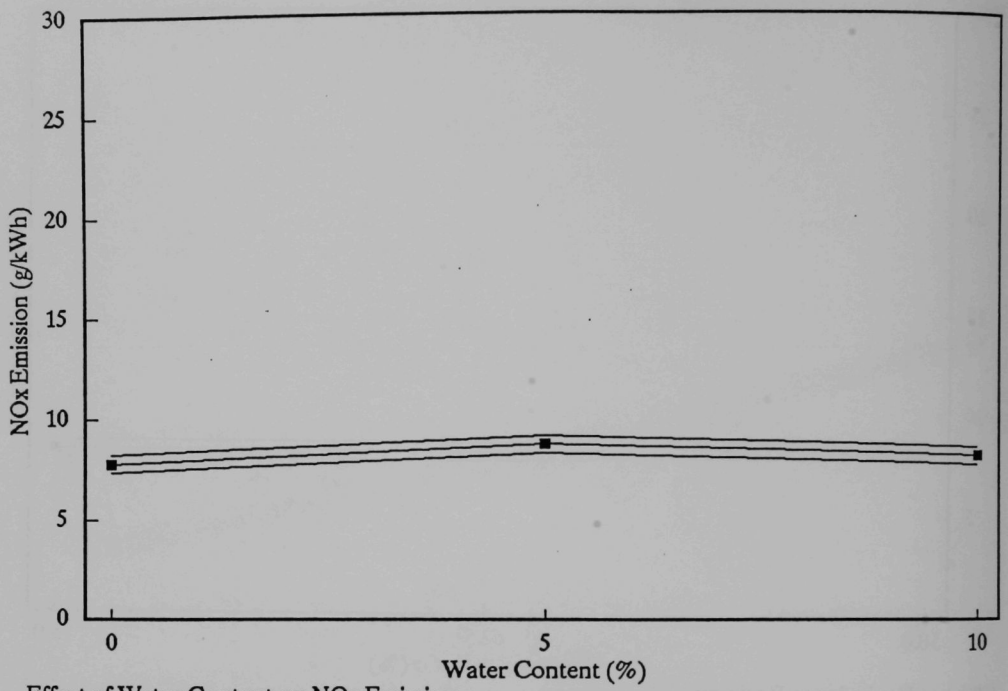
Effect of Injection Timing on NOx Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on NOx Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on NOx Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on NOx Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)

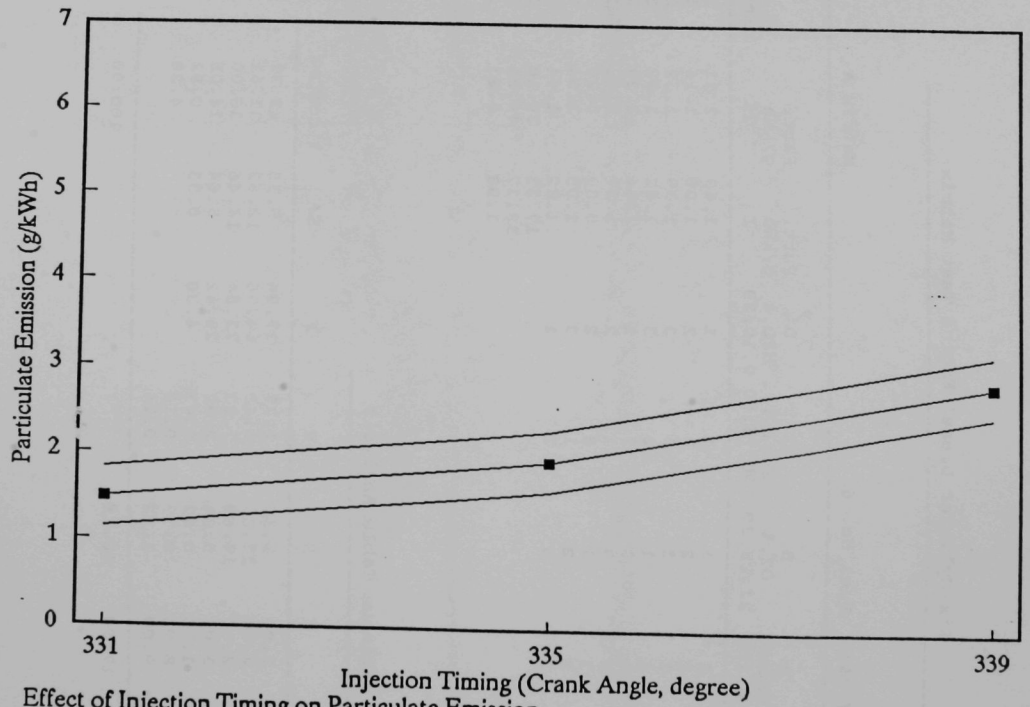
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

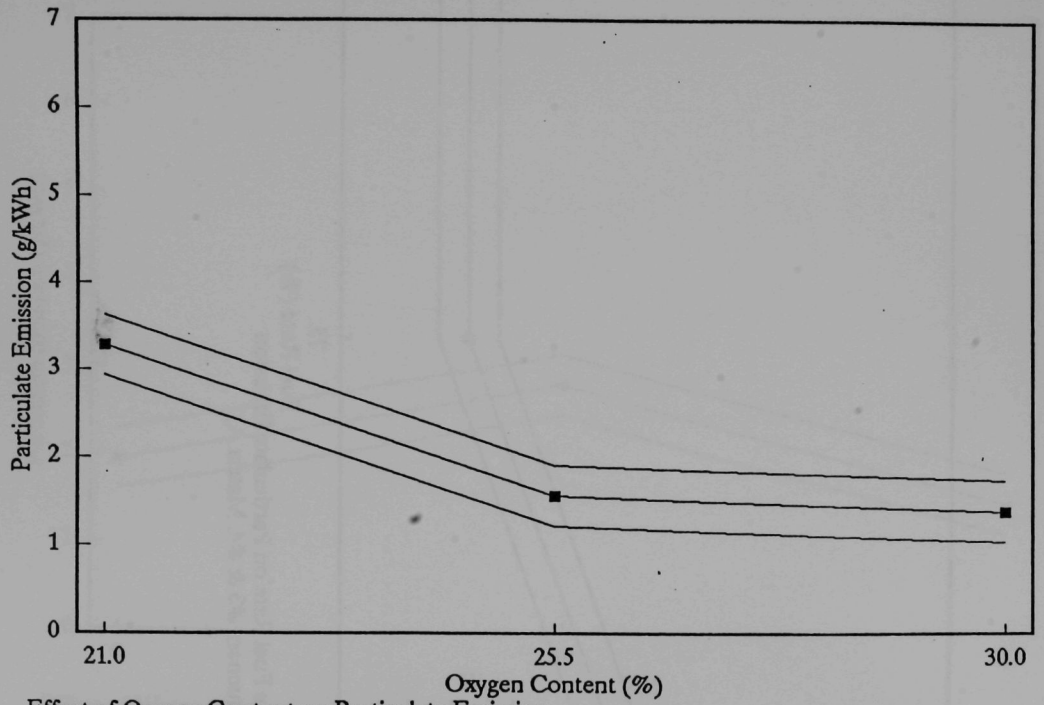
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Part. g/kWh I	Part. g/kWh II	Mean
1	1	1	1	1	1.69	2.11	1.49
2	1	2	2	2	1.06	1.16	1.93
3	1	3	3	3	1.39	1.52	2.82
4	2	1	2	3	1.82	1.92	3.27
5	2	2	3	1	1.84	3.29	1.57
6	2	3	1	2	1.27	1.42	1.39
7	3	1	3	2	5.89	6.20	1.43
8	3	2	1	3	1.05	1.04	1.45
9	3	3	2	1	1.32	1.44	3.36
Total					17.33	20.10	1.95
CF					33.37	44.89	2.83
Average					1.93	2.23	1.46

Variance Table Analysis

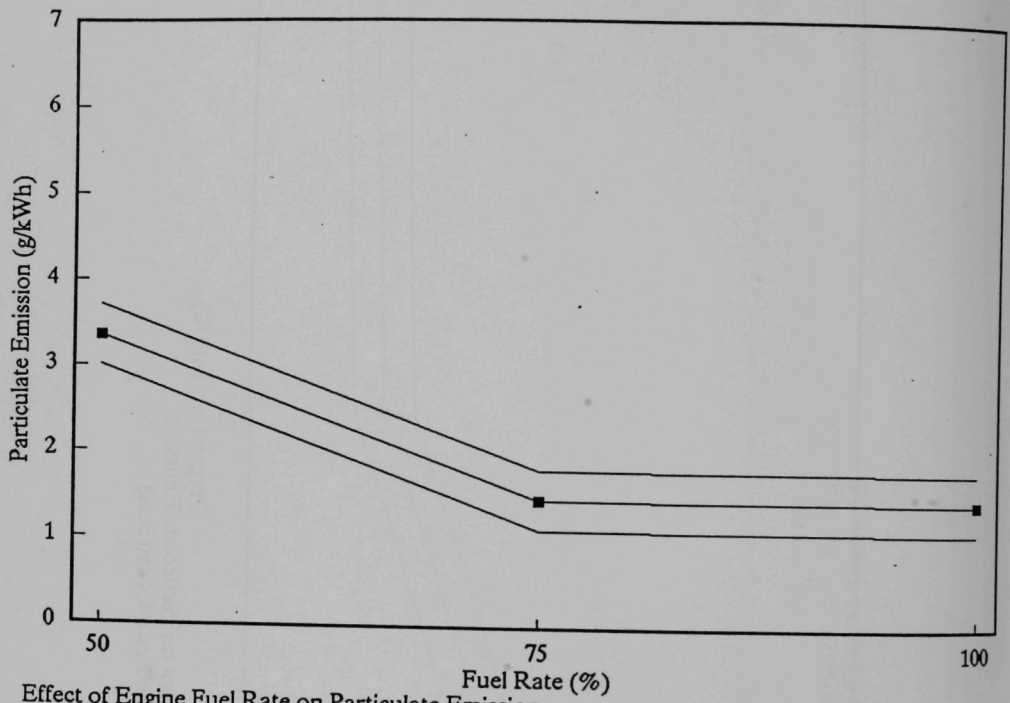
Source	f	S	V	F	S'	% contr.
Timing	2.00	5.55	2.77	27.96	5.35	13.33
Oxygen	2.00	12.89	6.45	64.96	12.69	31.61
Fuel	2.00	14.65	7.33	73.84	14.46	36.00
Water	2.00	5.84	2.92	29.42	5.64	14.05
Replicat.	1.00	0.43	0.43	4.30	0.33	0.82
e	8.00	0.79	0.10			4.20
Pooled e	9.00	1.22	0.14			
T	17.00	40.15				100.00



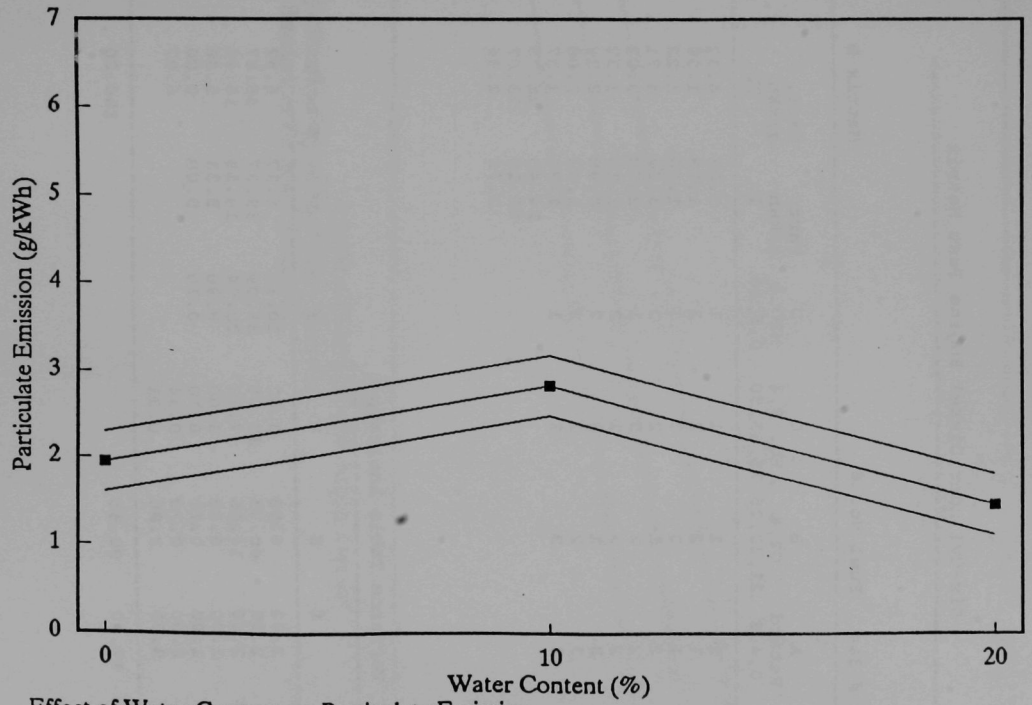
Effect of Injection Timing on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Engine Fuel Rate on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)

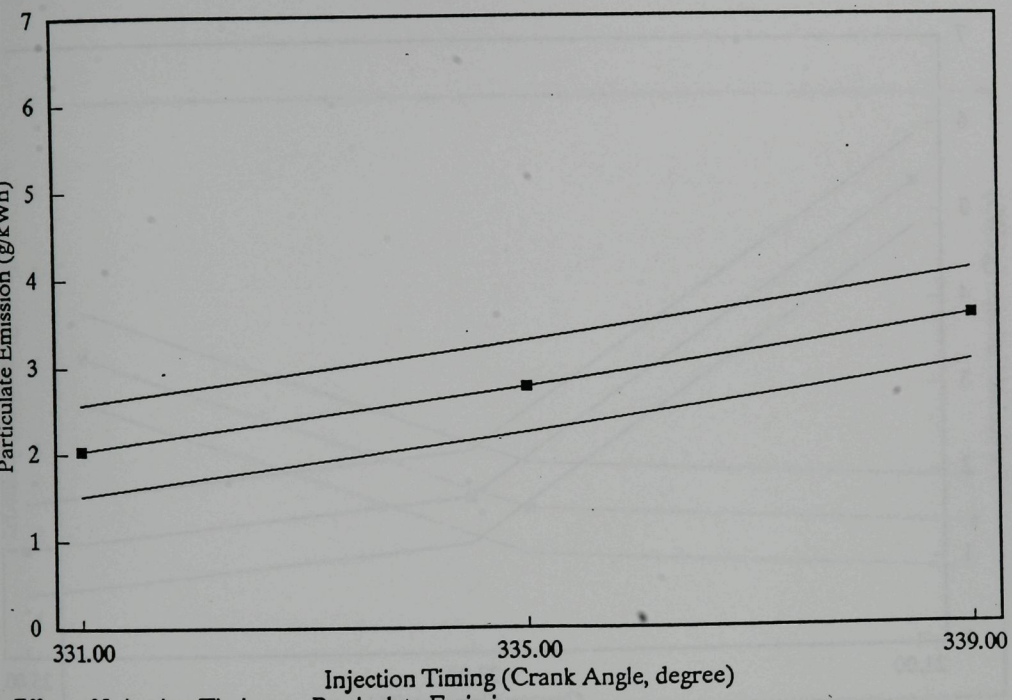
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

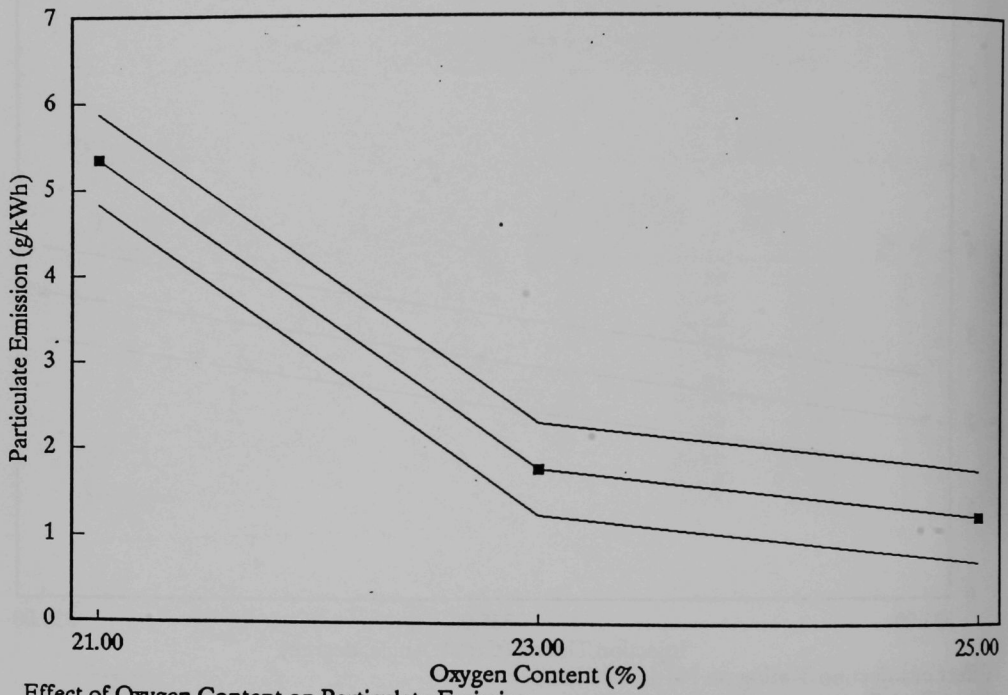
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Part. g/kWh I	Part. g/kWh II	Mean
1	1	1	1	1	3.03	4.32	2.04
2	1	2	2	2	1.19	1.38	2.77
3	1	3	3	3	1.10	1.22	3.55
4	2	1	2	3	3.69	4.71	5.35
5	2	2	3	1	2.70	3.02	1.78
6	2	3	1	2	1.16	1.32	1.23
7	3	1	3	2	8.98	7.36	2.03
8	3	2	1	3	1.32	1.05	2.26
9	3	3	2	1	1.22	1.37	4.06
Total					24.40	25.75	2.61
CF					66.15	73.67	3.56
Average					2.71	2.86	2.18

Variance Table Analysis

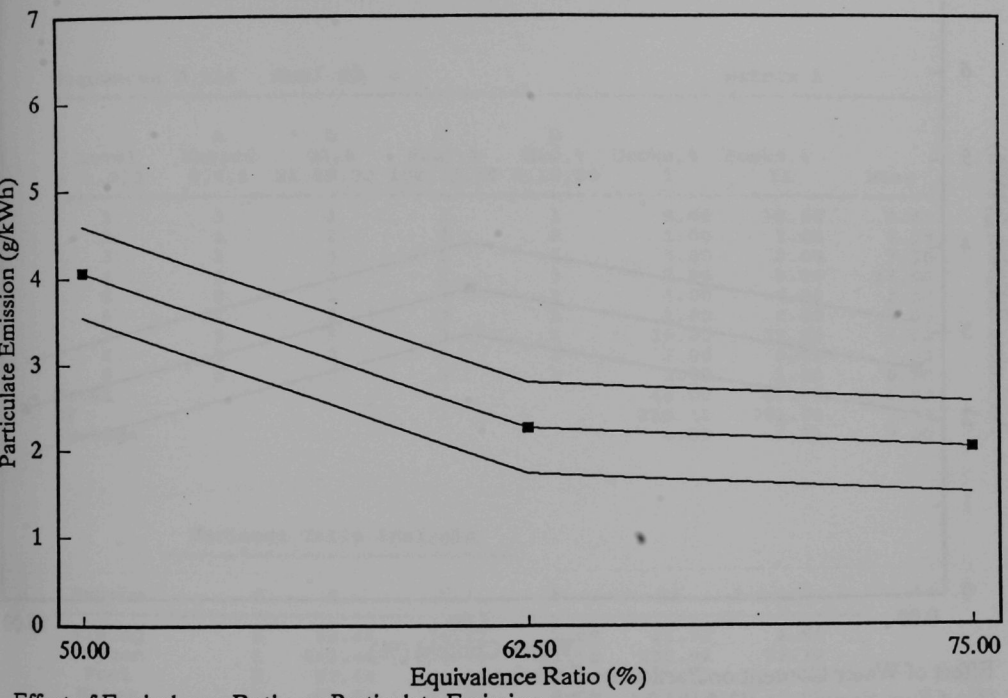
Source	f	S	V	F	S'	% contr.
Timing	2.00	6.85	3.42	10.16	6.17	6.82
Oxygen	2.00	60.05	30.02	89.09	59.37	65.57
Eq. R	2.00	14.86	7.43	22.04	14.18	15.66
Water	2.00	6.00	3.00	8.90	5.33	5.88
Replicat.	1.00	0.10	0.10	0.30	0.00	0.00
e	8.00	2.70	0.34			6.07
Pooled e	9.00	2.80	0.31			
T	17.00	90.55				100.00



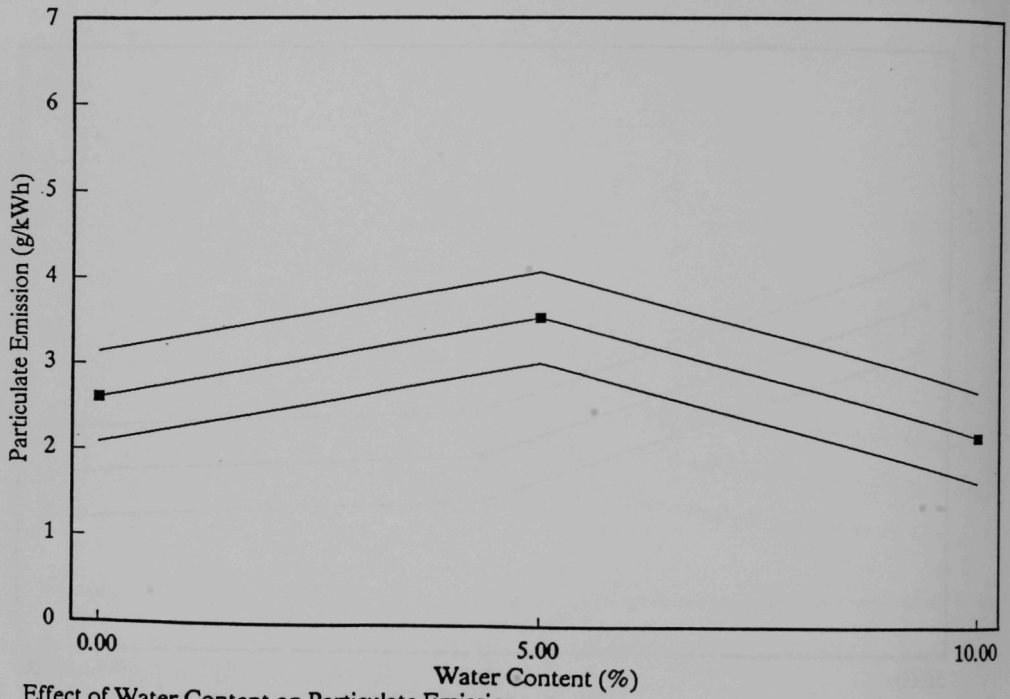
Effect of Injection Timing on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Particulate Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)

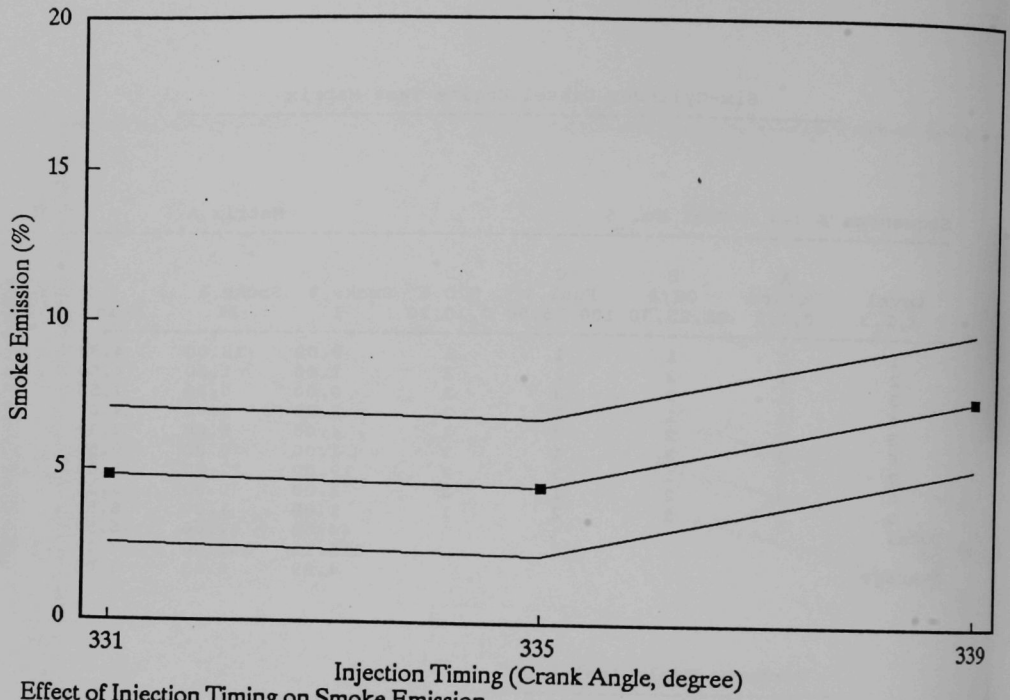
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

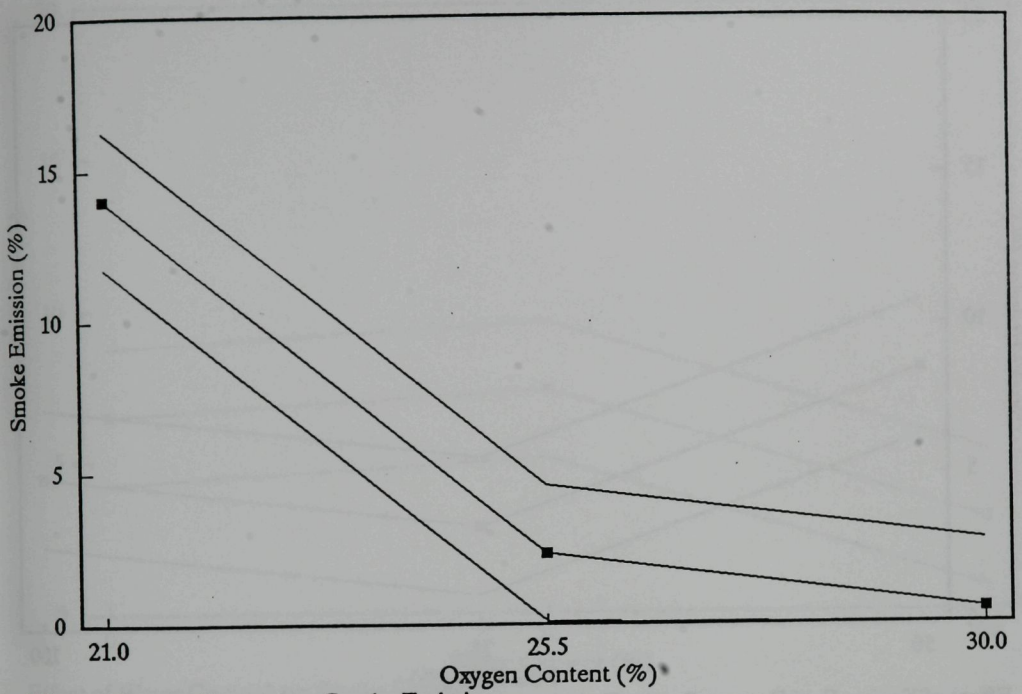
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Smoke,% I	Smoke,% II	Mean
1	1	1	1	1	9.00	18.00	4.83
2	1	2	2	2	1.00	1.00	4.50
3	1	3	3	3	0.00	0.00	7.50
4	2	1	2	3	7.00	9.00	14.00
5	2	2	3	1	4.00	6.00	2.33
6	2	3	1	2	1.00	0.00	0.50
7	3	1	3	2	19.00	22.00	5.00
8	3	2	1	3	2.00	0.00	3.33
9	3	3	2	1	1.00	1.00	8.50
Total					44.00	57.00	6.50
CF					215.11	361.00	7.33
Average					4.89	6.33	3.00

Variance Table Analysis

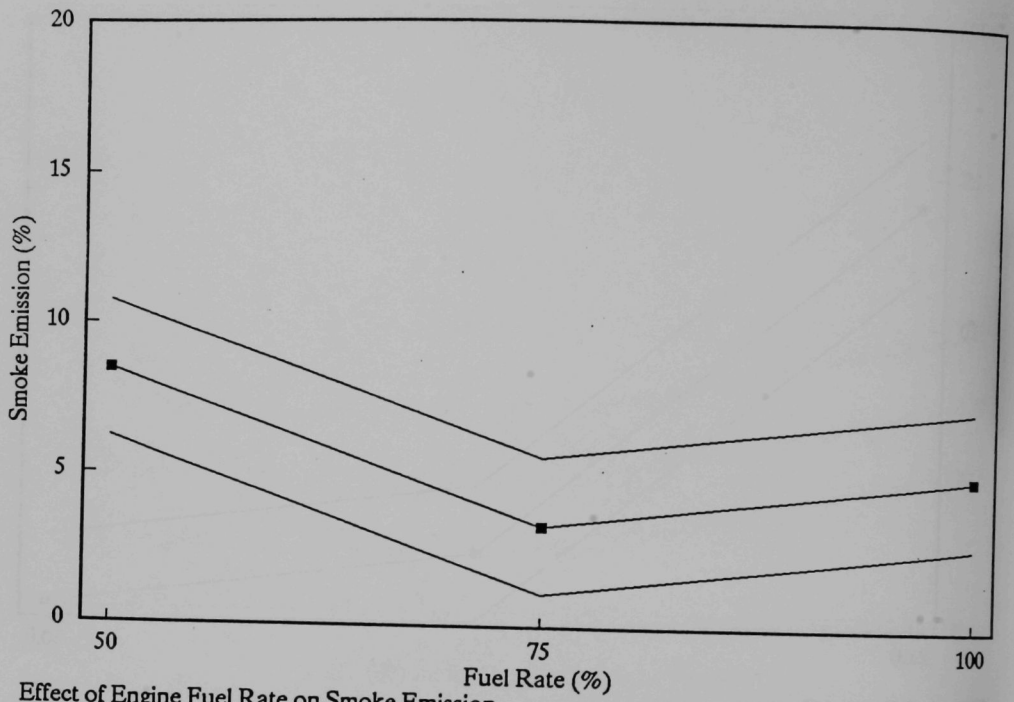
Source	f	S	V	F	S'	% contr.
Timing	2	32.44	16.22	3.08	21.92	2.51
Oxygen	2	643.44	321.72	61.12	632.92	72.39
Fuel	2	83.44	41.72	7.93	72.92	8.34
Water	2	63.44	31.72	6.03	52.92	6.05
Replicat.	1	9.39	9.39	1.78	4.13	0.47
e	8	42.11	5.26			10.24
Pooled e	9	51.50	5.72			
T	17	874.28				100.00



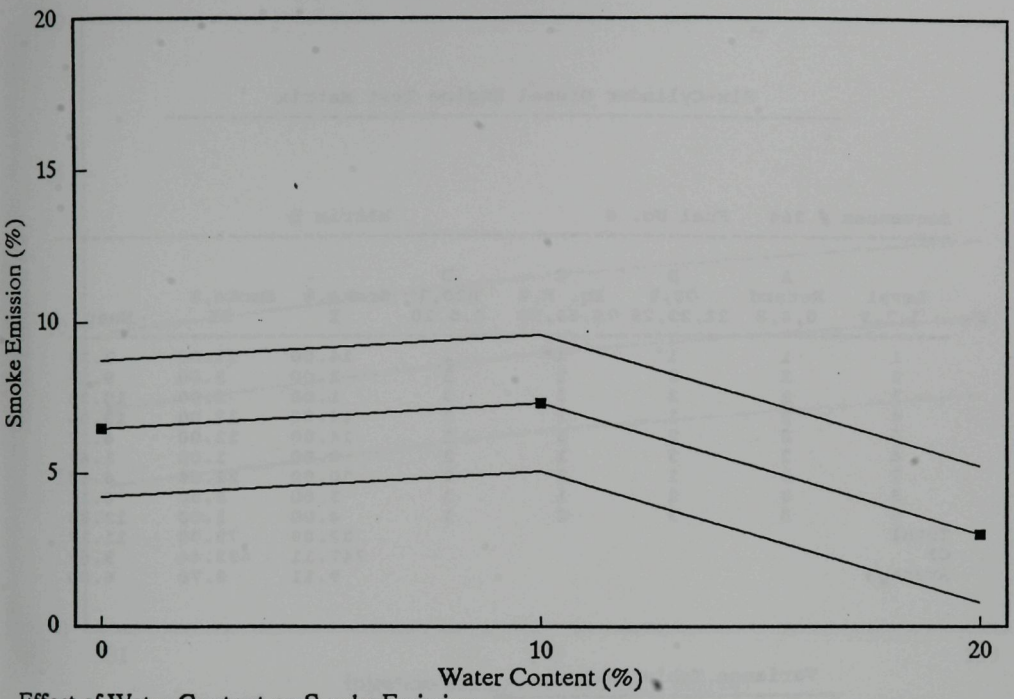
Effect of Injection Timing on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Engine Fuel Rate on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix A)

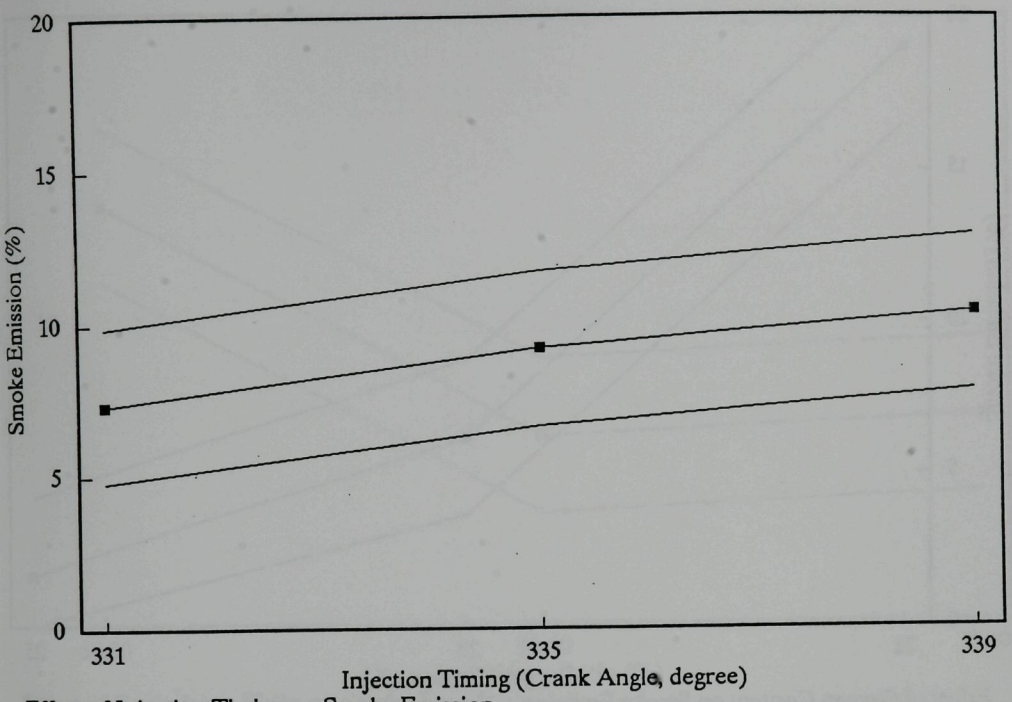
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

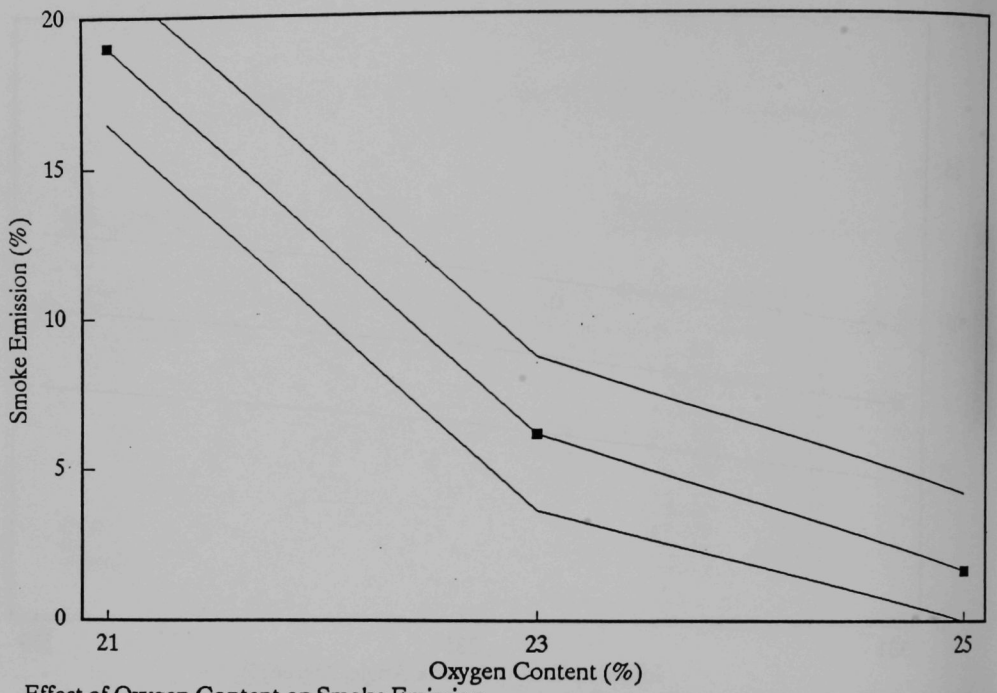
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Smoke,% I	Smoke,% II	Mean
1	1	1	1	1	14.00	21.00	7.33
2	1	2	2	2	2.00	3.00	9.17
3	1	3	3	3	1.00	3.00	10.33
4	2	1	2	3	14.00	13.00	19.00
5	2	2	3	1	14.00	13.00	6.17
6	2	3	1	2	0.00	1.00	1.67
7	3	1	3	2	30.00	22.00	6.83
8	3	2	1	3	3.00	2.00	6.17
9	3	3	2	1	4.00	1.00	13.83
Total					82.00	79.00	11.17
CF					747.11	693.44	9.67
Average					9.11	8.78	6.00

Variance Table Analysis

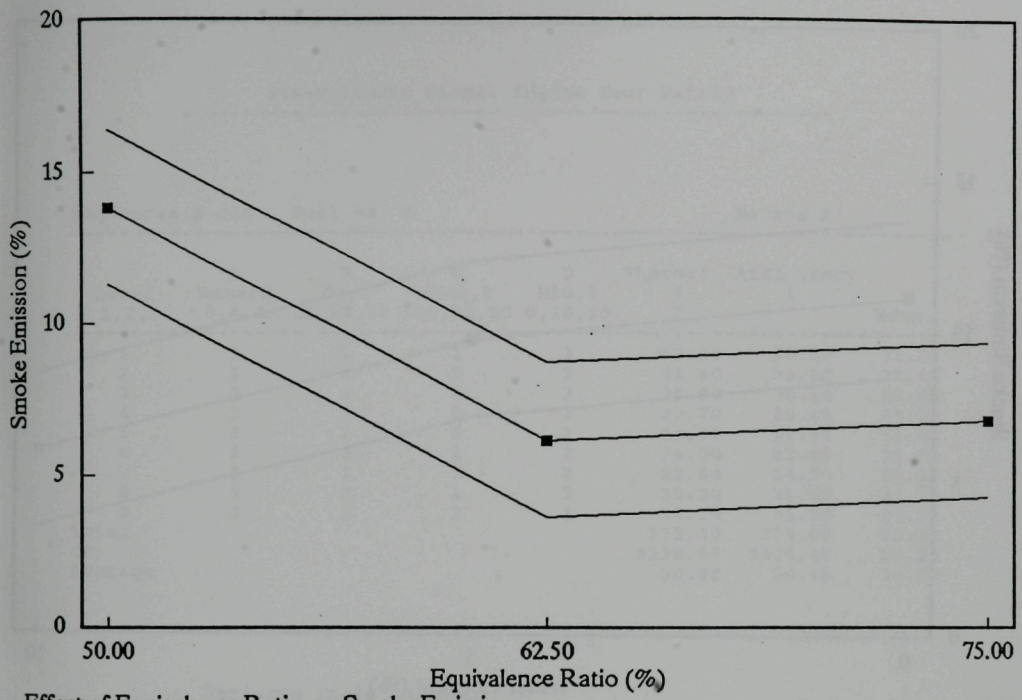
Source	f	S	V	F	S′	% contr.
Timing	2	27.44	13.72	1.69	11.19	0.82
Oxygen	2	970.78	485.39	59.74	954.53	69.93
Eq. R	2	216.44	108.22	13.32	200.19	14.67
Water	2	84.78	42.39	5.22	68.53	5.02
Replicat.	1	0.50	0.50	0.06	0.00	0.00
e	8	65.00	8.13			9.56
Pooled e	9	65.50	7.28			
T	17	1364.94				100.00



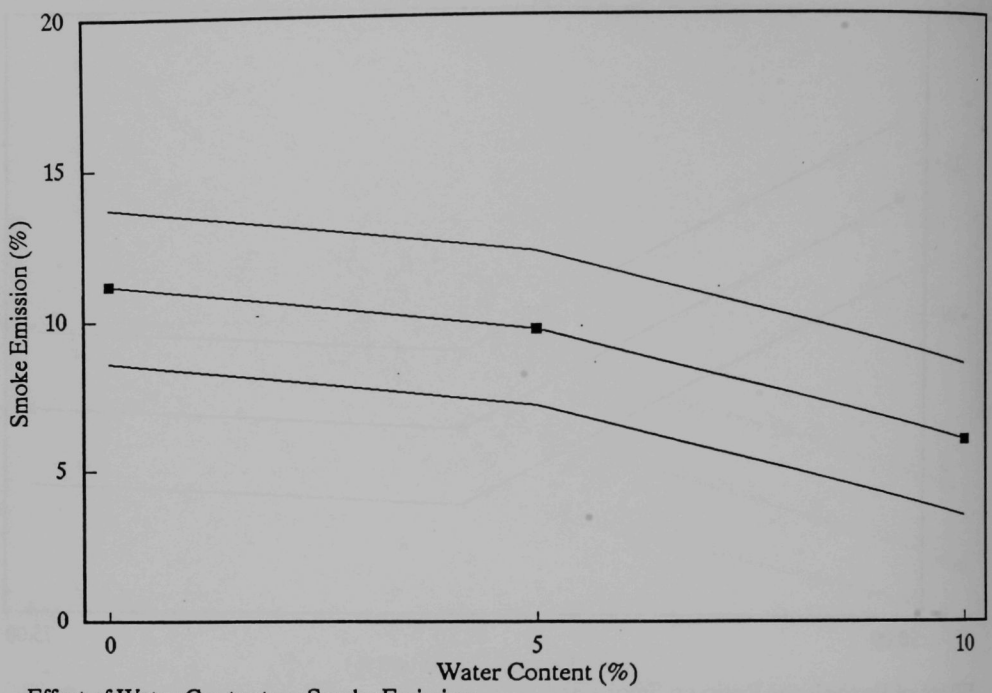
Effect of Injection Timing on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Smoke Emission
(No.6 Fuel, Sequences #3 & #4, Matrix B)

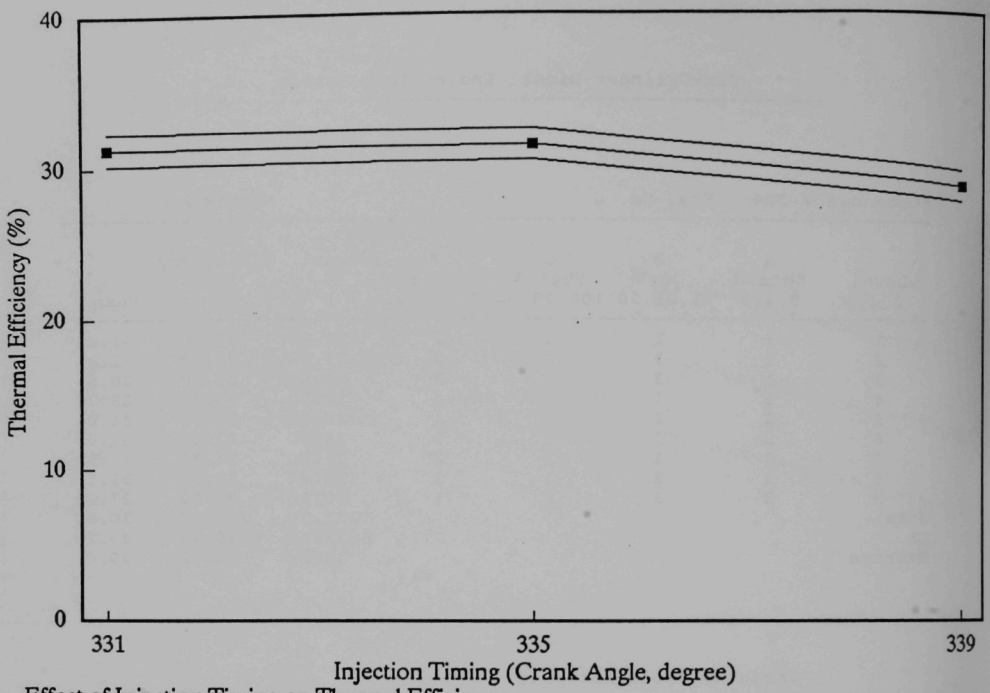
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

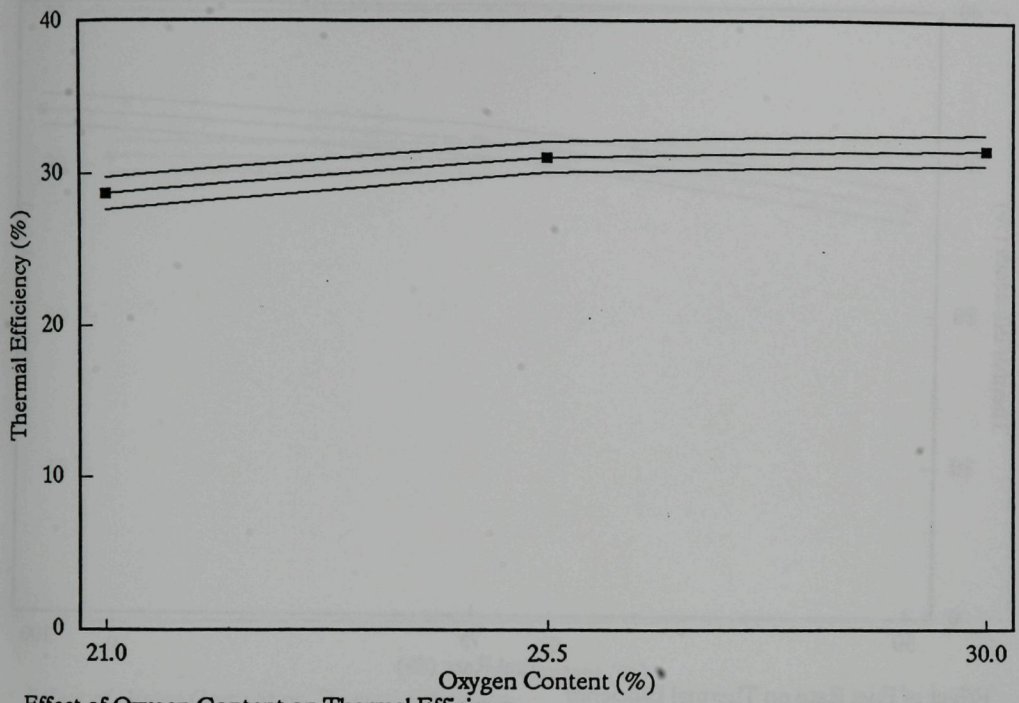
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Thermal % I	Efficiency % II	Mean
1	1	1	1	1	32.20	32.00	31.23
2	1	2	2	2	31.40	33.10	31.43
3	1	3	3	3	28.60	30.10	28.65
4	2	1	2	3	30.70	30.40	28.70
5	2	2	3	1	29.80	27.90	31.00
6	2	3	1	2	36.00	33.80	31.62
7	3	1	3	2	22.60	24.30	32.97
8	3	2	1	3	30.90	32.90	31.13
9	3	3	2	1	30.10	31.10	27.22
Total					272.30	275.60	30.52
CF					8238.59	8439.48	30.20
Average					30.26	30.62	30.60

Variance Table Analysis

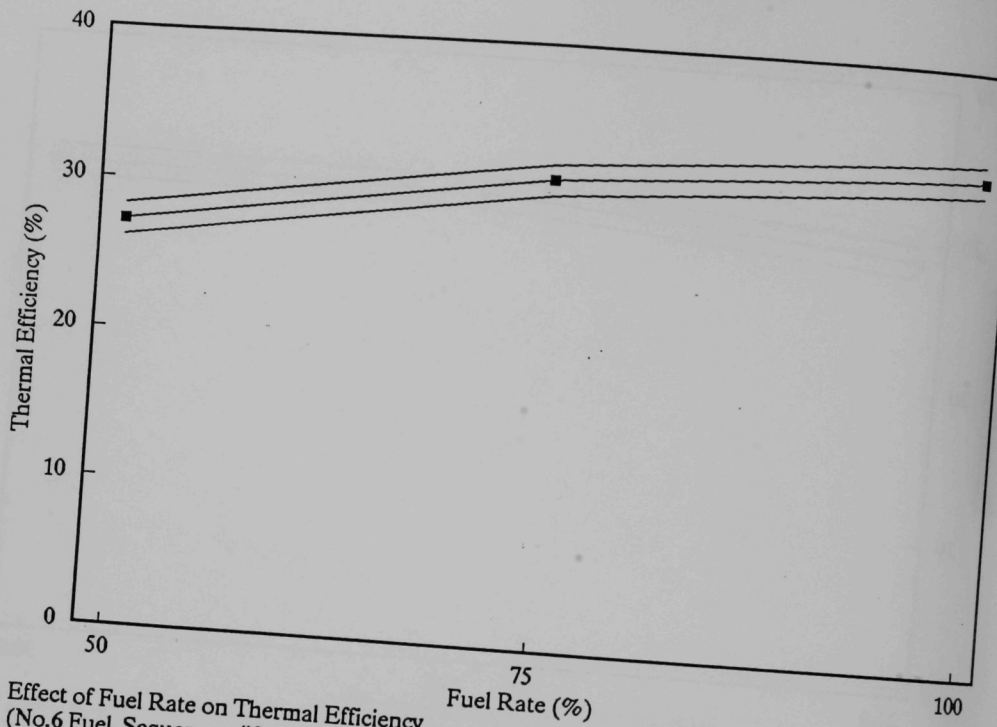
Source	f	S	V	F	S′	% contr.
Timing	2	28.92	14.46	11.34	26.37	15.32
Oxygen	2	28.35	14.18	11.12	25.80	14.99
Fuel	2	103.53	51.76	40.60	100.98	58.66
Water	2	0.53	0.27	0.21	-2.02	-1.17
Replicat.	1	0.60	0.60	0.47	0.00	0.00
e	8	10.20	1.28			12.20
Pooled e	9	10.81	1.20			
T	17	172.14				100.00



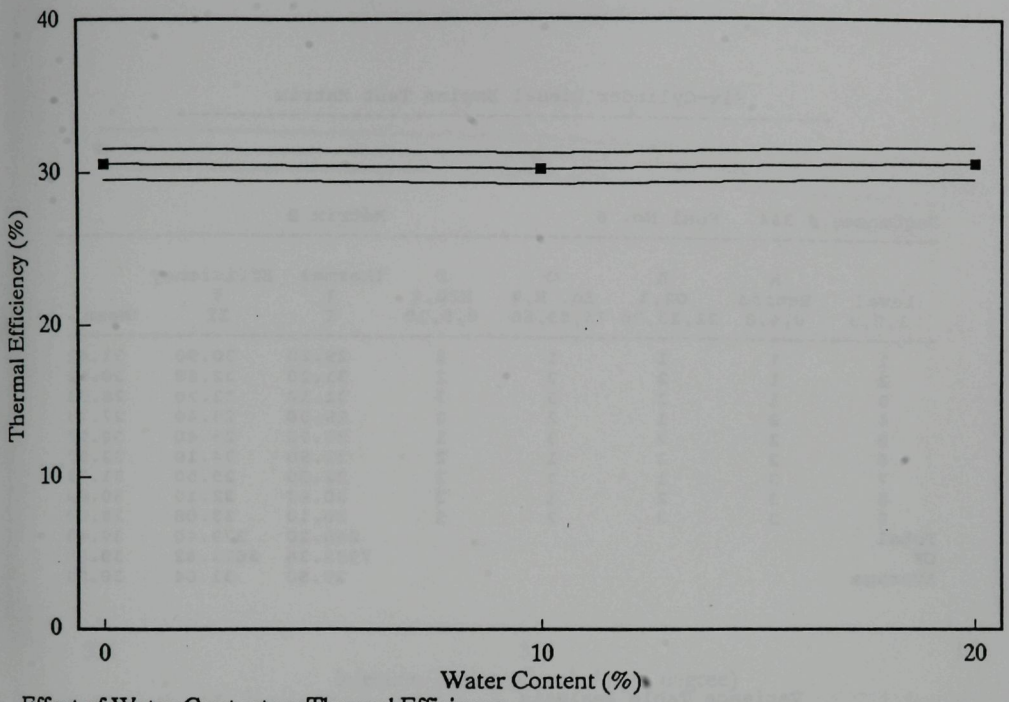
Effect of Injection Timing on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Fuel Rate on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix A)

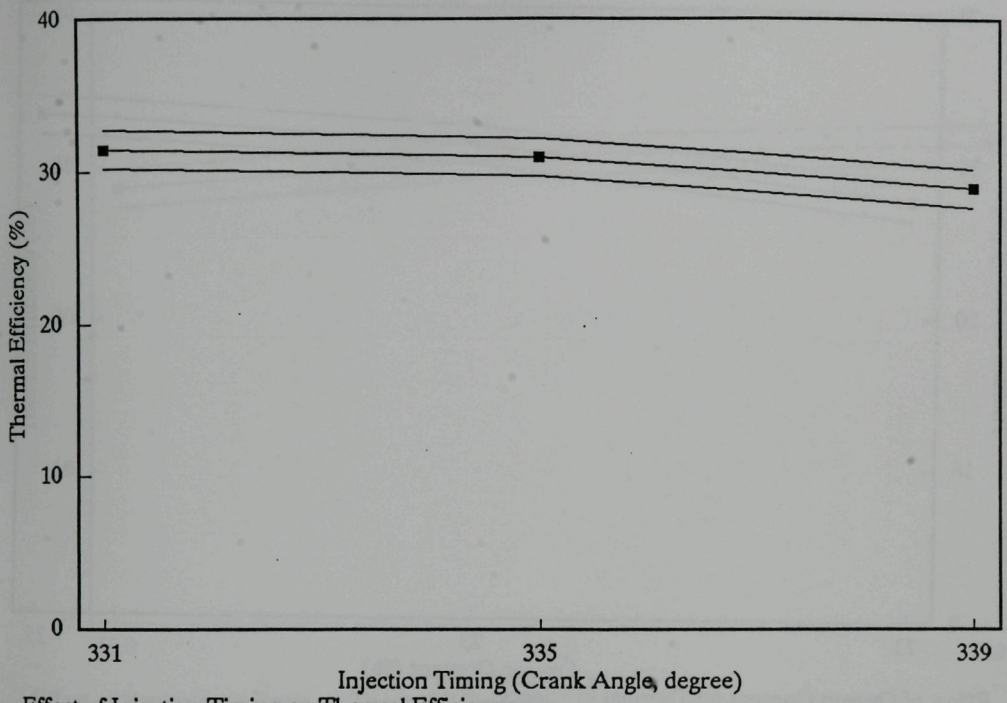
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

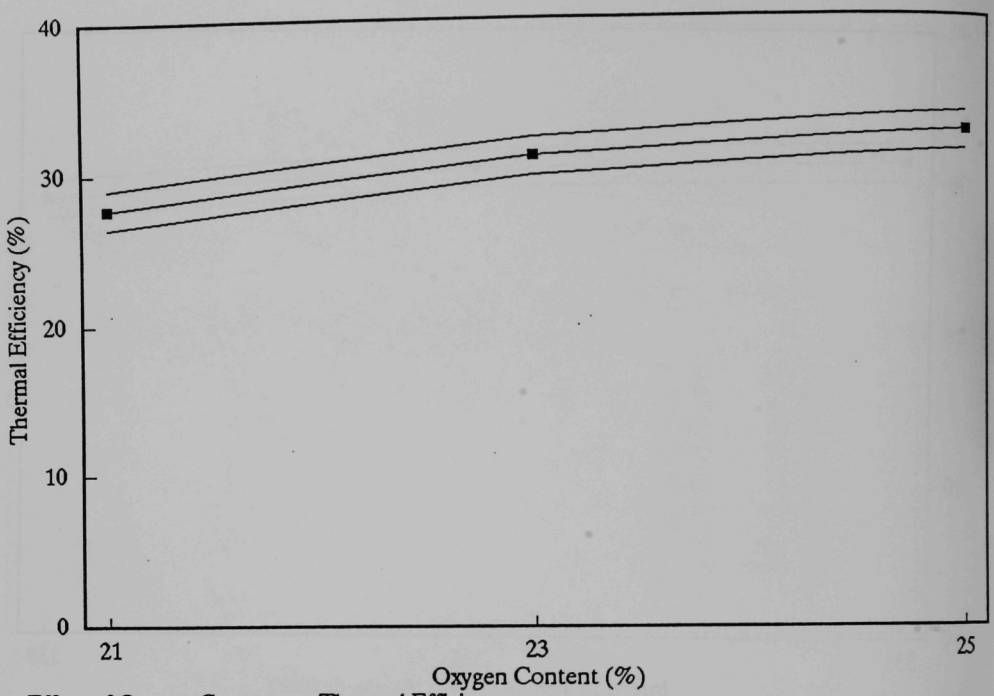
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Thermal % I	Efficiency % II	Mean
1	1	1	1	1	29.30	30.90	31.42
2	1	2	2	2	31.20	32.80	30.92
3	1	3	3	3	31.10	33.20	28.93
4	2	1	2	3	29.80	28.40	27.73
5	2	2	3	1	29.90	29.40	30.97
6	2	3	1	2	33.90	34.10	32.57
7	3	1	3	2	22.50	25.50	31.78
8	3	2	1	3	30.40	32.10	30.88
9	3	3	2	1	30.10	33.00	28.60
Total					268.20	279.40	30.43
CF					7992.36	8673.82	30.00
Average					29.80	31.04	30.83

Variance Table Analysis

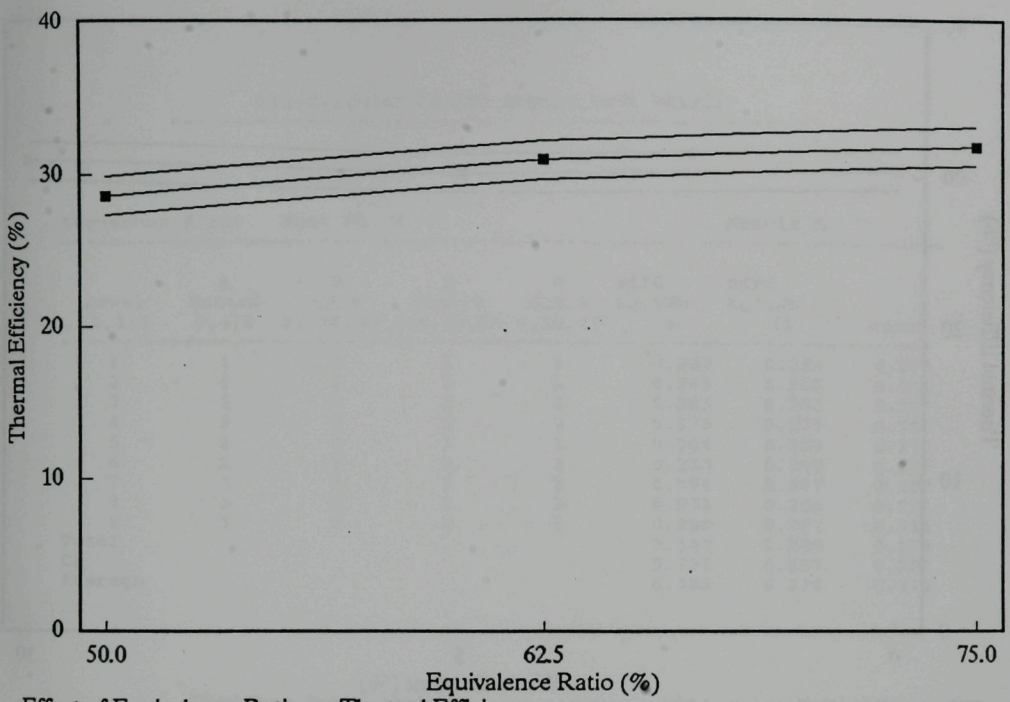
Source	f	S	V	F	S′	% contr.
Timing	2	20.70	10.35	9.13	18.43	12.81
Oxygen	2	72.75	36.38	32.08	70.48	48.98
Eq. R	2	32.31	16.16	14.25	30.05	20.88
Water	2	2.08	1.04	0.92	-0.18	-0.13
Replicat.	1	6.97	6.97	6.15	5.84	4.06
e	8	9.07	1.13			13.40
Pooled e	9	16.04	1.78			
T	17	143.89				100.00



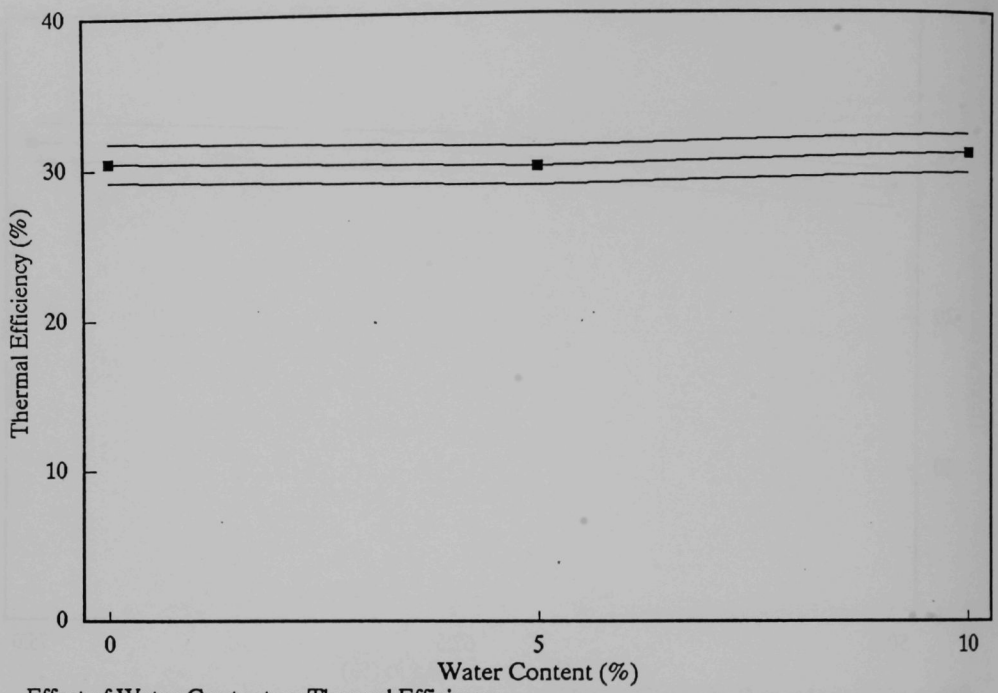
Effect of Injection Timing on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Thermal Efficiency
(No.6 Fuel, Sequences #3 & #4, Matrix B)

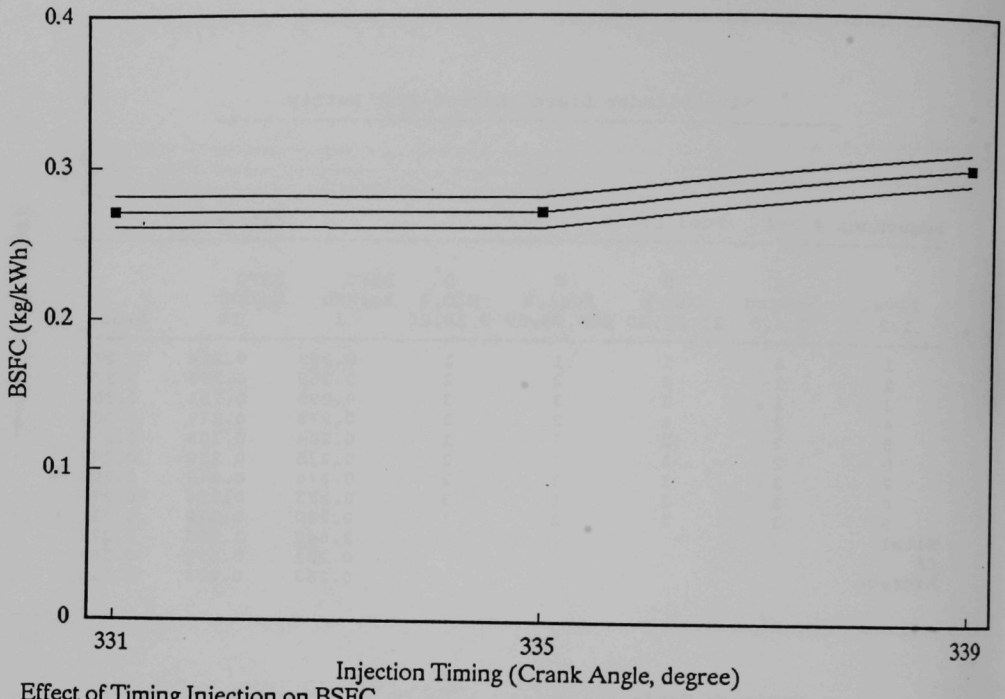
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

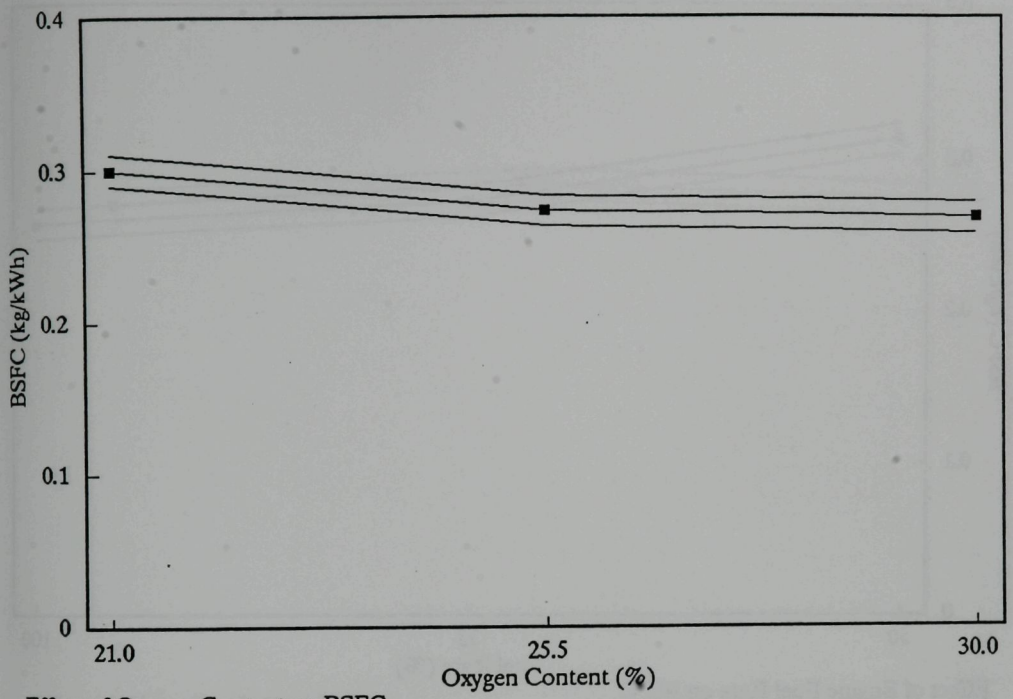
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	BSFC kg/kWh I	BSFC kg/kWh II	Mean
1	1	1	1	1	0.263	0.264	0.271
2	1	2	2	2	0.269	0.255	0.271
3	1	3	3	3	0.295	0.281	0.300
4	2	1	2	3	0.275	0.277	0.300
5	2	2	3	1	0.284	0.303	0.273
6	2	3	1	2	0.235	0.250	0.269
7	3	1	3	2	0.374	0.347	0.257
8	3	2	1	3	0.273	0.256	0.271
9	3	3	2	1	0.280	0.272	0.314
Total					2.548	2.505	0.278
CF					0.721	0.697	0.288
Average					0.283	0.278	0.276

Variance Table Analysis

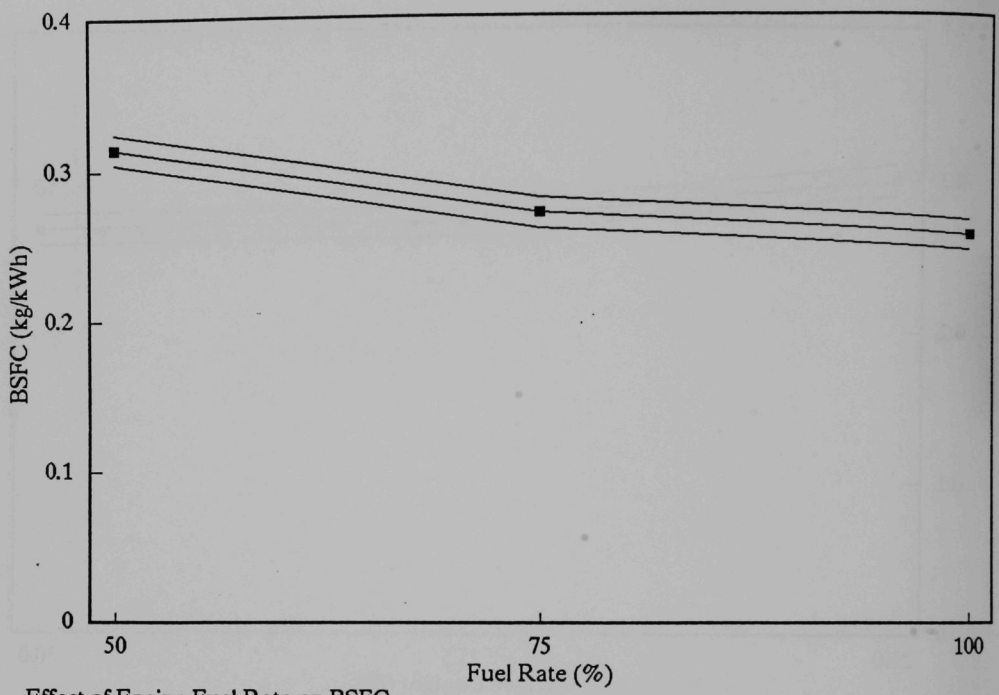
Source	f	S	V	F	S′	% contr.
Timing	2	3.46E-03	1.73E-03	1.49E+01	3.23E-03	16.98
Oxygen	2	3.41E-03	1.70E-03	1.47E+01	3.17E-03	16.68
Fuel	2	1.06E-02	5.30E-03	4.56E+01	1.04E-02	54.48
Water	2	5.28E-04	2.64E-04	2.27E+00	2.96E-04	1.55
Replicat.	1	1.03E-04	1.03E-04	8.84E-01	0.00E+00	0.00
e	8	9.30E-04	1.16E-04			10.31
Pooled e	9	1.03E-03	1.15E-04			
T	17	1.90E-02				100.00



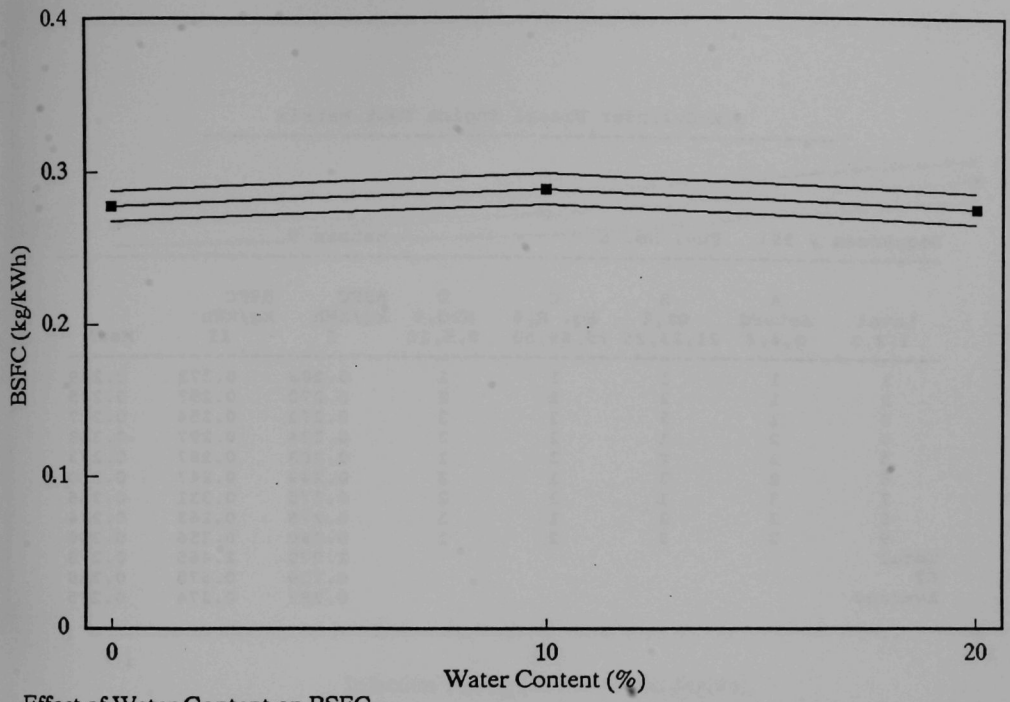
Effect of Timing Injection on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Engine Fuel Rate on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix A)

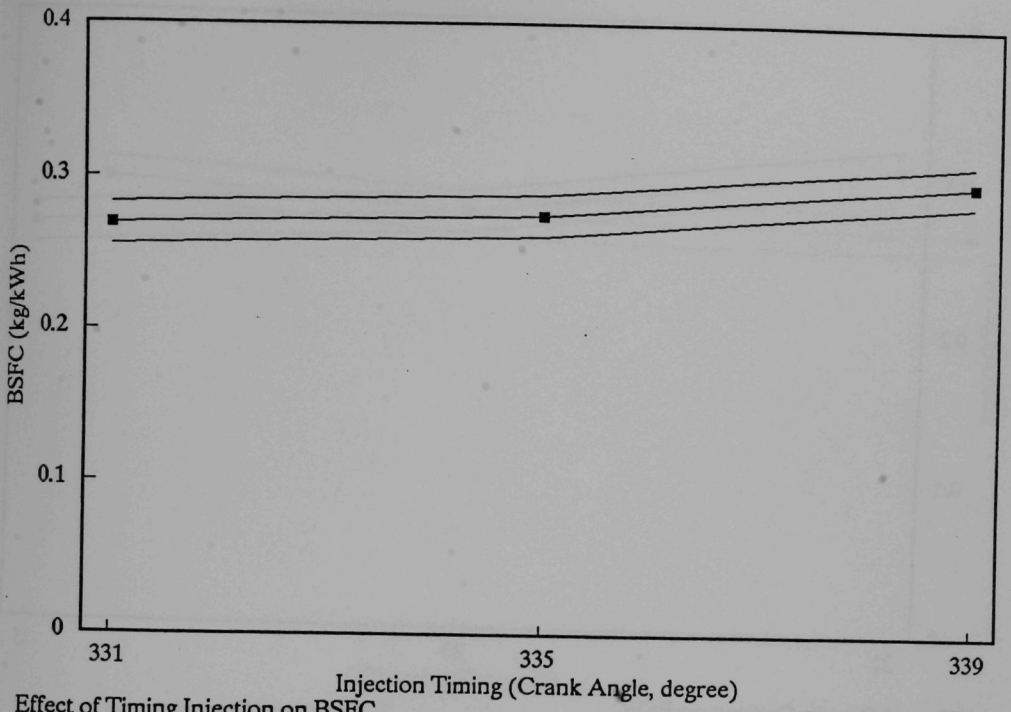
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

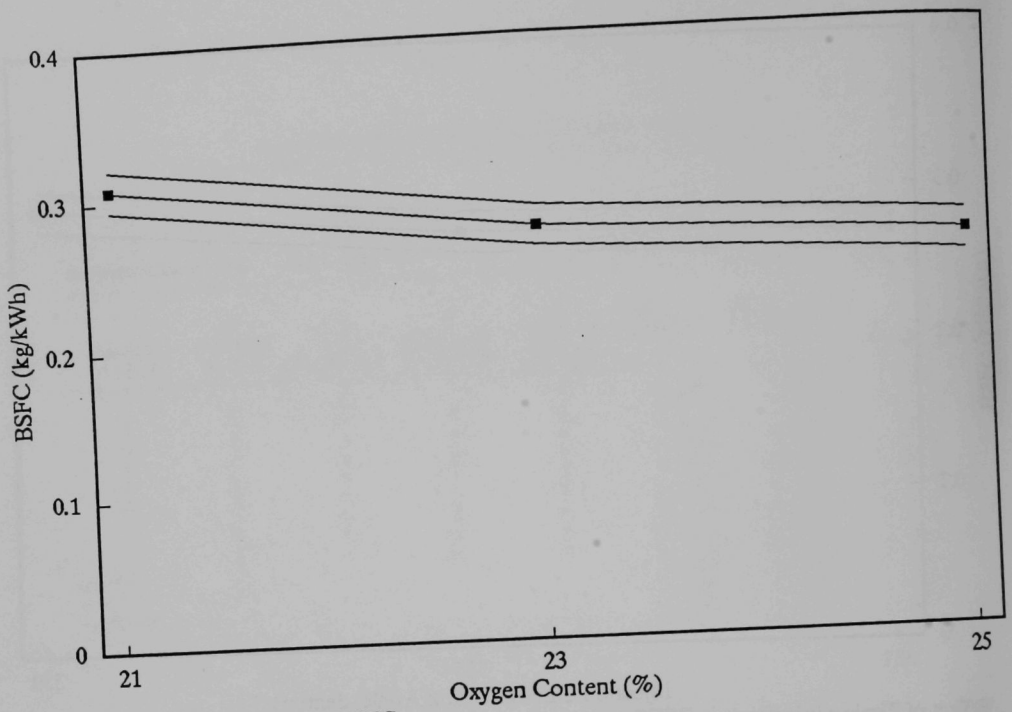
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	BSFC kg/kWh I	BSFC kg/kWh II	Mean
1	1	1	1	1	0.288	0.273	0.269
2	1	2	2	2	0.270	0.257	0.275
3	1	3	3	3	0.272	0.254	0.297
4	2	1	2	3	0.284	0.297	0.308
5	2	2	3	1	0.283	0.287	0.273
6	2	3	1	2	0.249	0.247	0.260
7	3	1	3	2	0.375	0.331	0.266
8	3	2	1	3	0.278	0.263	0.274
9	3	3	2	1	0.280	0.256	0.300
Total					2.579	2.465	0.278
CF					0.739	0.675	0.288
Average					0.287	0.274	0.275

Variance Table Analysis

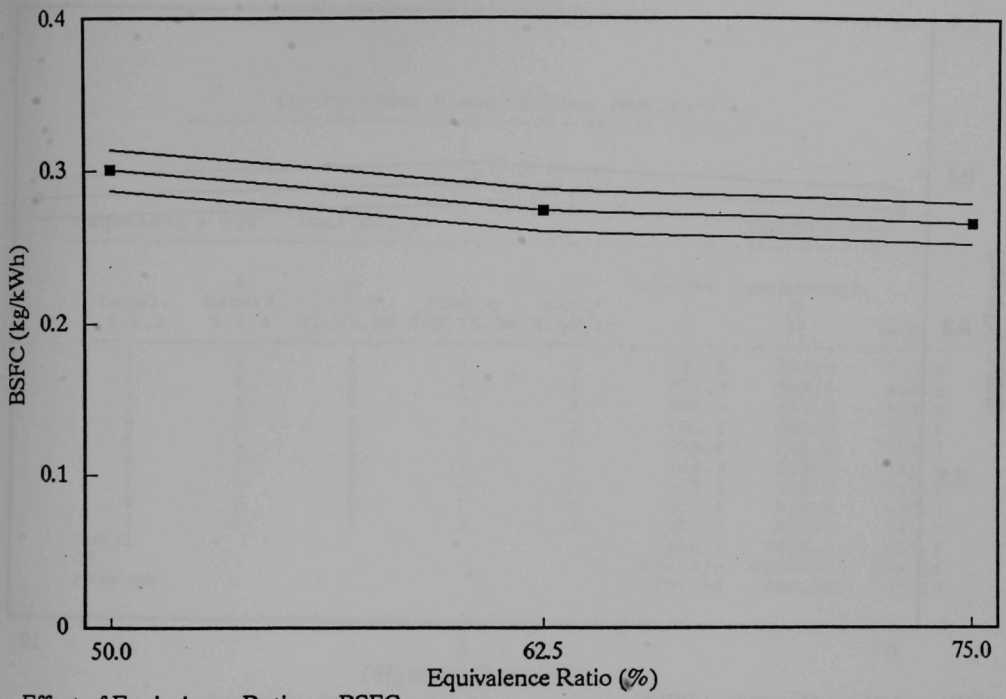
Source	f	S	V	F	S'	% contr.
Timing	2	2.67E-03	1.34E-03	9.73E+00	2.40E-03	14.64
Oxygen	2	7.48E-03	3.74E-03	2.72E+01	7.20E-03	43.95
Eq. R	2	3.82E-03	1.91E-03	1.39E+01	3.54E-03	21.61
Water	2	5.98E-04	2.99E-04	2.17E+00	3.23E-04	1.97
Replicat.	1	7.22E-04	7.22E-04	5.25E+00	5.85E-04	3.57
e	8	1.10E-03	1.37E-04			14.26
Pooled e	9	1.82E-03	2.02E-04			
T	17	1.64E-02				100.00



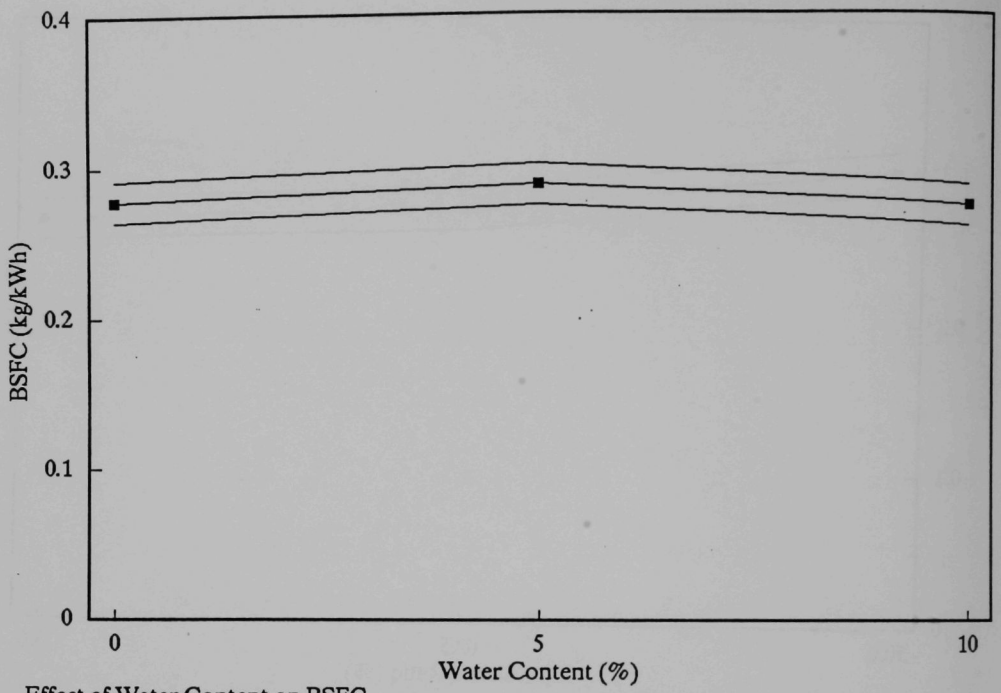
Effect of Timing Injection on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on BSFC
(No.6 Fuel, Sequences #3 & #4, Matrix B)

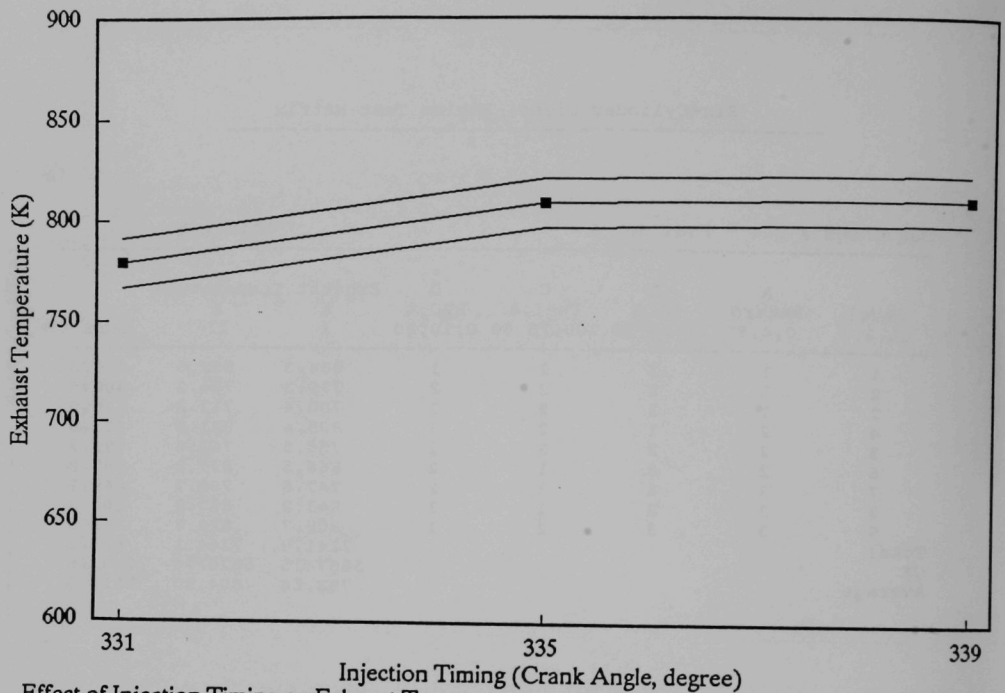
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

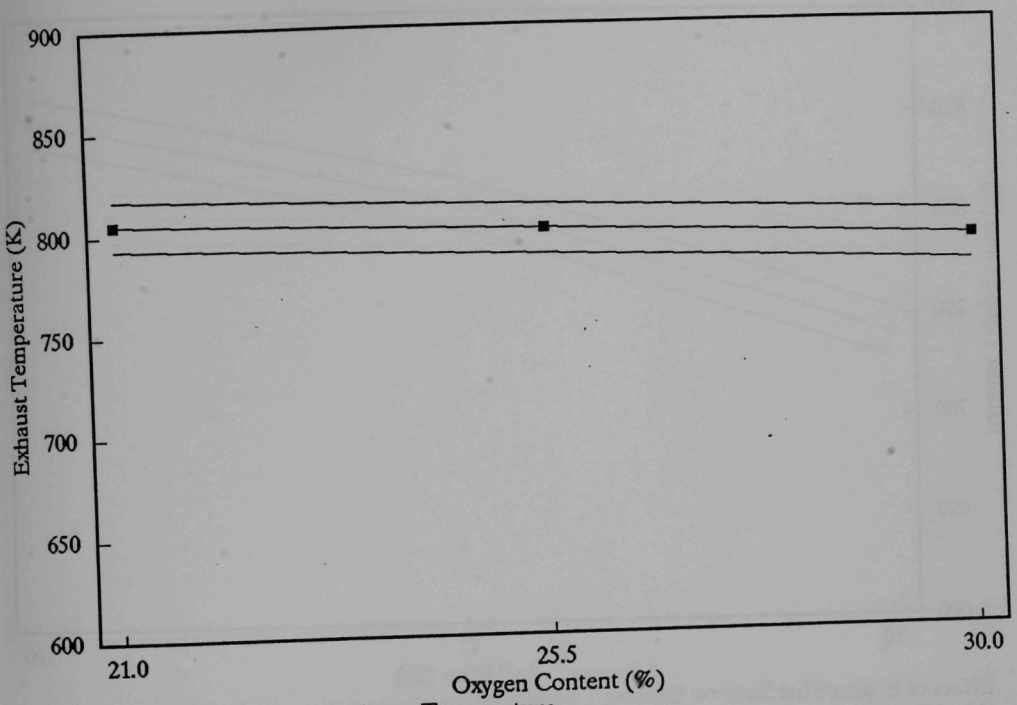
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Exhaust Temperature K I	K II	Mean
1	1	1	1	1	834.3	852.6	779.0
2	1	2	2	2	779.3	794.3	808.6
3	1	3	3	3	700.4	713.2	810.0
4	2	1	2	3	805.4	821.5	805.0
5	2	2	3	1	756.5	762.6	799.9
6	2	3	1	2	866.5	839.3	792.8
7	3	1	3	2	747.6	768.7	849.9
8	3	2	1	3	843.2	863.2	806.3
9	3	3	2	1	808.7	828.7	741.5
Total					7141.9	7244.1	807.2
CF					5667415	5830776	799.28
Average					793.54	804.90	791.15

Variance Table Analysis

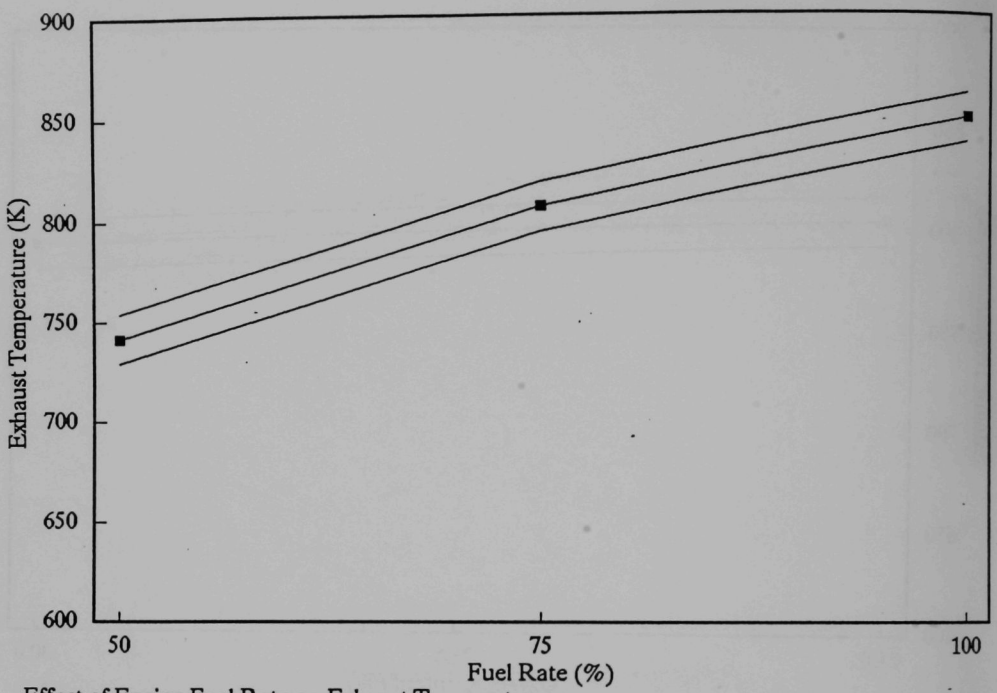
Source	f	S	V	F	S'	% contr.
Timing	2	3680.12	1840.06	15.96	3449.54	8.20
Oxygen	2	451.29	225.64	1.96	220.70	0.52
Fuel	2	35672.15	17836.07	154.70	35441.56	84.22
Water	2	776.05	388.03	3.37	545.47	1.30
Replicat.	1	580.27	580.27	5.03	464.98	1.10
e	8	922.33	115.29			4.66
Pooled e	9	1502.60	166.96			
T	17	42082.21				100.00



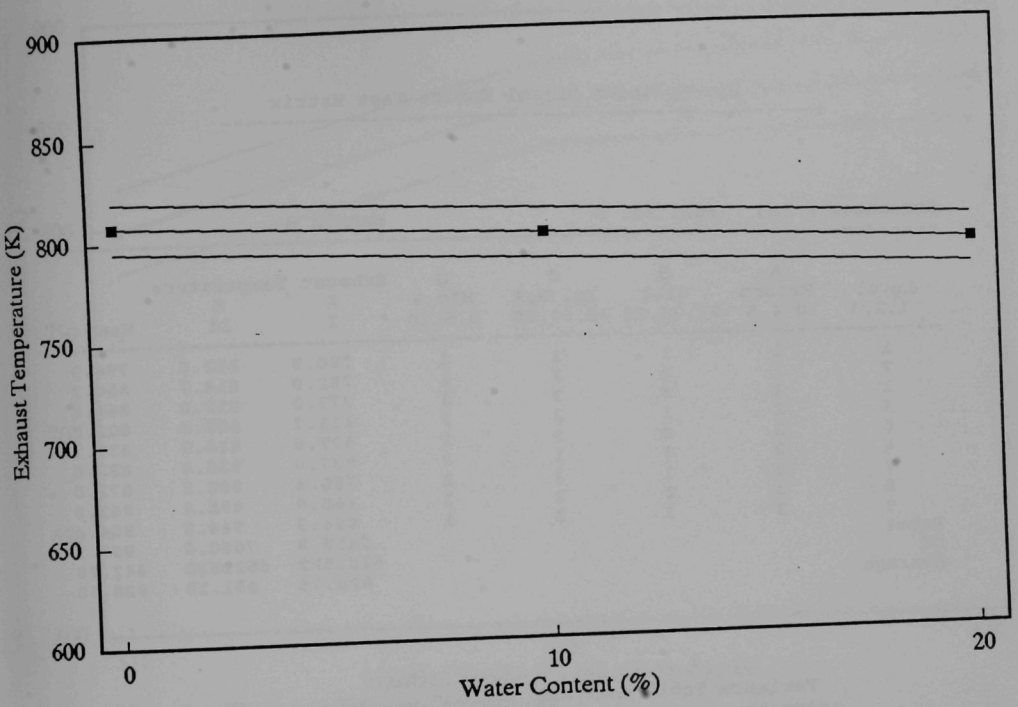
Effect of Injection Timing on Exhaust Temperature
(No.6 Fuel Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Exhaust Temperature
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Engine Fuel Rate on Exhaust Temperature
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Exhaust Temperature
(No.6 Fuel, Sequences #3 & #4, Matrix A)

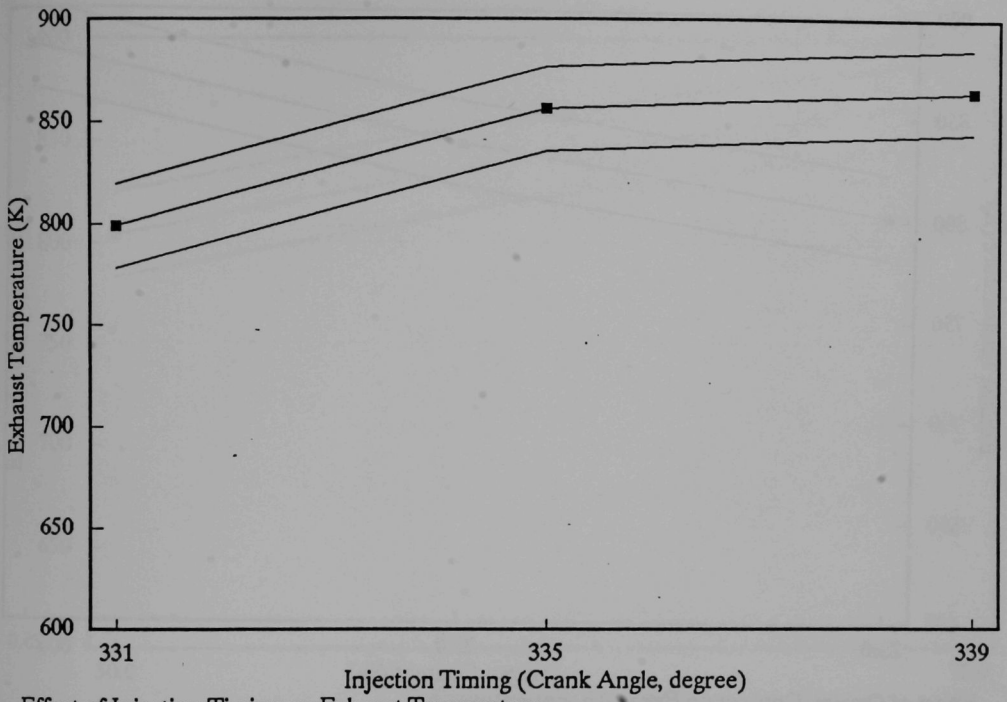
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

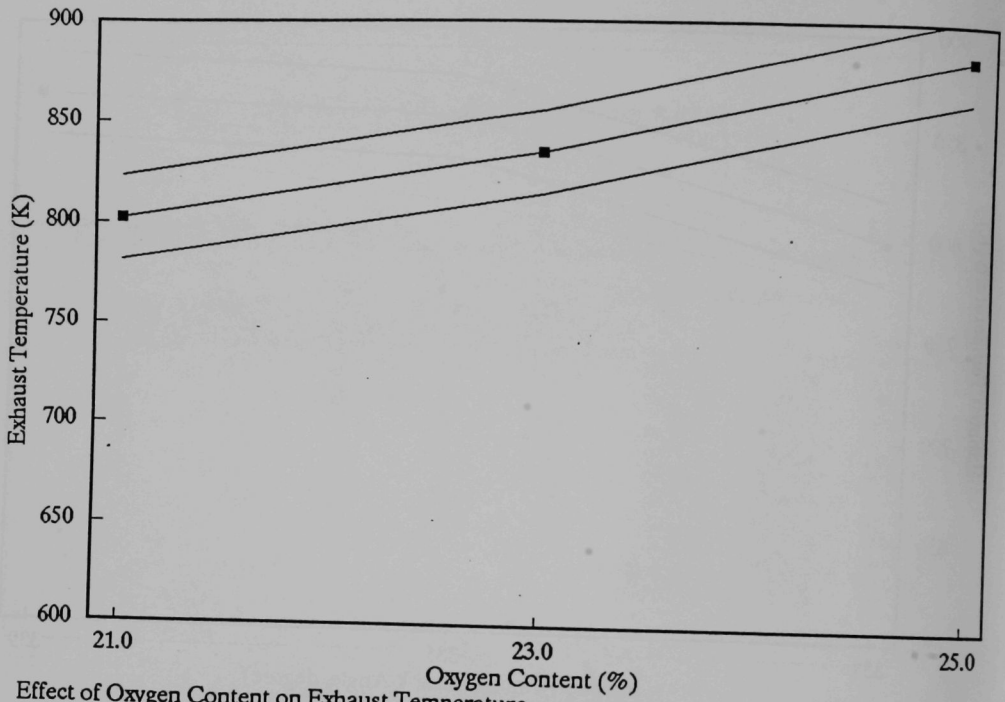
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Exhaust Temperature K I	K II	Mean
1	1	1	1	1	780.9	822.6	798.9
2	1	2	2	2	782.0	818.7	856.2
3	1	3	3	3	777.0	812.0	864.8
4	2	1	2	3	813.7	807.6	802.2
5	2	2	3	1	827.6	820.9	835.1
6	2	3	1	2	937.0	930.4	882.6
7	3	1	3	2	780.4	808.2	872.0
8	3	2	1	3	865.9	895.4	843.5
9	3	3	2	1	894.3	944.8	804.4
Total					7458.8	7660.6	848.5
CF					6181522	6520532	842.78
Average					828.76	851.18	828.60

Variance Table Analysis

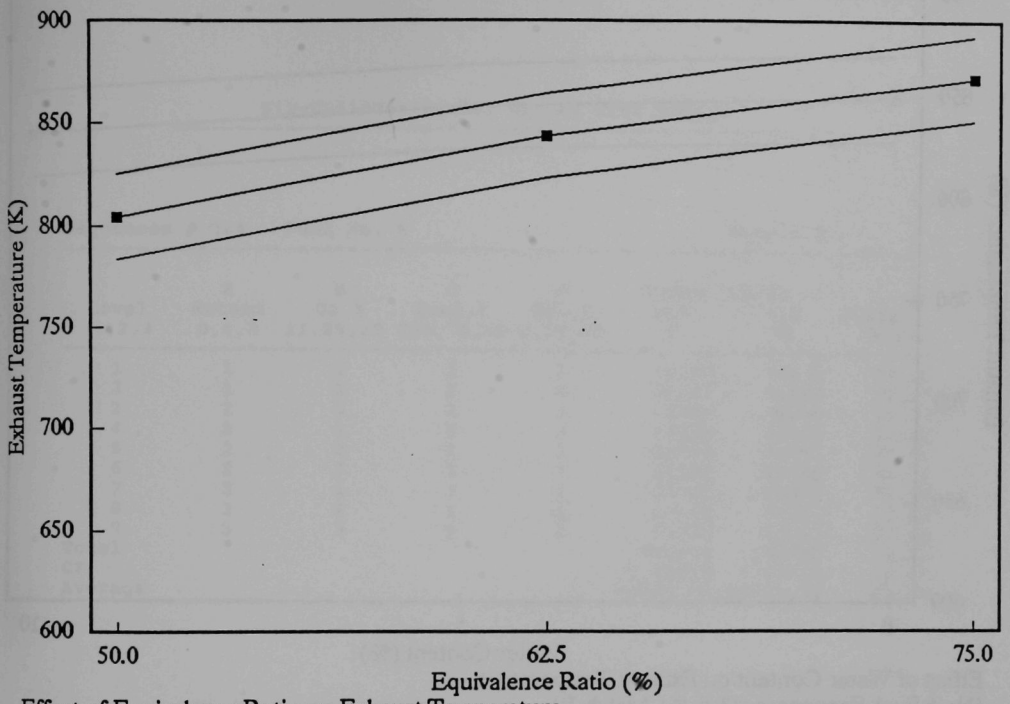
Source	f	S	V	F	S'	% contr.
Timing	2	15426.49	7713.25	30.06	14913.37	27.39
Oxygen	2	19582.99	9791.50	38.16	19069.87	35.03
Eq. R	2	13856.52	6928.26	27.00	13343.40	24.51
Water	2	1261.42	630.71	2.46	748.30	1.37
Replicat.	1	2262.40	2262.40	8.82	2005.84	3.68
e	8	2052.49	256.56			8.01
Pooled e	9	4314.89	479.43			
T	17	54442.32				100.00



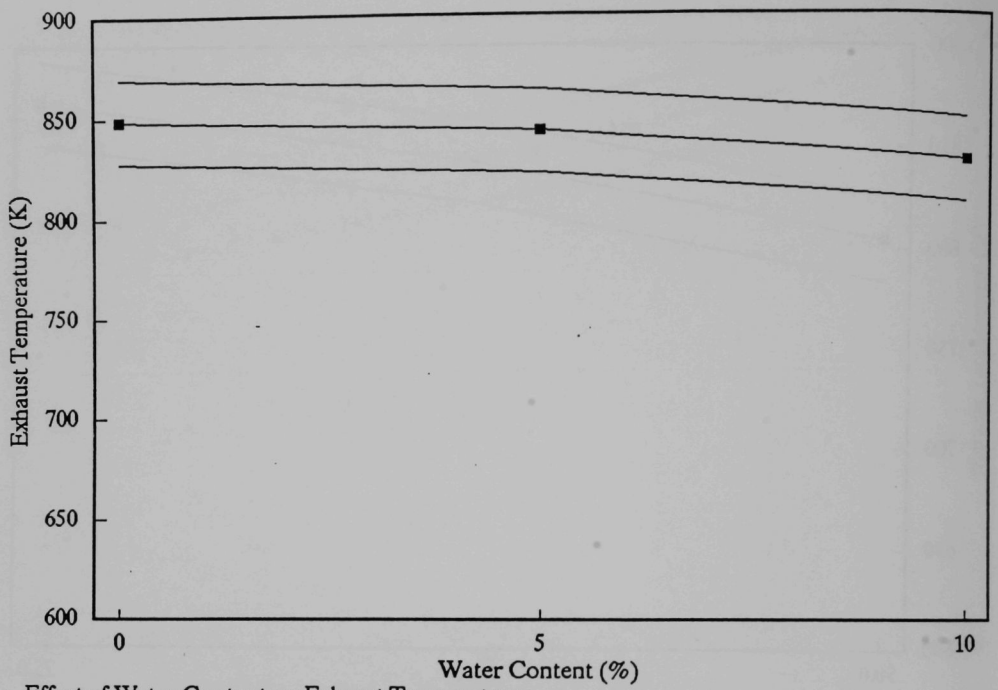
Effect of Injection Timing on Exhaust Temperature
(No.6 Fuel Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Exhaust Temperature
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on Exhaust Temperature
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Exhaust Temperature
(No.6 Fuel, Sequences #3 & #4, Matrix B)

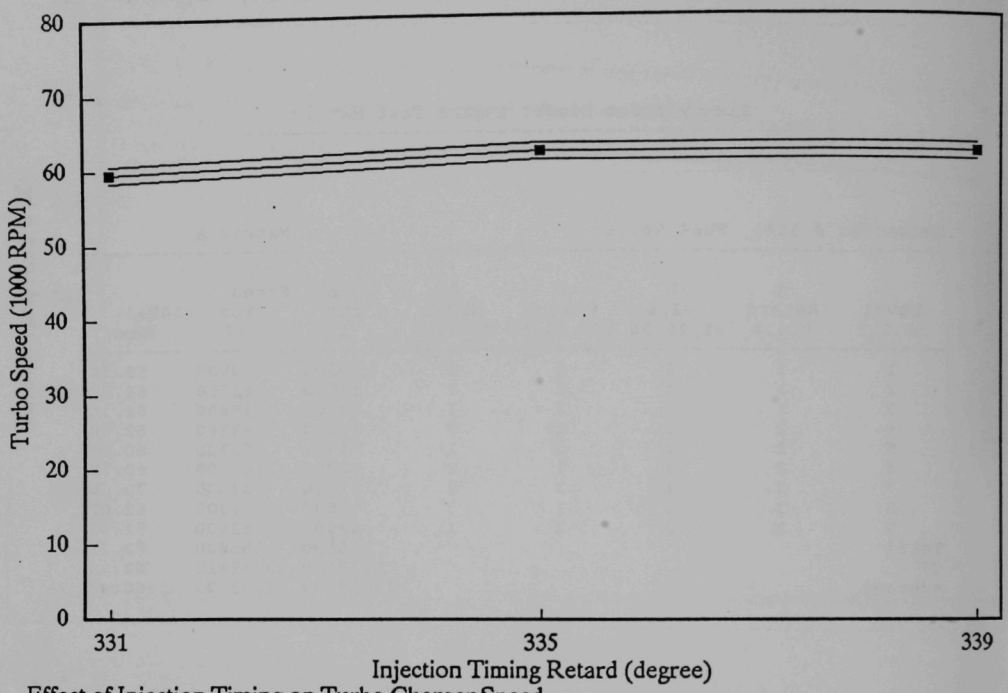
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

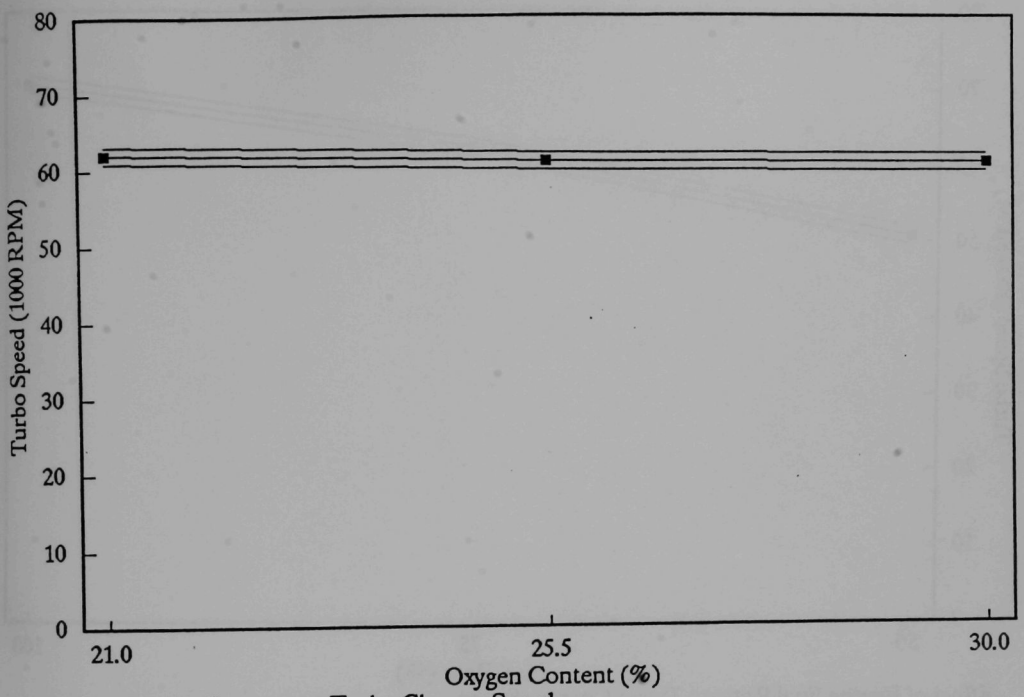
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Turbo rpm I	Speed rpm II	10E+3 Mean
1	1	1	1	1	70300	70800	59.52
2	1	2	2	2	58500	61200	62.07
3	1	3	3	3	47500	48800	62.12
4	2	1	2	3	62500	63200	62.00
5	2	2	3	1	51700	53300	60.92
6	2	3	1	2	72000	69700	60.78
7	3	1	3	2	51700	53500	70.60
8	3	2	1	3	69500	71300	62.02
9	3	3	2	1	62900	63800	51.08
Total					546600	555600	62.13
CF					3.3E+10	3.4E+10	61.10
Average					60733.33	61733.33	60.47

Variance Table Analysis

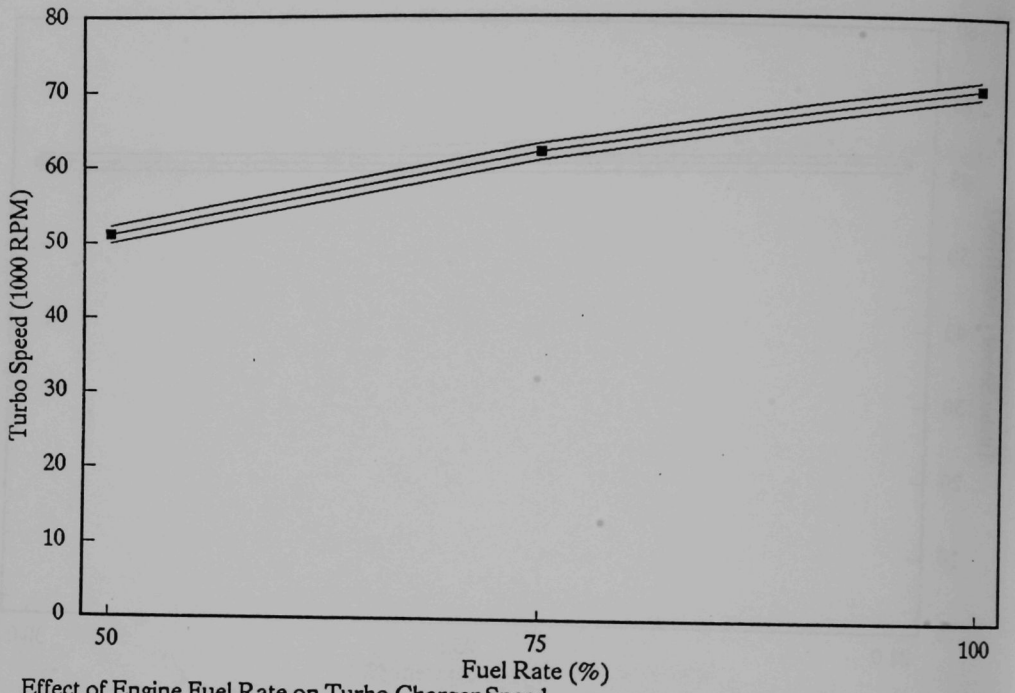
Source	f	S	V	F	S'	% contr.
Timing	2	2.7E+07	1.3E+07	1.3E+01	2.5E+07	2.04
Oxygen	2	5.3E+06	2.7E+06	2.7E+00	3.4E+06	0.28
Fuel	2	1.1E+09	5.7E+08	5.8E+02	1.1E+09	95.44
Water	2	8.5E+06	4.2E+06	4.3E+00	6.5E+06	0.54
Replicat.	1	4.5E+06	4.5E+06	4.5E+00	3.5E+06	0.29
e	8	7.9E+06	9.9E+05			1.40
Pooled e	9	1.2E+07	1.4E+06			
T	17	1.2E+09				100.00



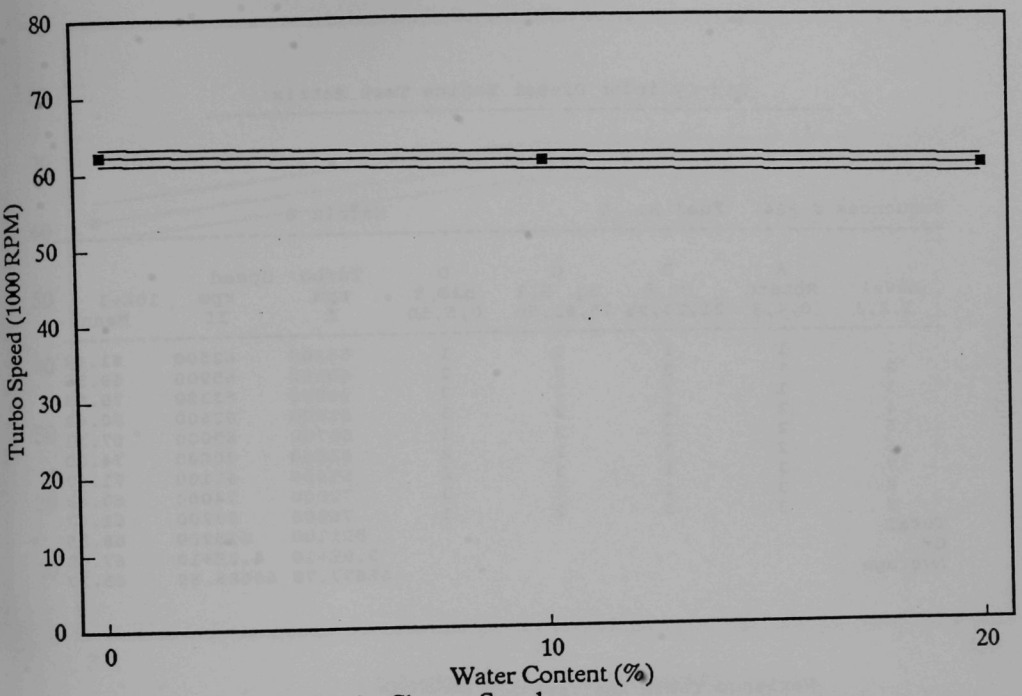
Effect of Injection Timing on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Turbo Charger Speed
(No.2 Fuel, Sequences #3 & #4, Matrix A)



Effect of Engine Fuel Rate on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix A)

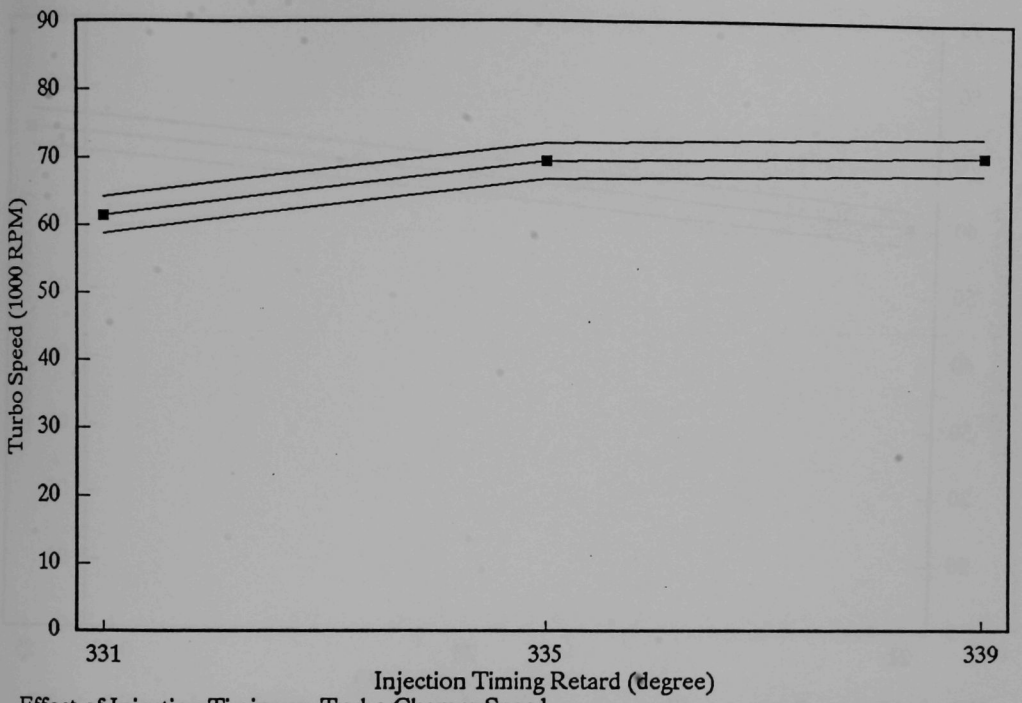
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

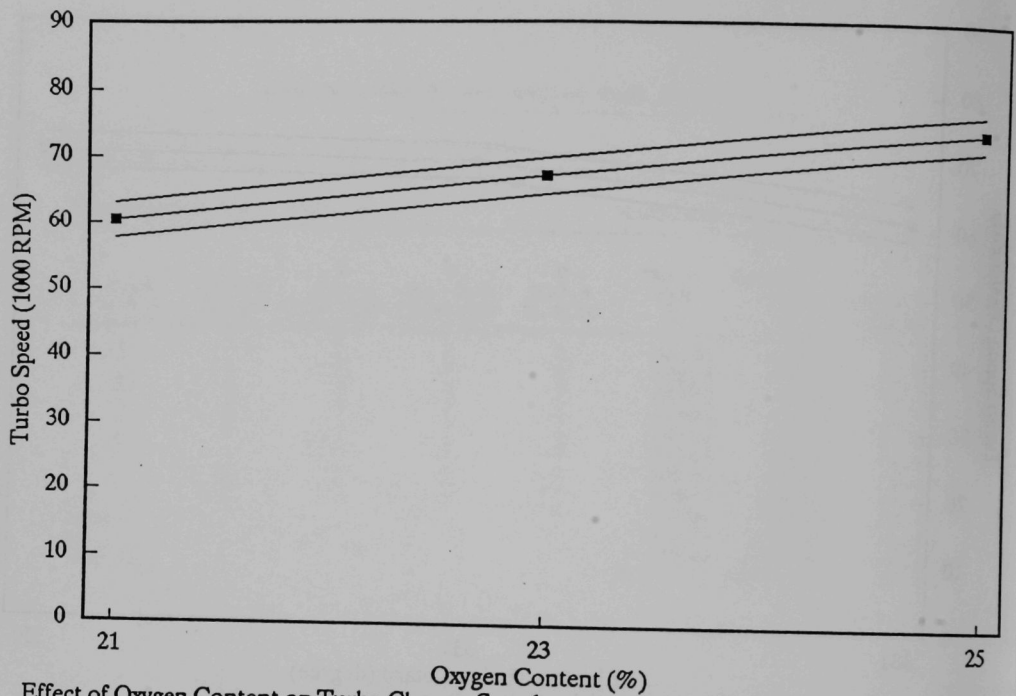
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Turbo rpm I	Speed rpm II	10E+3 Mean
1	1	1	1	1	58100	62500	61.42
2	1	2	2	2	60200	65900	69.55
3	1	3	3	3	58500	63300	70.58
4	2	1	2	3	61800	62600	60.42
5	2	2	3	1	65700	65000	67.13
6	2	3	1	2	81600	80600	74.00
7	3	1	3	2	56400	61100	71.47
8	3	2	1	3	72000	74000	68.42
9	3	3	2	1	76800	83200	61.67
Total					591100	618200	68.55
CF					3.9E+10	4.2E+10	67.63
Average					65677.78	68688.89	65.37

Variance Table Analysis

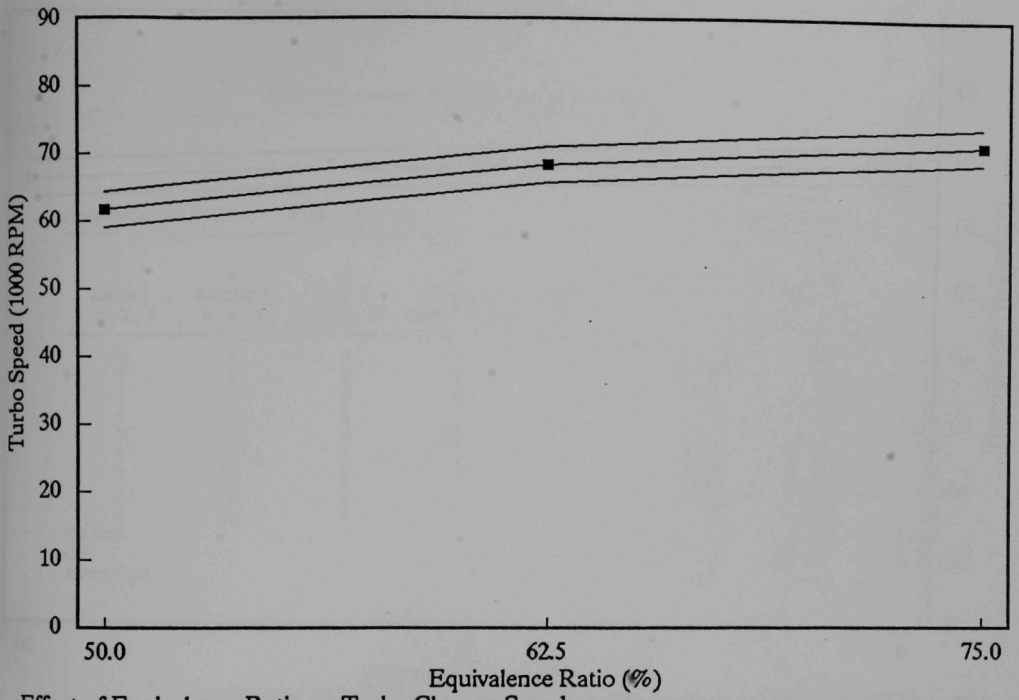
Source	f	S	V	F	S'	% contr.
Timing	2	3.0E+08	1.5E+08	3.9E+01	2.9E+08	23.35
Oxygen	2	5.5E+08	2.8E+08	7.1E+01	5.5E+08	43.24
Eq. R	2	3.0E+08	1.5E+08	3.9E+01	2.9E+08	23.29
Water	2	3.2E+07	1.6E+07	4.1E+00	2.4E+07	1.93
Replicat.	1	4.1E+07	4.1E+07	1.0E+01	3.7E+07	2.92
e	8	3.1E+07	3.9E+06			5.26
Pooled e	9	7.2E+07	8.0E+06			
T	17	1.3E+09				100.00



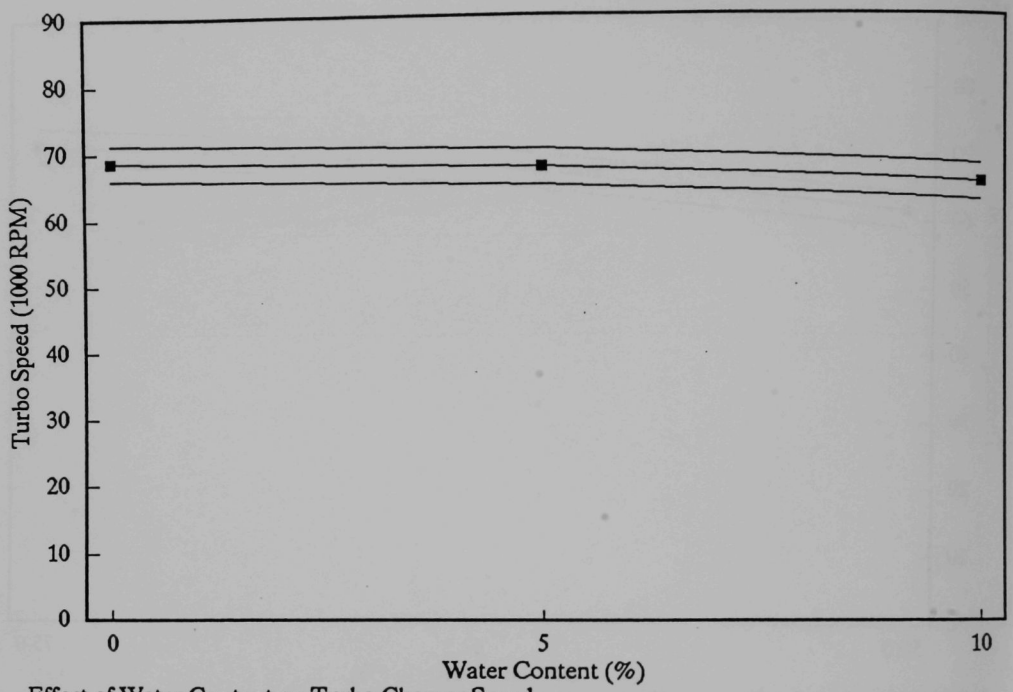
Effect of Injection Timing on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Turbo Charger Speed
(No.6 Fuel, Sequences #3 & #4, Matrix B)

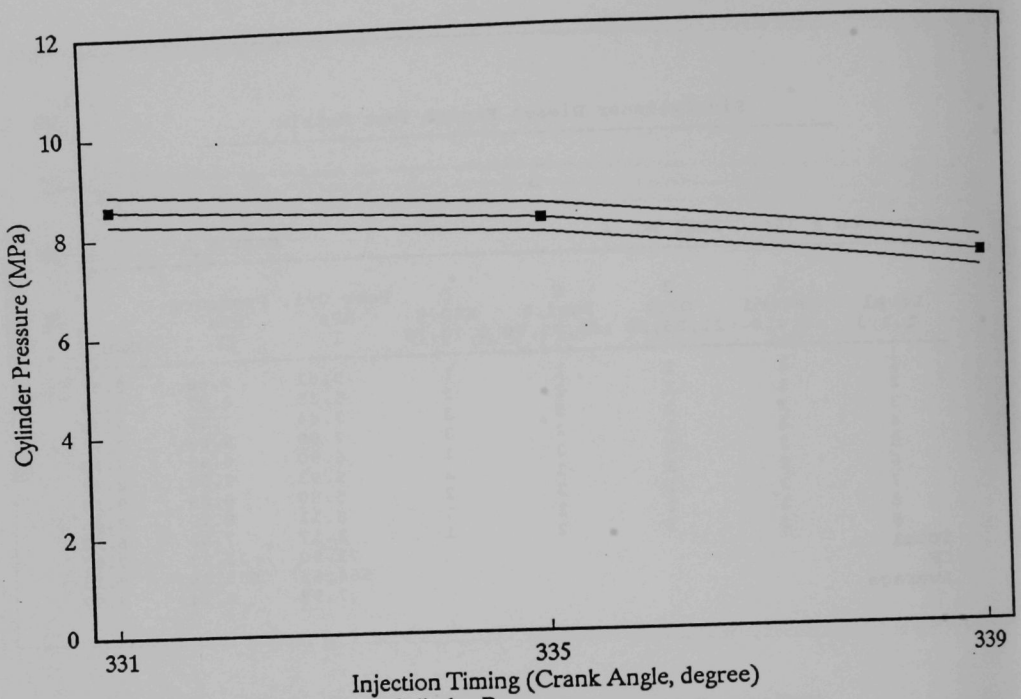
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix A

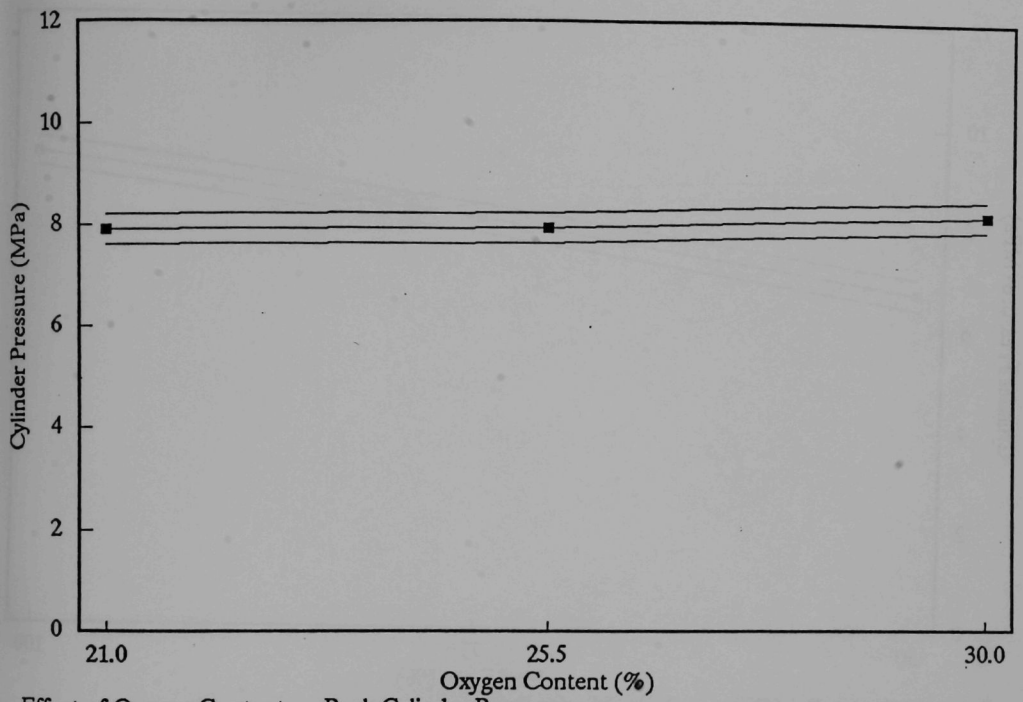
Level 1,2,3	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Peak Cyl. Pressure MPa I	MPa II	Mean
1	1	1	1	1	9.61	9.66	8.57
2	1	2	2	2	8.35	8.97	8.19
3	1	3	3	3	7.44	7.39	7.33
4	2	1	2	3	7.99	8.08	7.91
5	2	2	3	1	6.90	6.65	7.96
6	2	3	1	2	9.93	9.58	8.22
7	3	1	3	2	5.80	6.29	9.28
8	3	2	1	3	8.11	8.79	8.06
9	3	3	2	1	7.17	7.82	6.75
Total					71.30	73.23	7.97
CF					564.85	595.85	8.15
Average					7.92	8.14	7.97

Variance Table Analysis

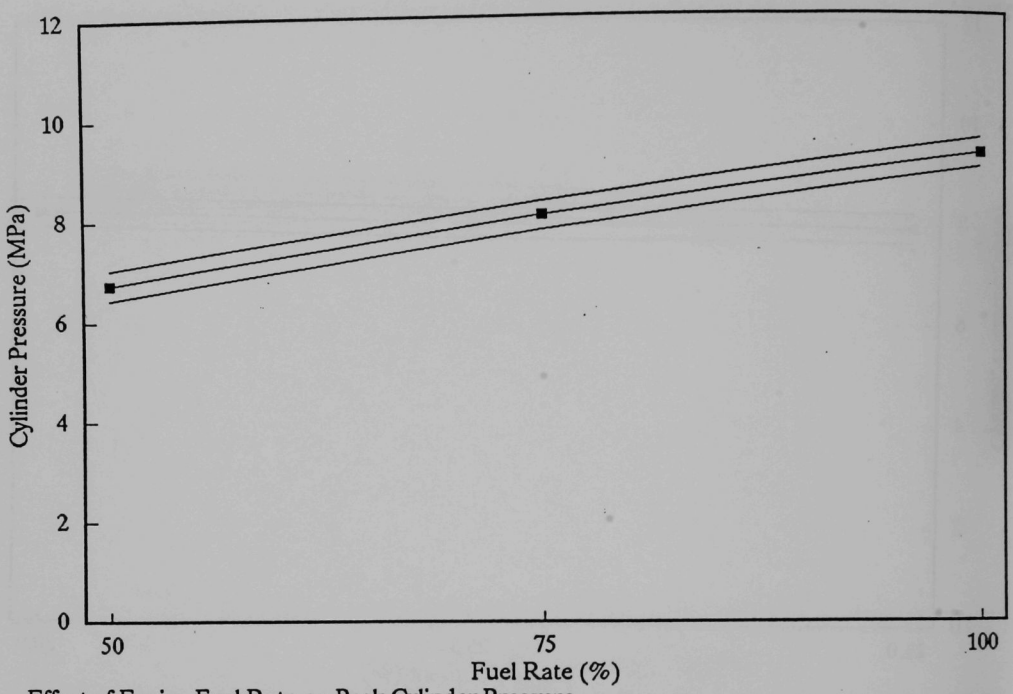
Source	f	S	V	F	S'	% contr.
Timing	2	4.84	2.42	29.93	4.68	18.37
Oxygen	2	0.34	0.17	2.12	0.18	0.71
Fuel	2	19.29	9.64	119.29	19.13	75.12
Water	2	0.14	0.07	0.85	0.00	0.00
Replicat.	1	0.21	0.21	2.56	0.13	0.50
e	8	0.65	0.08			5.31
Pooled e	9	0.85	0.09			
T	17	25.46				100.00



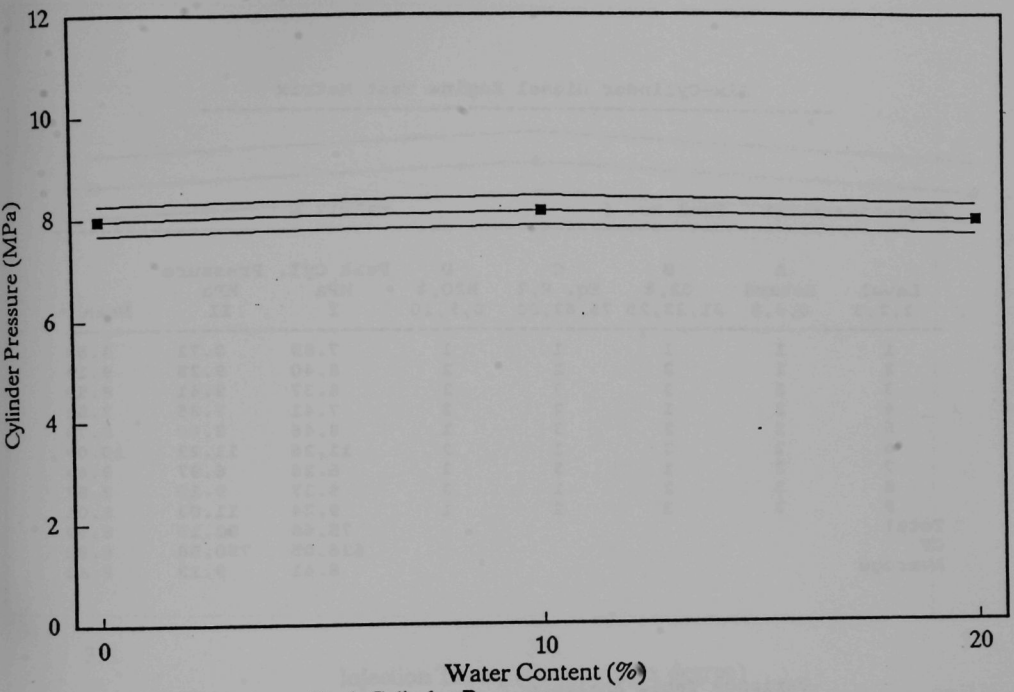
Effect of Injection Timing on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Engine Fuel Rate on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix A)

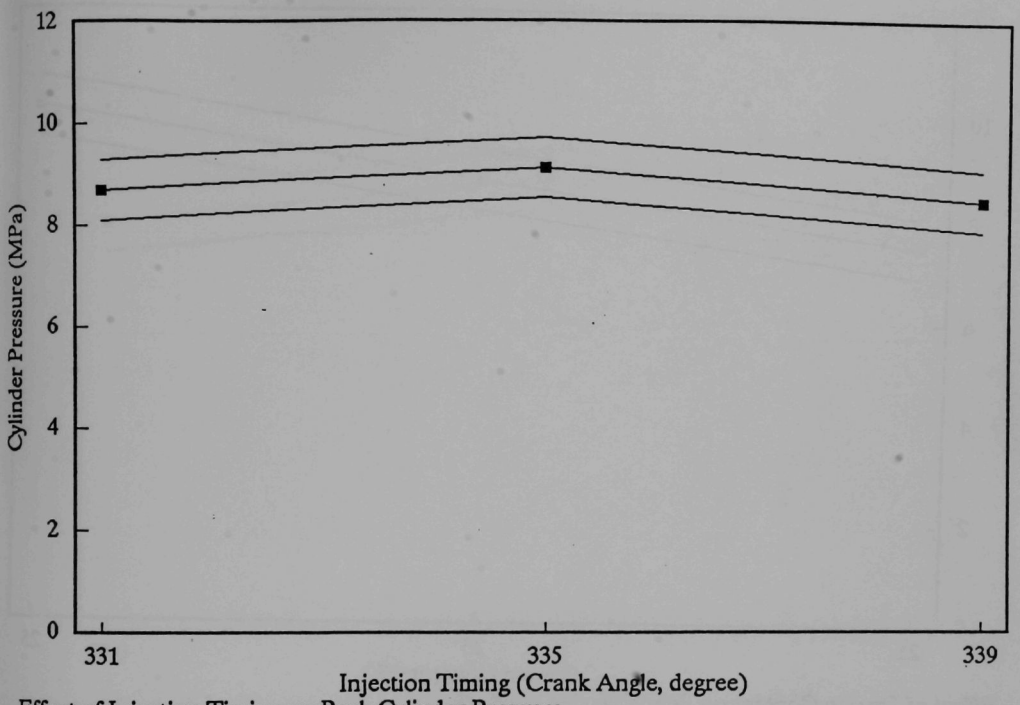
Six-Cylinder Diesel Engine Test Matrix

Sequences # 3&4 Fuel No. 6 Matrix B

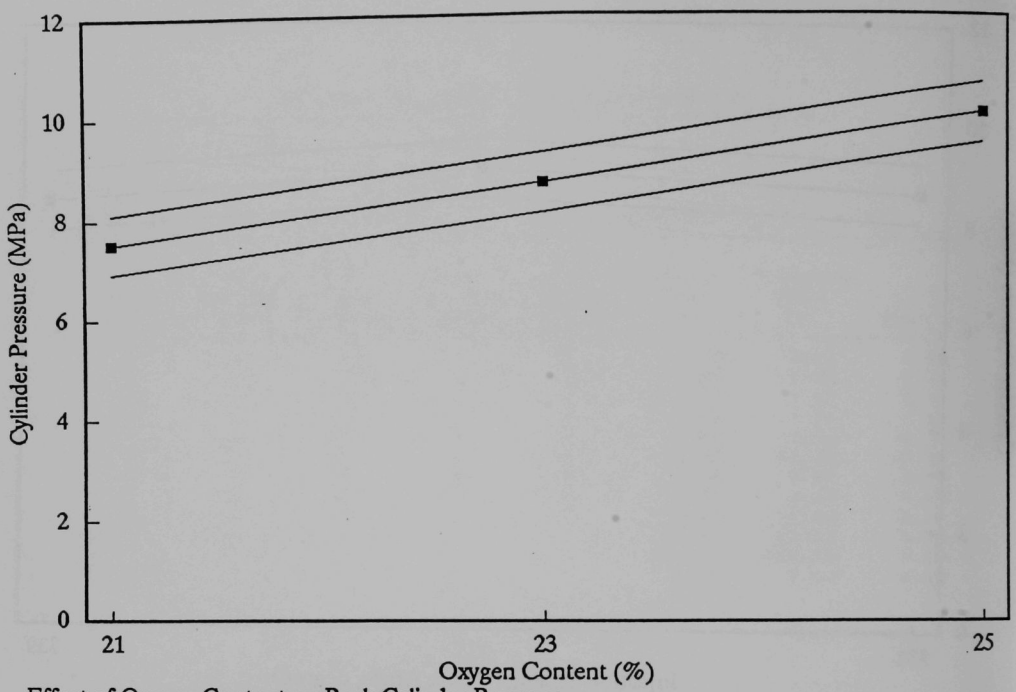
Level 1,2,3	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Peak Cyl. Pressure MPa I	MPa II	Mean
1	1	1	1	1	7.89	8.72	8.68
2	1	2	2	2	8.40	9.28	9.13
3	1	3	3	3	8.37	9.41	8.50
4	2	1	2	3	7.41	7.85	7.52
5	2	2	3	1	8.46	8.60	8.70
6	2	3	1	2	11.26	11.23	10.09
7	3	1	3	2	6.26	6.97	9.43
8	3	2	1	3	8.37	9.10	8.87
9	3	3	2	1	9.24	11.03	8.01
Total					75.66	82.19	8.99
CF					636.05	750.58	8.90
Average					8.41	9.13	8.42

Variance Table Analysis

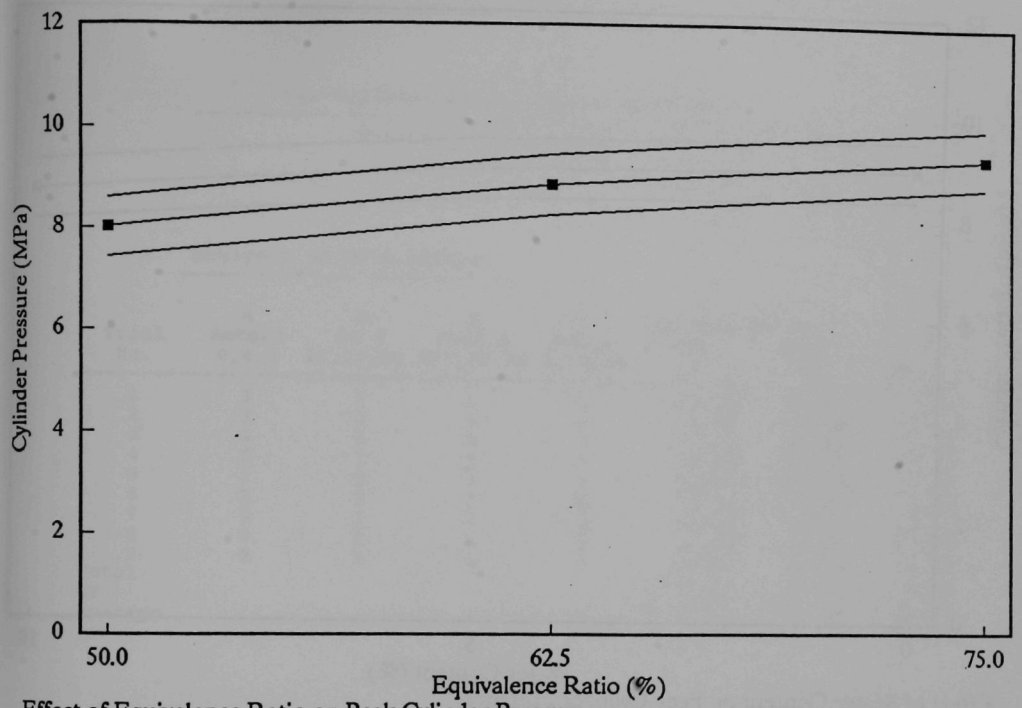
Source	f	S	V	F	S'	% contr.
Timing	2	1.30	0.65	4.61	1.02	3.19
Oxygen	2	19.91	9.95	70.40	19.62	61.42
Eq. R	2	6.11	3.05	21.60	5.83	18.23
Water	2	1.13	0.57	4.01	0.85	2.66
Replicat.	1	2.37	2.37	16.75	2.23	6.97
e	8	1.13	0.14			7.52
Pooled e	9	3.50	0.39			
T	17	31.95				100.00



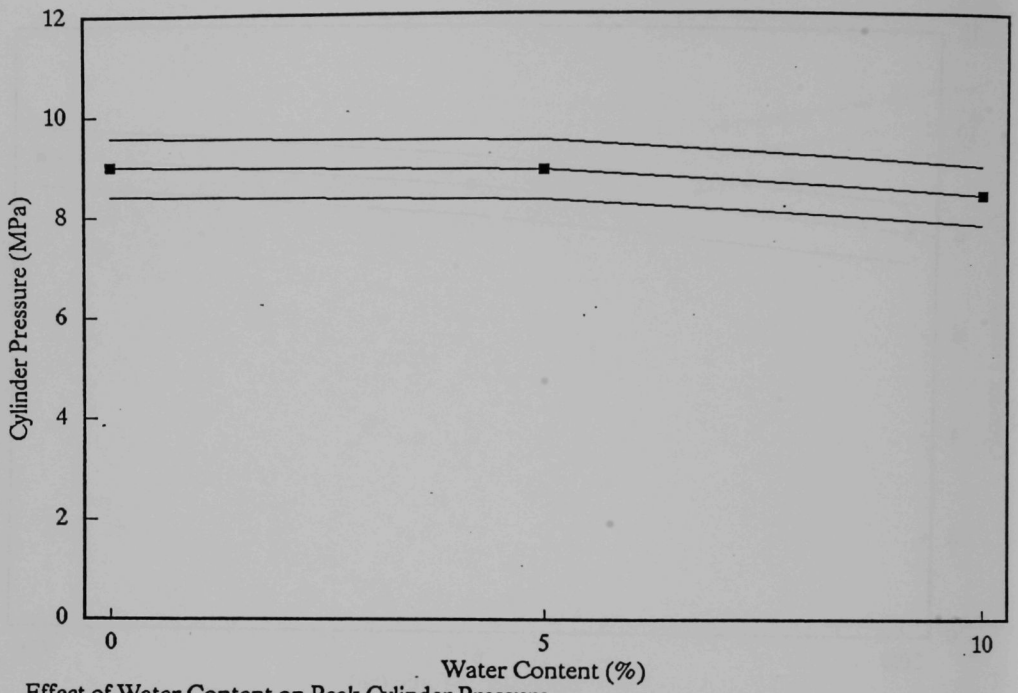
Effect of Injection Timing on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Equivalence Ratio on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Peak Cylinder Pressure
(No.6 Fuel, Sequences #3 & #4, Matrix B)

Six-Cylinder Diesel Engine Test Matrix

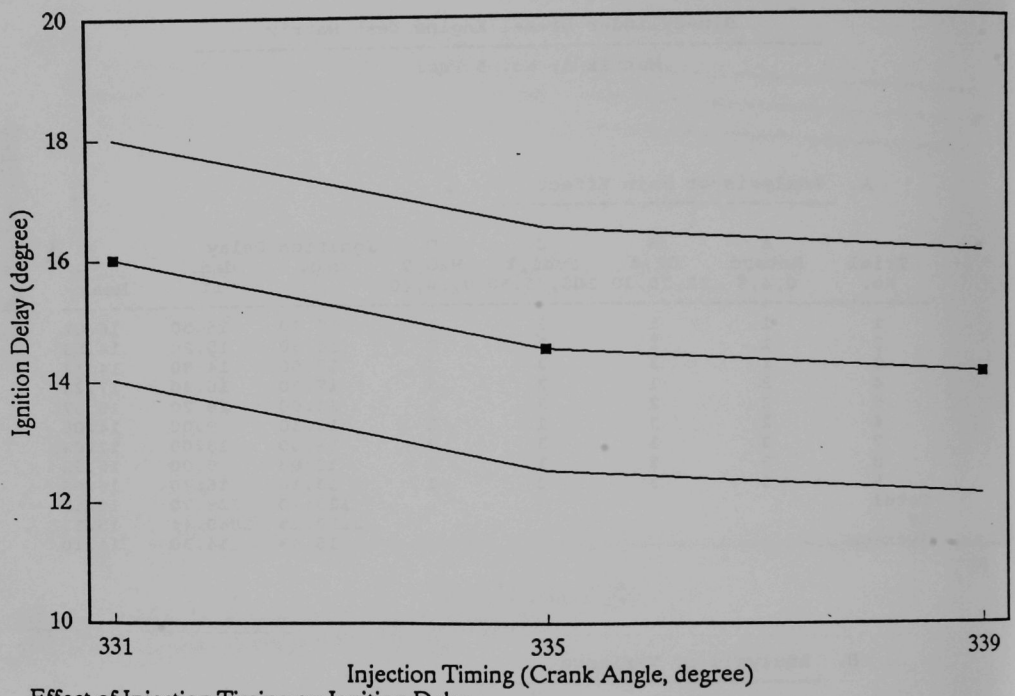
Matrix A, No. 6 Fuel

A. Analysis of Main Effect

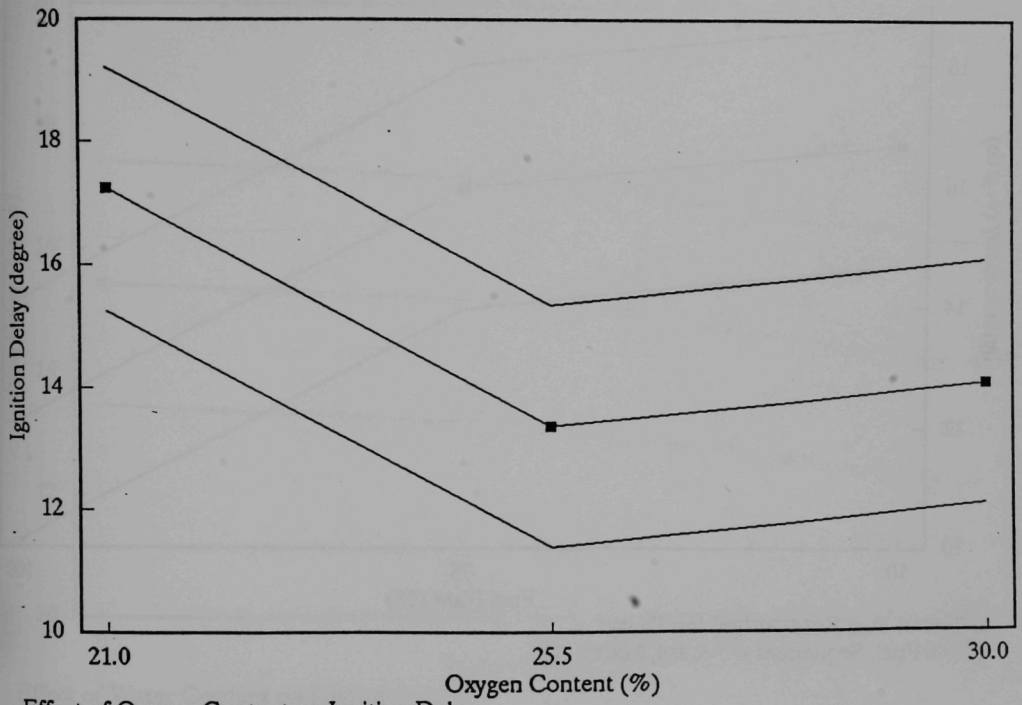
Trial No.	A Retard 0,4,8	B O2,% 21,25,30	C Fuel,% 100,75,50	D H2O,% 0,10,20	Ignition Delay deg. I	deg. II	Mean
1	1	1	1	1	15.70	16.50	16.02
2	1	2	2	2	16.30	15.20	14.53
3	1	3	3	3	17.60	14.80	14.13
4	2	1	2	3	17.90	16.30	17.23
5	2	2	3	1	14.50	16.20	13.37
6	2	3	1	2	13.30	9.00	14.08
7	3	1	3	2	19.00	18.00	12.08
8	3	2	1	3	12.00	6.00	15.92
9	3	3	2	1	13.10	16.70	16.68
Total					139.40	128.70	15.45
CF					2159.15	1840.41	15.13
Average					15.49	14.30	14.10

B. Analysis of Variance

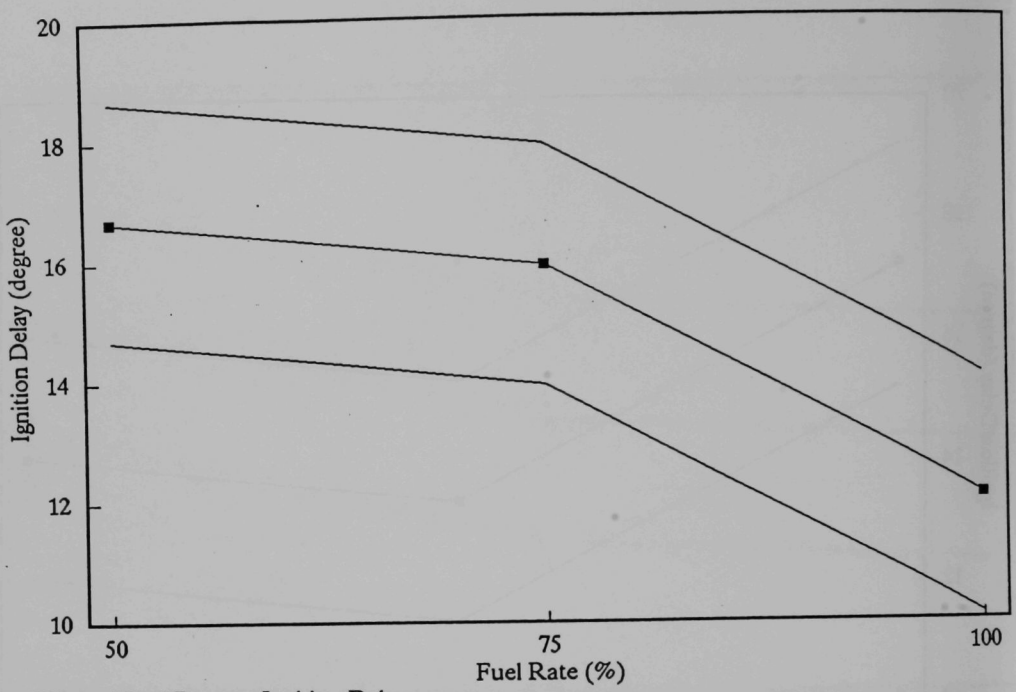
Source	f	S	V	F	S'	% contr.
Timing	2	11.81	5.91	1.27	1.00	0.55
Oxygen	2	50.77	25.39	5.47	41.49	22.64
Load	2	72.88	36.44	7.85	63.60	34.70
Water	2	5.98	2.99	0.64	0.00	0.00
e	9	41.79	4.64		77.17	42.11
T	17	183.25			183.25	100.00



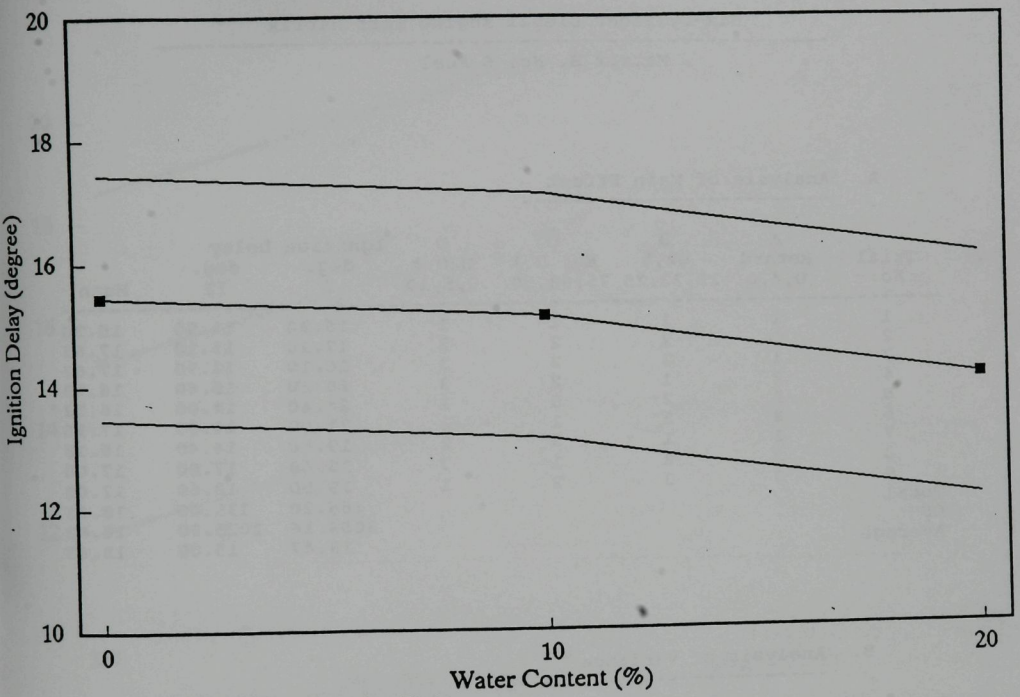
Effect of Injection Timing on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Oxygen Content on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Fuel Rate on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix A)



Effect of Water Content on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix A)

Six-Cylinder Diesel Engine Test Matrix

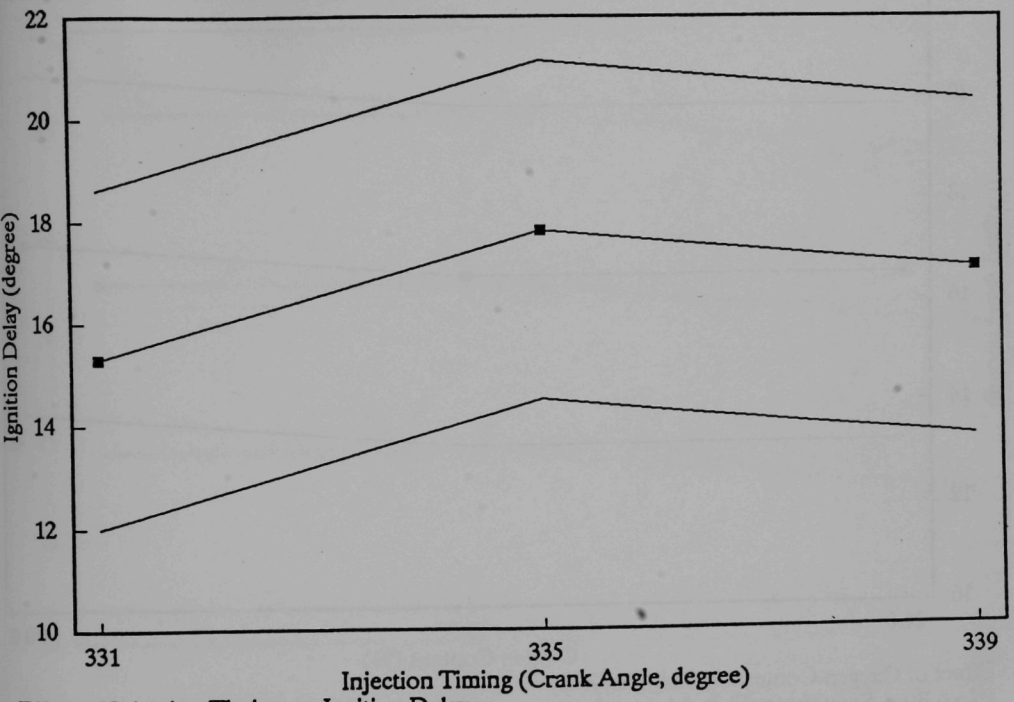
Matrix B, No. 6 Fuel

A. Analysis of Main Effect

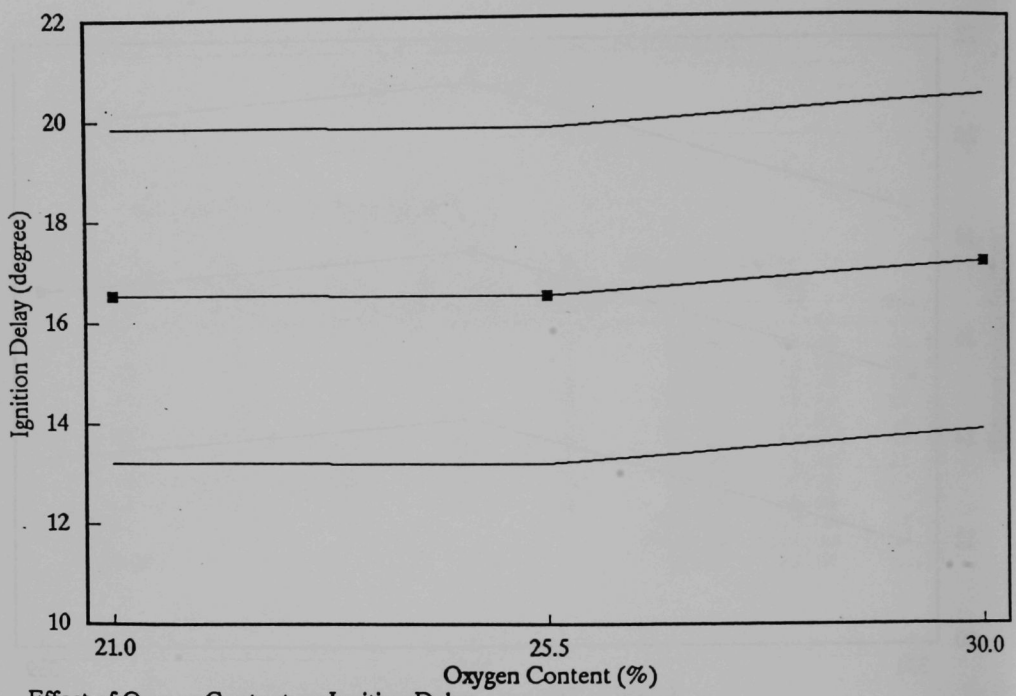
Trial No.	A Retard 0,4,8	B O2,% 21,23,25	C Eq. R,% 75,63,50	D H2O,% 0,5,10	Ignition Delay deg. I	deg. II	Mean
1	1	1	1	1	16.90	14.80	15.30
2	1	2	2	2	17.20	13.10	17.83
3	1	3	3	3	16.10	13.70	17.07
4	2	1	2	3	18.20	15.40	16.53
5	2	2	3	1	24.40	14.00	16.52
6	2	3	1	2	21.00	14.00	17.15
7	3	1	3	2	19.50	14.40	16.18
8	3	2	1	3	13.40	17.00	17.00
9	3	3	2	1	19.50	18.60	17.02
Total					166.20	135.00	18.03
CF					3069.16	2025.00	16.53
Average					18.47	15.00	15.63

B. Analysis of Variance

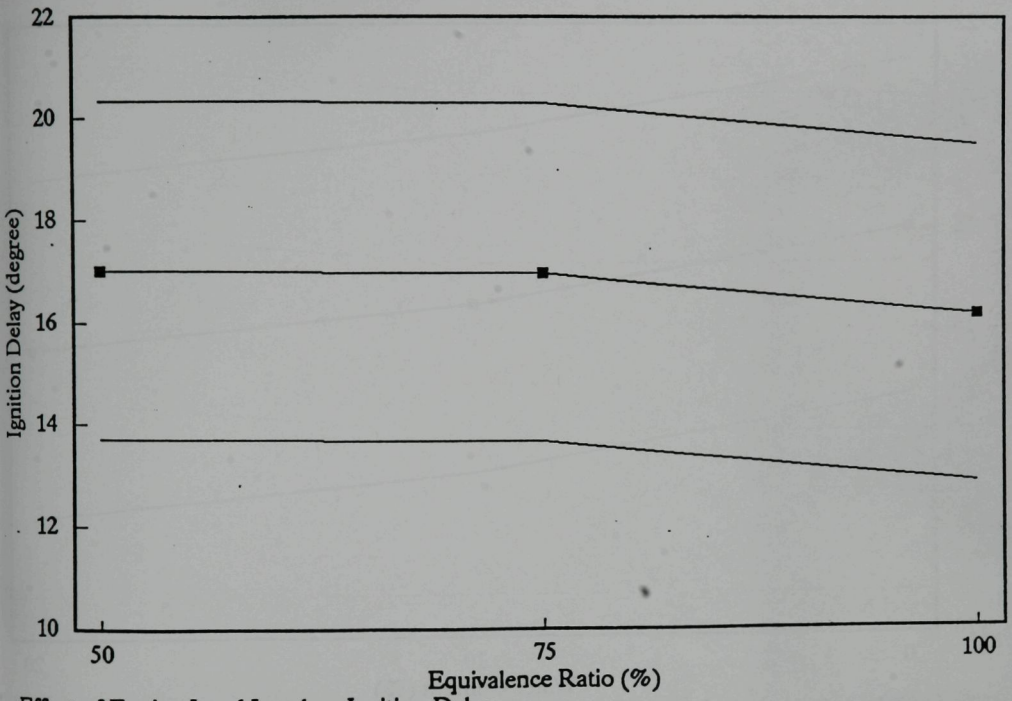
Source	f	S	V	F	S'	% contr.
Timing	2	20.25	10.13	0.79	--	12.81
Oxygen	2	1.56	0.78	0.06	--	0.99
Load	2	2.72	1.36	0.11	--	1.72
Water	2	17.64	8.82	0.69	--	11.16
e	9	115.88	12.88		--	73.31
T	17	158.06			158.06	100.00



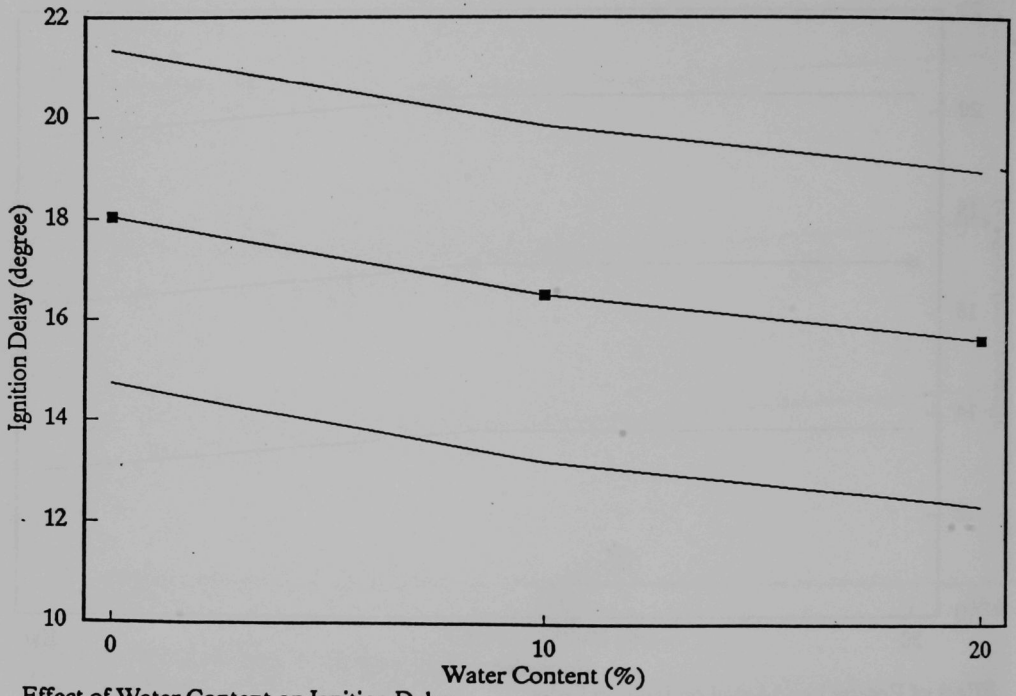
Effect of Injection Timing on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Oxygen Content on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Engine Load Level on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix B)



Effect of Water Content on Ignition Delay
(No.6 Fuel, Sequences #3 & #4, Matrix B)

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