

EFFECT OF A DIESEL FUEL ADDITIVE  
ON THE PARTICULATE EMISSIONS OF A  
SINGLE-CYLINDER COMPRESSION-IGNITION ENGINE

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## ABSTRACT

A single-cylinder diesel engine was operated with both a baseline fuel and a additive-modified fuel to determine the variation in particulate emissions between the two fuels. Exhaust gases were sampled through a constant volume sampling dilution chamber and drawn through a filter medium on which the particulate matter deposited. It was determined that particulate emissions increased with the modified fuel with respect to the baseline fuel. Furthermore, the effects appear to be dependent on engine speed.

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## I. INTRODUCTION

Since the oil crises of the 1970s, much attention has been placed upon means to increase the efficiency with which internal combustion engines convert hydrocarbon fuels to power. One approach has been the use of additives mixed into the fuel to promote more complete combustion. Another has been the increased use of diesel engines, with their advantages in fuel economy over traditional spark-ignition (SI) engines, in light- and medium-duty automotive applications in addition to their traditional use in heavy-duty equipment [1]. A major disadvantage of the diesel, or compression-ignition (CI), engine is that its exhaust is laden with particulate matter, whereas smoke is not a significant problem in the SI engine [2]. One method to reduce diesel particulate emissions is the use of fuel additives [3]. It is therefore advantageous to develop a diesel fuel additive that will not only increase fuel economy but also decrease particulate emissions for CI engines.

## BACKGROUND

For many years, particulate emissions were referred to generally as "smoke" until approximately 1973 when the physical, chemical, and biological aspects and their environmental effects were recognized [1]. Particulate pollutants are defined as carbonaceous solid or liquid matter (soot), resulting from incom- bustible (usually inorganic) components of the fuel, on which some uncombusted or incompletely burned organic compounds have become absorbed [2]. What is commonly referred to as smoke is an aerosol of submicron size solid and liquid particles, formed due

to poor mixing of fuel and air, present in the exhaust gas stream [4]. At high temperatures (above 800 K), particulate matter is primarily comprised of solid carbon spherules which are insoluble in the atmosphere. As temperature decreases, soluble hydrocarbons begin to condense on the particles [2]. Hence, particulates are comprised of both an insoluble portion and a soluble portion.

The Environmental Protection Agency (EPA) has shown that, aside from being unaesthetic, particulates pose significant risks to health. Specifically, it is components in the soluble organic fraction that tend to be mutagenic and potentially carcinogenic in Ames bioassay tests [5]. Therefore, it is desirable to monitor and control if not eliminate diesel particulates.

Particulate measurement techniques are used to determine the amount of particulate matter emitted to the atmosphere and are typically made on a mass basis. In collecting diesel particulate samples, the atmospheric dilution process is simulated in constant volume sampling (CVS) dilution tunnels per federally proposed procedure [6]. In CVS testing, all or part of the exhaust is diluted with air. The diluted mixture is then drawn through a pre-weighed filter medium on which the particulates are deposited. Knowing the mass of particulates collected, the volume of diluted mixture drawn through the filter, and the dilution ratio, particulate emission data may be calculated. The dilution ratio, indicating the amount of air mixed with exhaust to simulate atmospheric dilution, is the ratio of the molar flow of diluted exhaust to the molar flow of raw exhaust [7] and is determined from the concentrations of an exhaust gas tracer, typically carbon dioxide ( $\text{CO}_2$ ). The most common format for data presentation is exhaust particulate concentration (mass of particulates per unit volume of exhaust) corrected to standard conditions.

Several factors complicate the measurement of particulates and bring into question the validity of samples collected from dilution tunnels. Most important of these is the modelling of atmospheric dilution in a CVS dilution tunnel and the effects of dilution ratio and filter temperature on particulate samples. Previous investigators have presented conflicting data in this area.

Frisch et al. [8] studied the effects of fuel type and dilution ratio on particulate emission measurements for a Caterpillar 3208 direct injection naturally aspirated engine operated at steady-state. Varying the dilution ratio from 1-to-1 (no dilution) to 50-to-1 resulted in an increase in particulate concentration with increasing dilution ratio. The increases were attributed to condensation of hydrocarbons on the soot as a result of lower temperatures in the dilution tunnel.

Black and High [9] completed a series of experiments with a Caterpillar 3304 diesel engine operated under steady-state conditions using dilution ratios of 10-to-1, 20-to-1, and 275-to-1. They showed that the particulate samples were not affected by amount of dilution.

MacDonald et al. [7] developed a CVS dilution tunnel which allows independent variation of dilution ratio and filter temperature. Using an Opel 0.5 liter single-cylinder engine derived from a production 2.1 liter diesel, they demonstrated that particulate concentration decreased with both increasing temperature and dilution ratio. Hence, they established that the soluble fraction of a particulate sample is not only a function of temperature but also of dilution ratio.

Since particulate emission measurements are based on mass, the particulate concentration determined experimentally is a

function of sampling temperature and dilution ratio. Furthermore, in most CVS dilution tunnels, filter temperature and dilution ratio vary simultaneously and inversely with variation of dilution air [10].

The EPA has specified that the quantity of dilution air be adequate to maintain a filter temperature of 325 K or less for regulation purposes [6]. The significance of this temperature has not been demonstrated, nor is it clear whether such a temperature will lead to consistent particulate samples, independent of sample temperature and dilution ratio.

## **OBJECTIVE**

The objective of this investigation was to determine if a developmental diesel fuel additive presented any benefits with respect to particulate emissions. This was accomplished by studying the quantitative effect of the additive-modified fuel on the particulate emissions of a single-cylinder CI engine as compared to the exhaust particulates measured using the baseline fuel without the additive.

## **SCOPE AND LIMITATIONS**

Although many fuel additives have been developed in the pursuit of increased fuel economy, this investigation concerns itself with only one of the additives currently under development. Furthermore, it is limited to the effects observed from combustion in a single-cylinder diesel research engine and does not address the additional concerns associated with using the fuel in a multi-cylinder production-type engine.

## **REPORT ORGANIZATION**

The following report entails a discussion of the test apparatus and procedures employed, presents the results, lists findings and observation from which conclusions follow, and, lastly, recommends future actions to be taken.

## II. EXPERIMENTAL

### TEST APPARATUS

The test engine used was a Labeco Cooperative Lubrication Research (CLR) single-cylinder compression-ignition engine. It has a bore and stroke of 3.61 in and 3.75 in, respectively, yielding a displacement of 42.5 in<sup>3</sup>, with a compression ratio of 16.7-to-1. Operation is on a naturally aspirated four-stroke cycle with direct injection. The combustion chamber is a "Mexican hat" design. The fuel injection system consists of a Bosch APE-1B pump with a Simms four-hole nozzle.

The baseline fuel was a low-sulfur custom diesel supplied by Phillips 66 Company. The modified fuel added to the baseline 5000 ppm of an additive containing a liquid organic platinum compound with hydrocarbons, provided by Fuel Tech of Houston.

The dilution tunnel employed was developed in Summer 1989 in anticipation of the current research. Modelled after the system used by MacDonald et al. [7], the tunnel, illustrated schematically in Figure 1, features a venturi tube through which prefiltered compressed air flows, creating a sub-atmospheric pressure at the throat. The low pressure inducts exhaust gases from the exhaust manifold sample tube into the tunnel, where the compressed air thoroughly mixes with and dilutes the exhaust gases. The diluted exhaust stream is then sampled and drawn through a filter medium with a vacuum pump [11]. Since only a portion of the exhaust is diluted, the resulting dilution system is relatively small in size. The filter media were 47 mm glass fiber discs manufactured by Gelman Sciences. Carbon dioxide concentrations were monitored with a Horiba CO<sub>2</sub> analyzer.

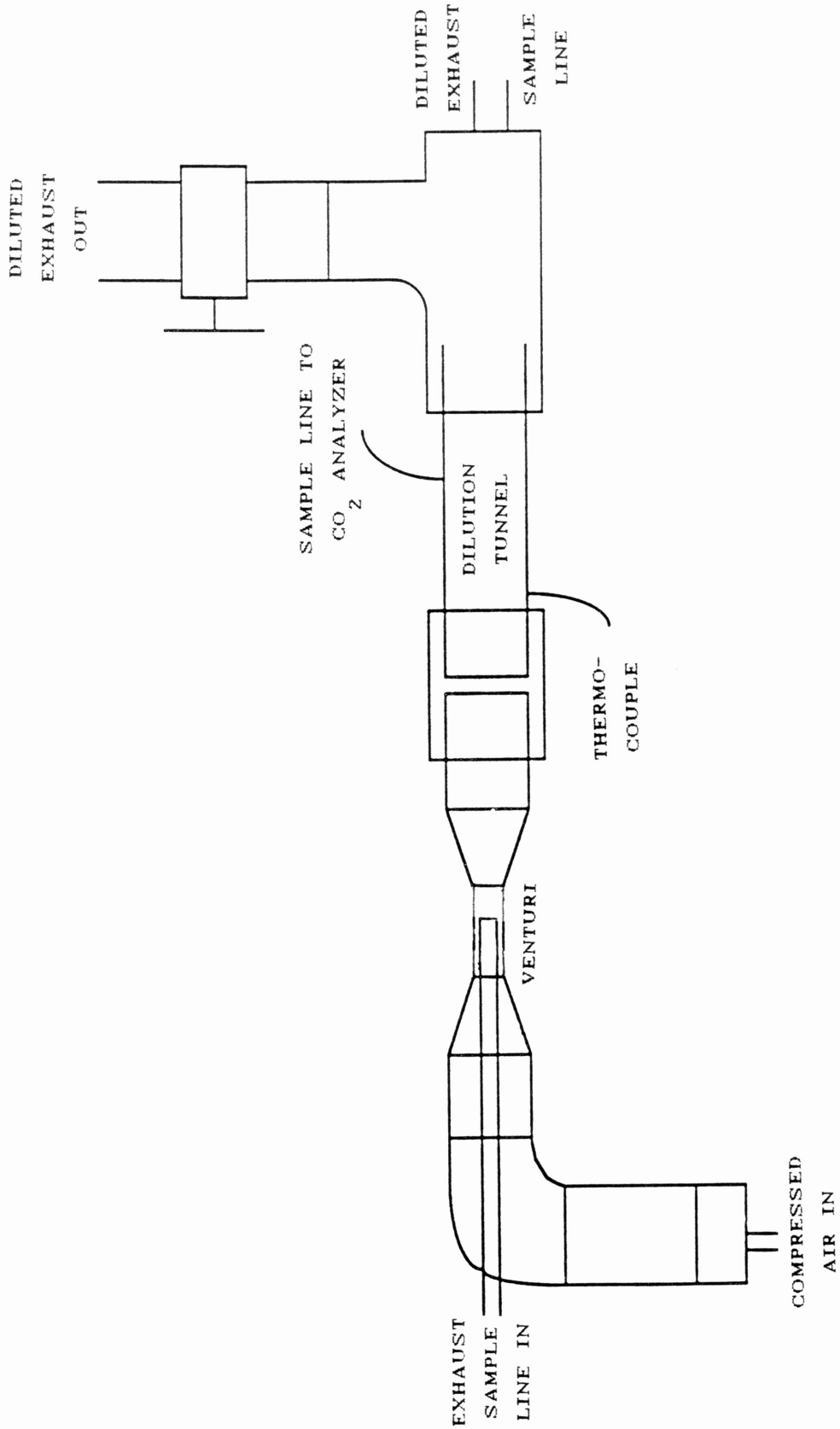


Figure 1 Constant Volume Sampling Dilution Tunnel



## OPERATING CONDITIONS

Steady-state operating conditions were chosen at three different engine speeds and three injection timings for each speed with constant specific fuel consumption. Engine speeds selected were 1300, 1600, and 1900 rpm with injection timings varying between 6 and 18 degrees before top dead center (bTDC). Specific fuel consumption was maintained at 230 g/bhp·hr. Engine speed was governed by the applied torque load.

The dilution system was operated at approximately constant dilution ratio of 12 throughout the tests. However, selection of the dilution ratio was limited by the dilution system, with moderate excursions in dilution ratio occurring on occasion. Also, since the dilution tunnel is of the CVS type, separate control of sample temperature and dilution ratio was not possible.

Testing began with the engine operating on the baseline fuel for which a thorough database was collected for all operating points prior to switching to the additive-modified fuel. Long-term operation on the modified fuel was to be observed for effects of the additive over time until variation in collected data had settled. Operation was then to return to baseline fuel to observe the transient effects in an attempt to return to emission levels existing prior to switching to the modified fuel.

Completion of the entire test matrix was not possible due to temporary suspension of the project in December 1989. As a result, thorough data sets were assembled only for the second injection timing marks for each engine speed (8 deg bTDC at 1300 rpm, 10.5 at bTDC for 1600 rpm, and 13 at bTDC for 1900 rpm). Furthermore, steady-state operation on modified fuel was not attained, nor did operation return to the baseline fuel.

## PROCEDURE

Preliminary to collecting samples, the filters were prepared by placing them in an oven at 525 K for 3 hours to evaporate moisture, allowed to cool, and weighed. Prewedged filters were stored in an evacuated dessicator prior to use.

When collecting a sample, a filter was installed in the filter assembly, and, with the filter assembly valve closed, the compressed air valve was opened and the air pressure was adjusted to 5 psig. The exhaust sample valve was then opened, and the engine and dilution tunnel were allowed to stabilize at the chosen test point. When equilibrium was reached, the filter assembly valve was opened, a stopwatch was started, and the vacuum pump was engaged, maintaining a constant flow rate of 180 scfh on the flowmeter. During the test, temperatures at the tunnel, filter, and flowmeter and the pressure drop across the filter were monitored. The  $\text{CO}_2$  concentrations in the raw exhaust and the diluted mixture were also monitored. The test was terminated when the pressure drop across the filter reached 14 in Hg or the flow rate could no longer be maintained at 180 scfh, whichever occurred first, at which time the filter valve was closed and the stopwatch was stopped. The elapsed time, temperatures, initial and final pressure drop, and  $\text{CO}_2$  concentrations for the raw exhaust, the diluted mixture, and the diluent air were recorded as well as the engine operating conditions (engine speed, brake power, fuel mass flow rate).

After a filter was loaded, it was removed from the filter assembly and dessicated for 36 hours before weighing. Each filter was weighed at least three times before recording the mass.

### III. DATA REDUCTION

The relationships used to manipulate the raw data into the desired form for results are included in Appendix A.

#### DILUTION RATIO

Upon completion of testing, it was necessary to relate the compiled data on the particulate samples collected from the diluted exhaust to the particulate levels in the undiluted exhaust. This was facilitated by calculating the dilution ratio (on a wet basis) from the  $\text{CO}_2$  concentrations of the raw exhaust, the diluted exhaust, and the diluent air. Since the  $\text{CO}_2$  analyzer measures concentrations on a dry basis, the readings were corrected to compensate for the water removed in the sampling process.

#### PARTICULATE MASS

The quantity of particulate mass trapped on a filter was determined by weighing the filter several times before and after loading. The measurements were taken after a minimum stabilization period of 36 hours in an evacuated dessicator. The lowest readings were recorded, for it was determined that they indicated the masses with the least contribution from any moisture due to humidity that may reside in the filter. The difference between the filter mass before and after loading was assumed to be the particulate mass.

## **PARTICULATE CONCENTRATION (PC)**

The concentration of particulates in the diluted exhaust was determined by dividing the particulate mass by the total volume of diluted exhaust drawn through the filter, which is simply the flow rate multiplied by the test time. This in turn was converted to the raw exhaust concentration by multiplying by the dilution ratio. The final result was corrected to standard conditions (273 K, 1 atm).

## **PARTICULATE EMISSION RATE (PER)**

The rate of particulate emission was determined by multiplying the particulate concentration by the mass flow rate of exhaust, which was found from the fuel flow rate, the density of exhaust gases, and the air-fuel ratio (calculated from stoichiometric considerations).

## **SPECIFIC PARTICULATE EMISSION (SPE)**

The specific particulate emission normalizes the total exhaust particulate mass to the work output from the engine. It was determined by dividing the particulate emission rate by the brake power measured at the engine output shaft.

## **PARTICULATE EMISSION INDEX (PEI)**

The particulate emission index normalizes the particulate mass to the mass of fuel consumed and was found by dividing the particulate emission rate by the fuel mass flow rate.

## IV. RESULTS

### VARIATION OF PC WITH ENGINE SPEED

Particulate concentration was found to remain relatively steady across the operational range for the baseline fuel, with a minimum at medium speed. The average PC was  $121.4 \text{ mg/m}^3$  at 1300 rpm,  $94.3 \text{ mg/m}^3$  at 1600 rpm, and  $107.0 \text{ mg/m}^3$  at 1900 rpm.

For the modified fuel, average PC increased slightly at 1300 rpm to  $134.9 \text{ mg/m}^3$ , jumped dramatically at 1600 rpm to  $202.9 \text{ mg/m}^3$ , and rose also at 1900 rpm to  $156.0 \text{ mg/m}^3$ . These values represent increases of 11.1%, 115.2%, and 45.8%, respectively, over the baseline levels. Data scatter increased greatly at 1600 rpm, significantly at 1900 rpm.

Figure 2 illustrates the variation of particulate concentration with engine speed for baseline and modified fuels.

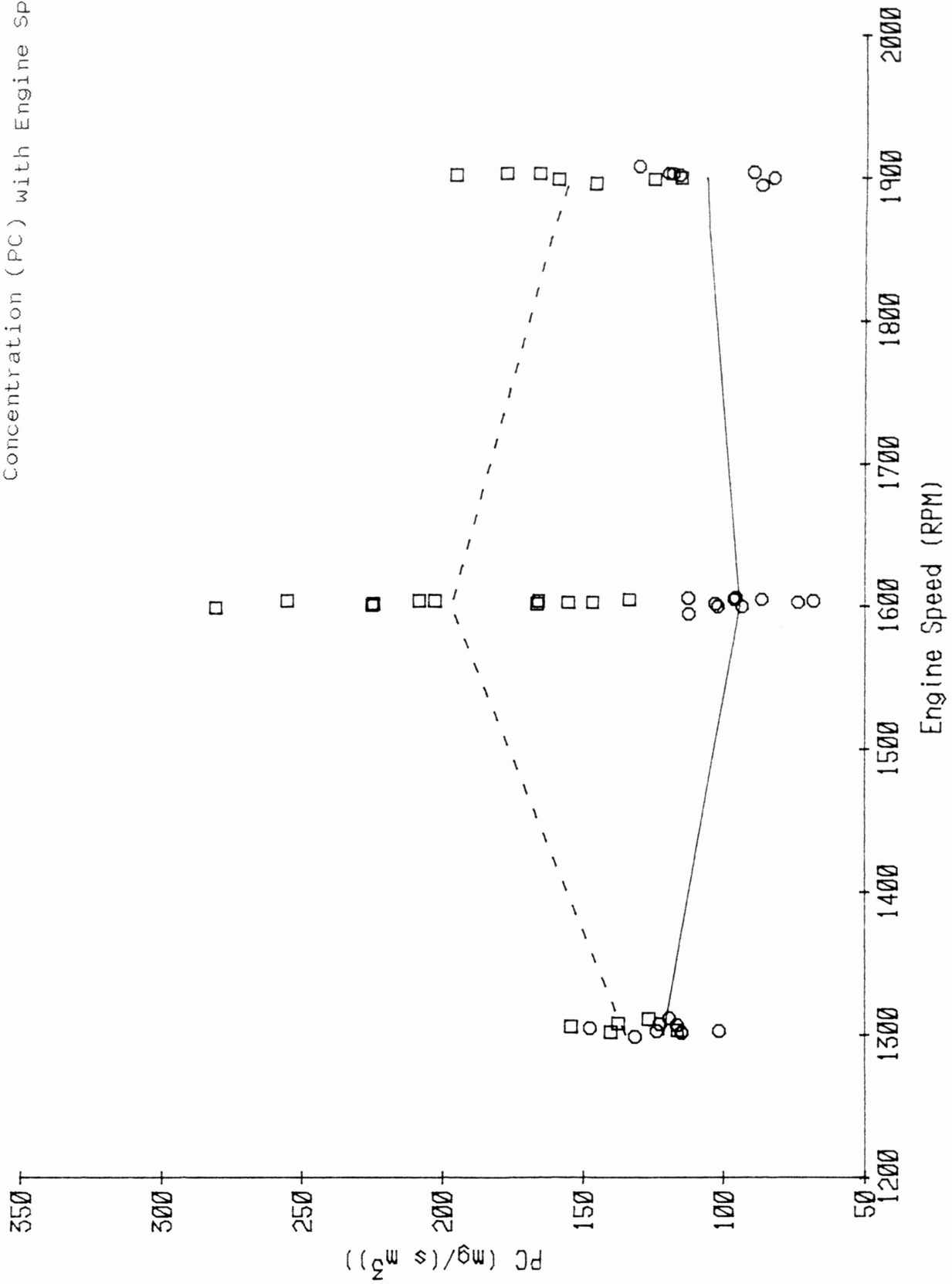
### VARIATION OF PER WITH ENGINE SPEED

Particulate emission rate remained approximately constant at lower engine speeds and exhibited a rise at high speed on the baseline fuel. The average PER was  $55.9 \text{ mg/min}$  at 1300 rpm,  $51.0 \text{ mg/min}$  at 1600 rpm, and  $65.0 \text{ mg/min}$  at 1900 rpm.

With the modified fuel, average PER displayed modest increase at 1300 rpm to  $61.0 \text{ mg/min}$ , then rose sharply and leveled off to  $110.0 \text{ mg/min}$  at 1600 rpm and  $98.6 \text{ mg/min}$  at 1900 rpm. These increases are 9.1%, 115.7%, and 51.7% with respect to baseline data.

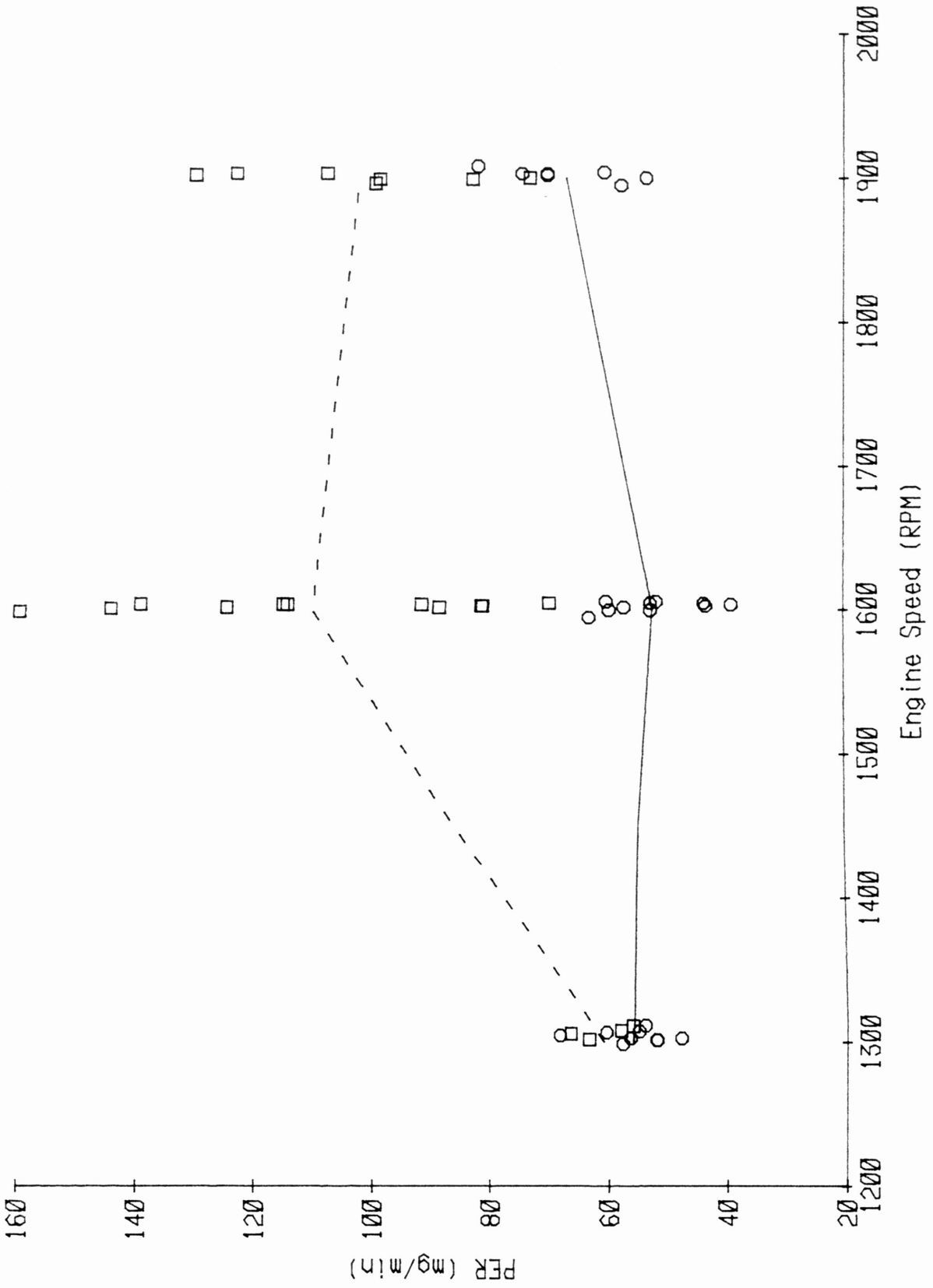
Variation of particulate emission rate with engine speed is depicted in Figure 3 for both fuels.

Figure 2 Variation of Particulate Concentration (PC) with Engine Speed



Baseline: 0 —      Modified: □ - -

Figure 3 Variation of Particulate  
Emission Rate (PER) with Engine Speed



Baseline: ○ — Modified: □ - -

## VARIATION OF SPE WITH ENGINE SPEED

The baseline fuel showed a significant decrease in specific particulate emission at higher engine speeds. Average SPE was found to be 0.764 g/bhp·hr at 1300 rpm, 0.567 g/bhp·hr at 1600 rpm, and 0.572 g/bhp·hr.

Comparitavely, average SPE for the modified fuel remained about the same at 1300 rpm with 0.796 g/bhp·hr, peaked at 1600 rpm with 1.185 g/bhp·hr, and tapering off at 1900 rpm to 0.879 g/bhp·hr. These levels represent increases of 4.2%, 109.0%, and 53.7%, respectively, over the baseline case.

Figure 4 shows variation of specific particulate emission with engine speed for both baseline and modified fuels.

## VARIATION OF PEI WITH ENGINE SPEED

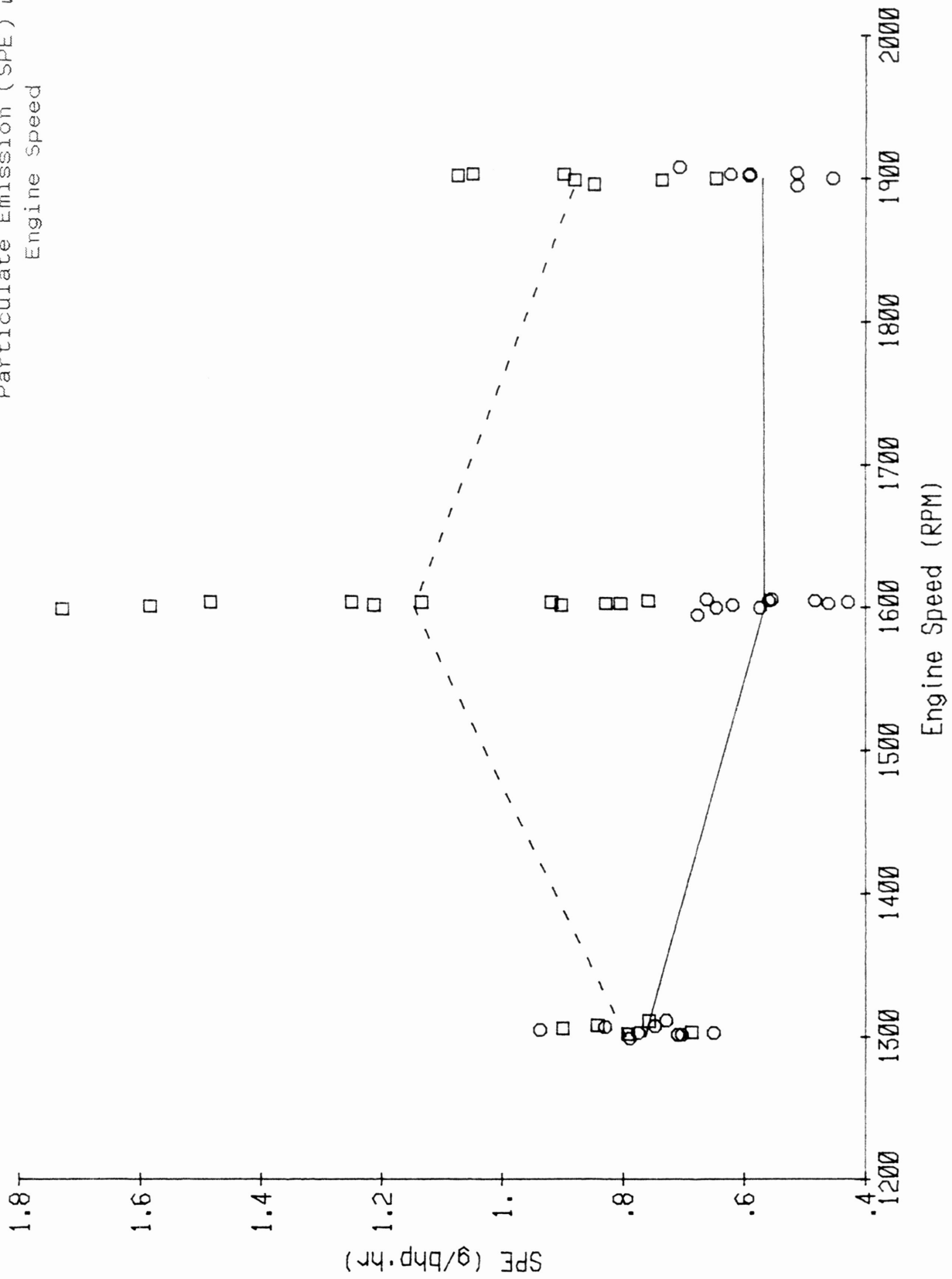
Operation on baseline fuel indicated similar trends for particulate emission index as for SPE. Average values for PEI were 3.36 g·part./kg·fuel at 1300 rpm, 2.49 g·part./kg·fuel at 1600 rpm, and 2.52 g·part./kg·fuel at 1900 rpm.

The modified fuel displayed increased levels at all speeds: 3.89 g·part./kg·fuel at 1300 rpm, 5.24 g·part./kg·fuel at 1600 rpm, and 3.96 g·part./kg·fuel at 1900 rpm. These values represent 15.8%, 110.4%, and 57.1% increases, respectively, over baseline levels.

Figure 5 presents variation of particulate emission index with engine speed for both fuels.

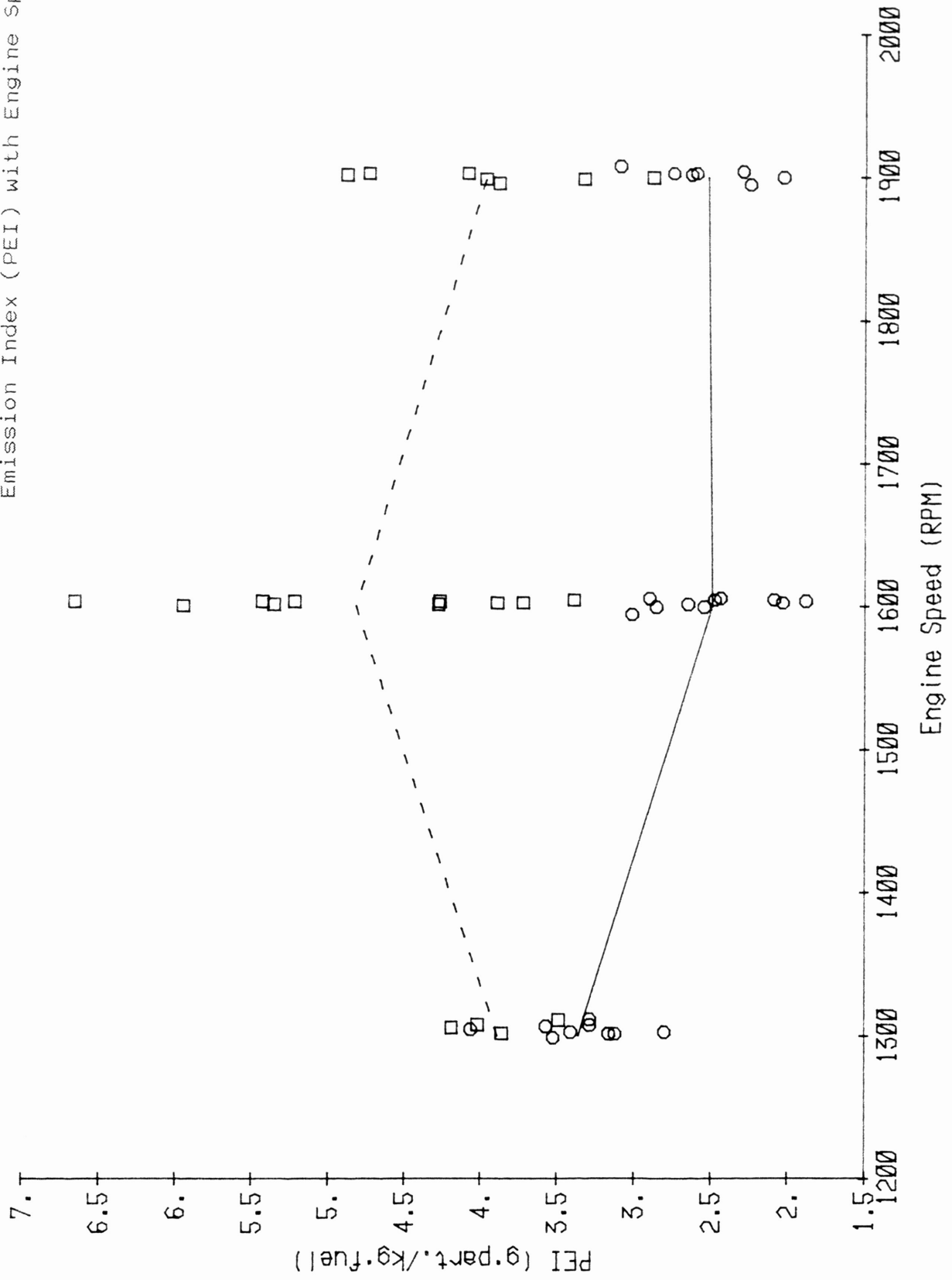


Figure 4 Variation of Specific Particulate Emission (SPE) with Engine Speed



Baseline: 0 — Modified: □ - -

Figure 5 Variation of Particulate Emission Index (PEI) with Engine Speed

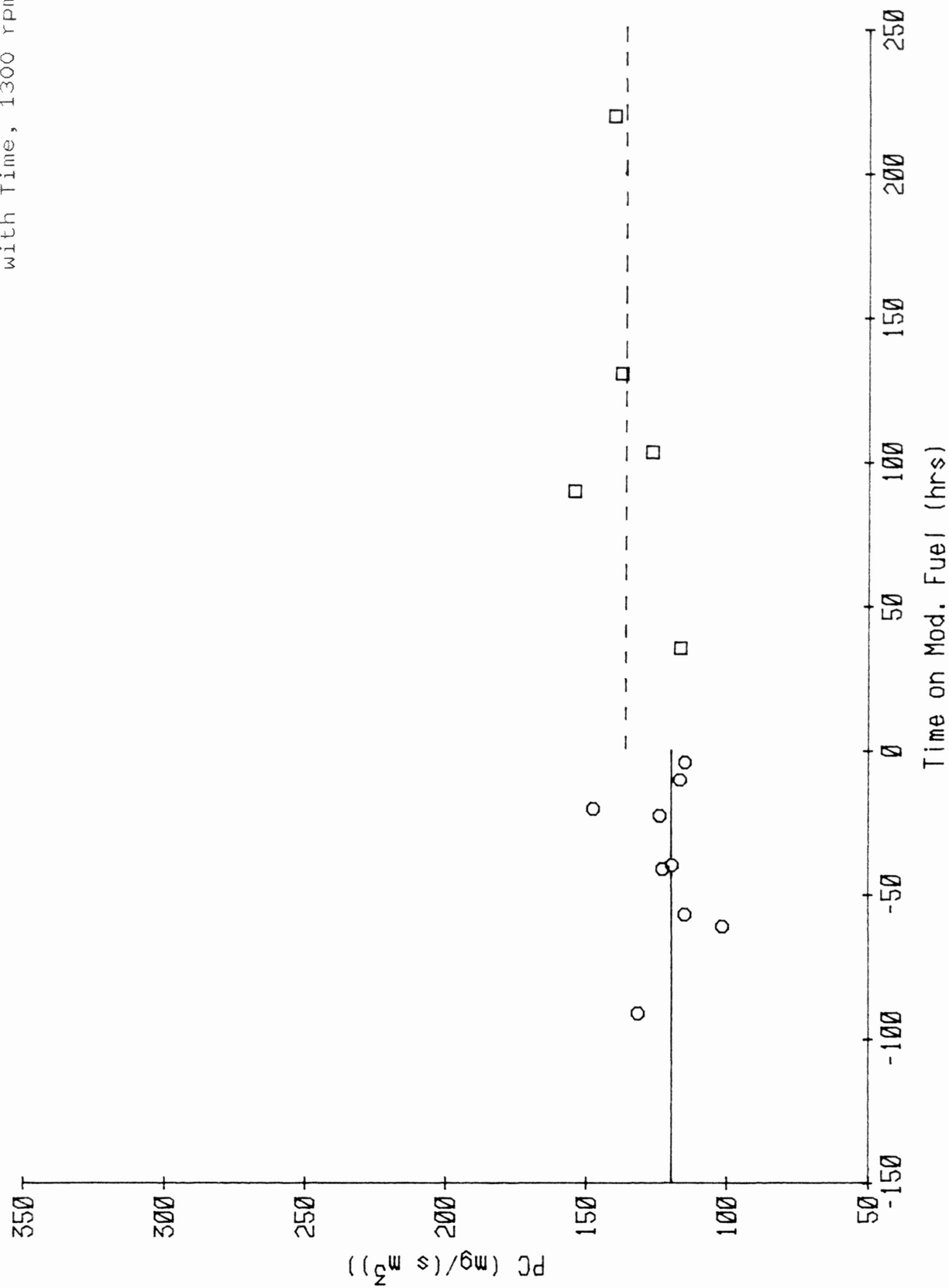


Baseline: ○ — Modified: □ - -

## VARIATION OF PC WITH TIME

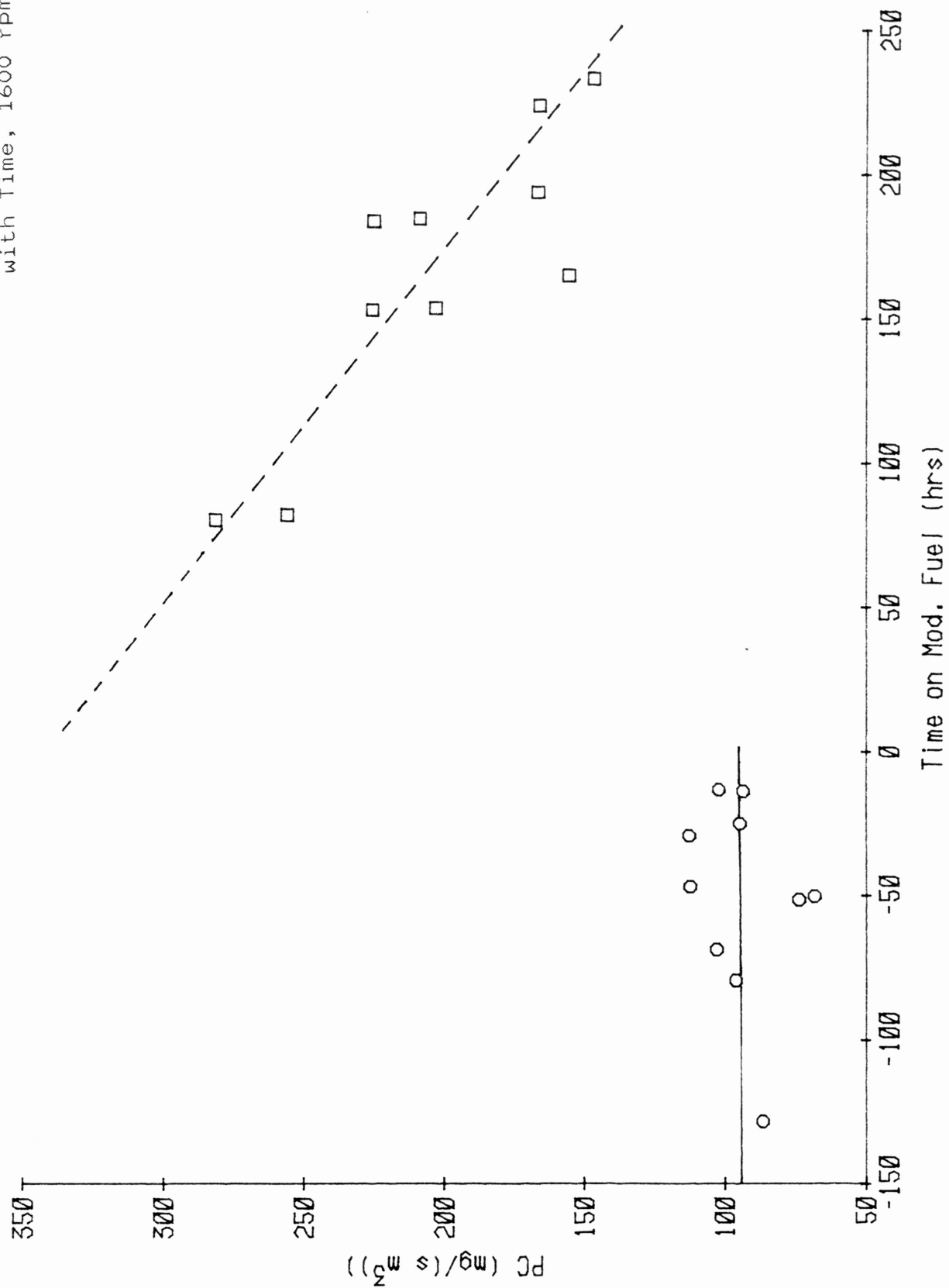
Figures 6 through 8 depict the variation of PC over time for 1300 rpm, 1600 rpm, and 1900 rpm, respectively. Note that the ordinate axis has been normalized to operating time on modified fuel; baseline operation shows as negative hours of operation. Baseline operation is assumed to be steady-state, and therefore PC is approximately time invariant for all three operating conditions. Figures 6 and 8 also indicate that PC is not greatly dependent on time. Figure 7, however, shows a marked initial increase in PC followed by a strong decreasing trend with increasing time. The function, approximated linearly, yields a  $0.738 \text{ mg/m}^3$  decrease in PC per hour of engine operation for the modified fuel. It is not clear why the transient effect was observed only for 1600 rpm.

Figure 6 Variation of PC  
with Time, 1300 rpm



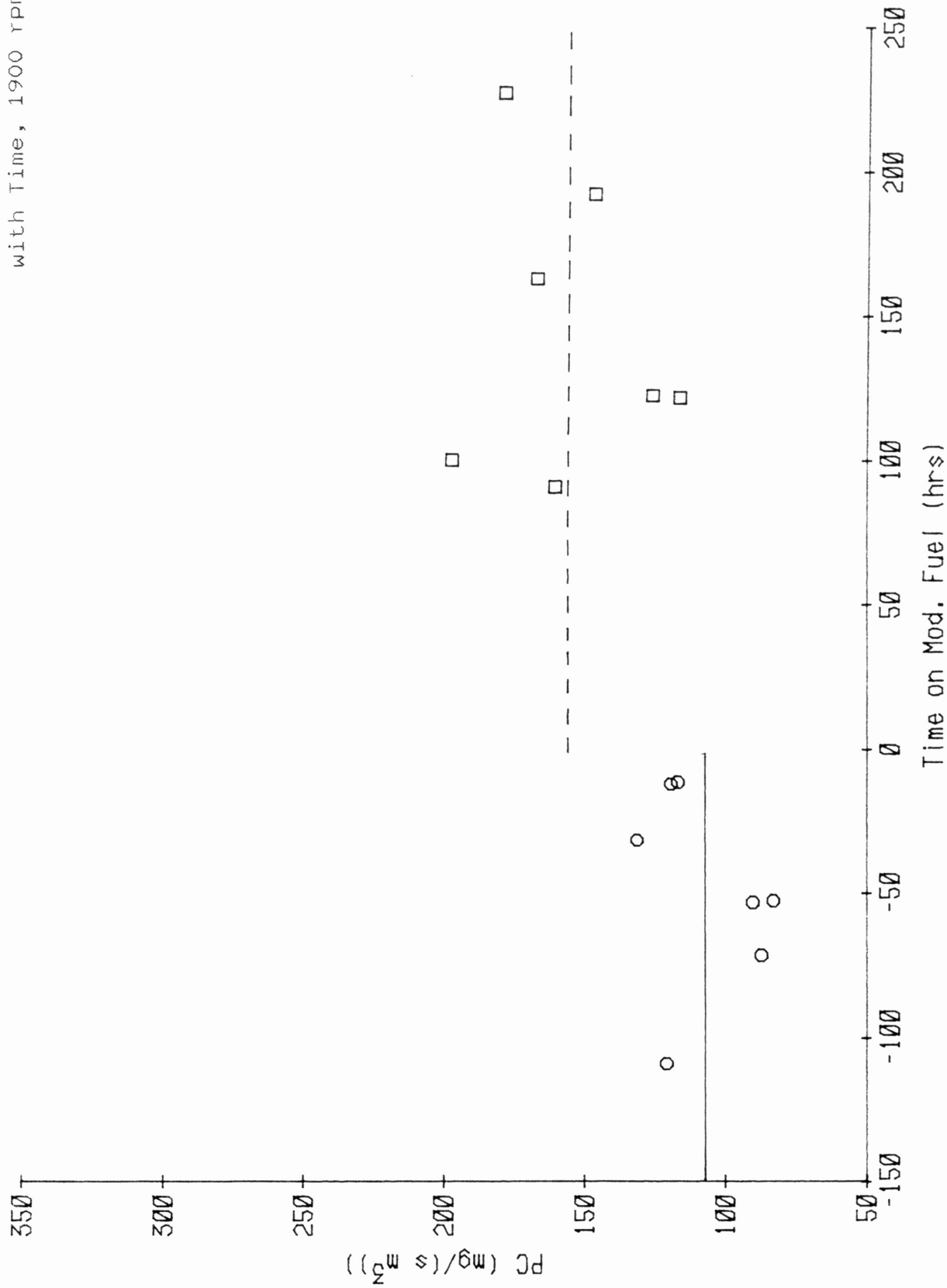
Baseline: 0 — Modified: □ - -

Figure 7 Variation of PC  
with Time, 1600 rpm



Baseline: 0 — Modified: □ - -

Figure 8 Variation of PC  
with Time, 1900 rpm

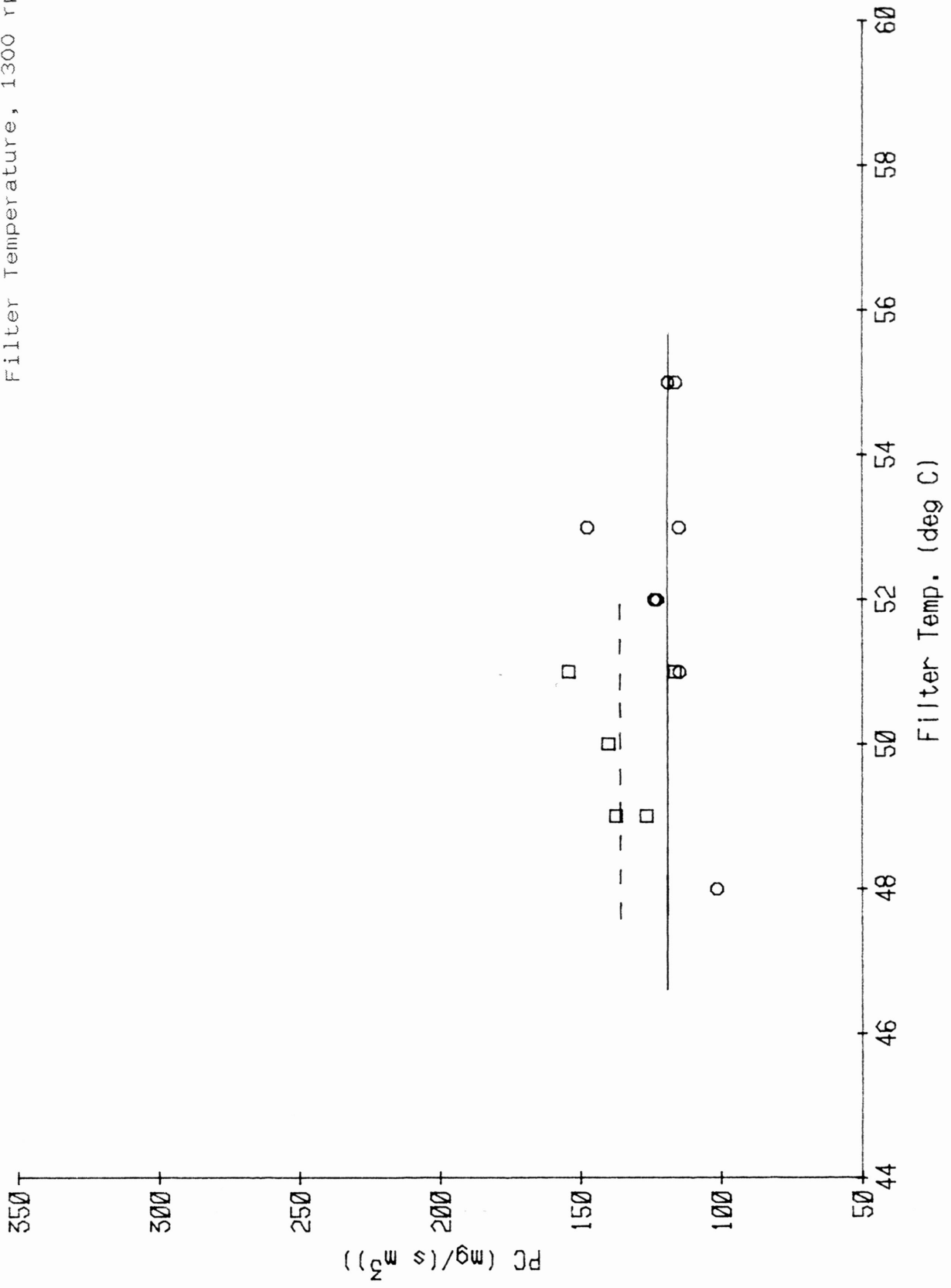


Baseline: ○ — Modified: □ - -

## VARIATION OF PC WITH FILTER TEMPERATURE

Figures 9 through 11 illustrate the effect of filter temperature on PC for 1300 rpm, 1600 rpm, and 1900 rpm, respectively. For the narrow range of sample temperatures obtained, no temperature dependence was observed for either fuel at both 1300 rpm and 1900 rpm. However, at 1600 rpm, Figure 10 demonstrates contradictory behaviour between the PCs for the two fuels. While PC decreases at a rate of  $4.87 \text{ mg/m}^3$  per deg C for the baseline fuel, PC for the modified fuel increases at a rate of  $7.17 \text{ mg/m}^3$  per deg C. An apparent explanation fails to present itself.

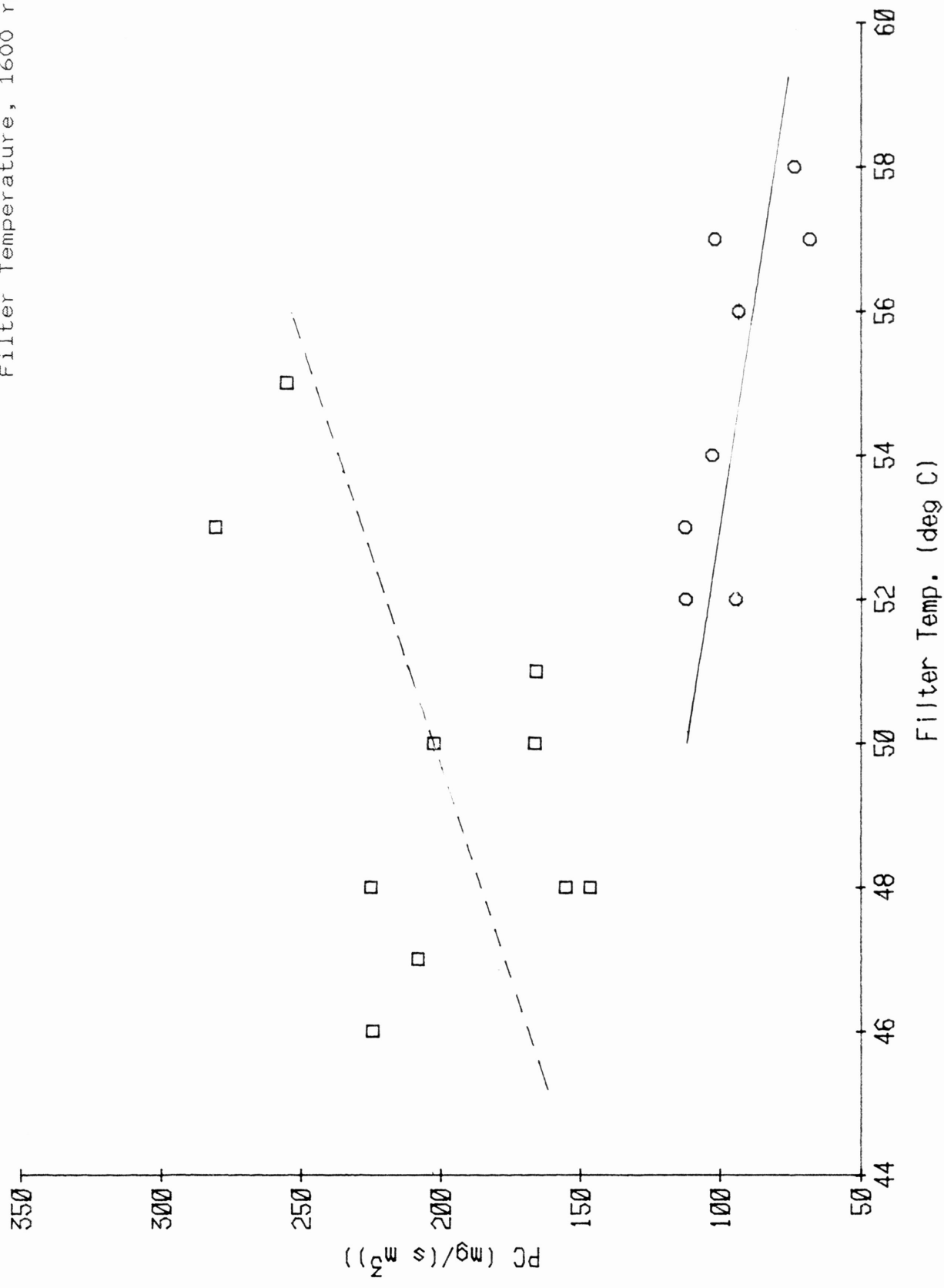
Figure 9 Variation of PC with  
Filter Temperature, 1300 rpm



Baseline: o — Modified: □ - -

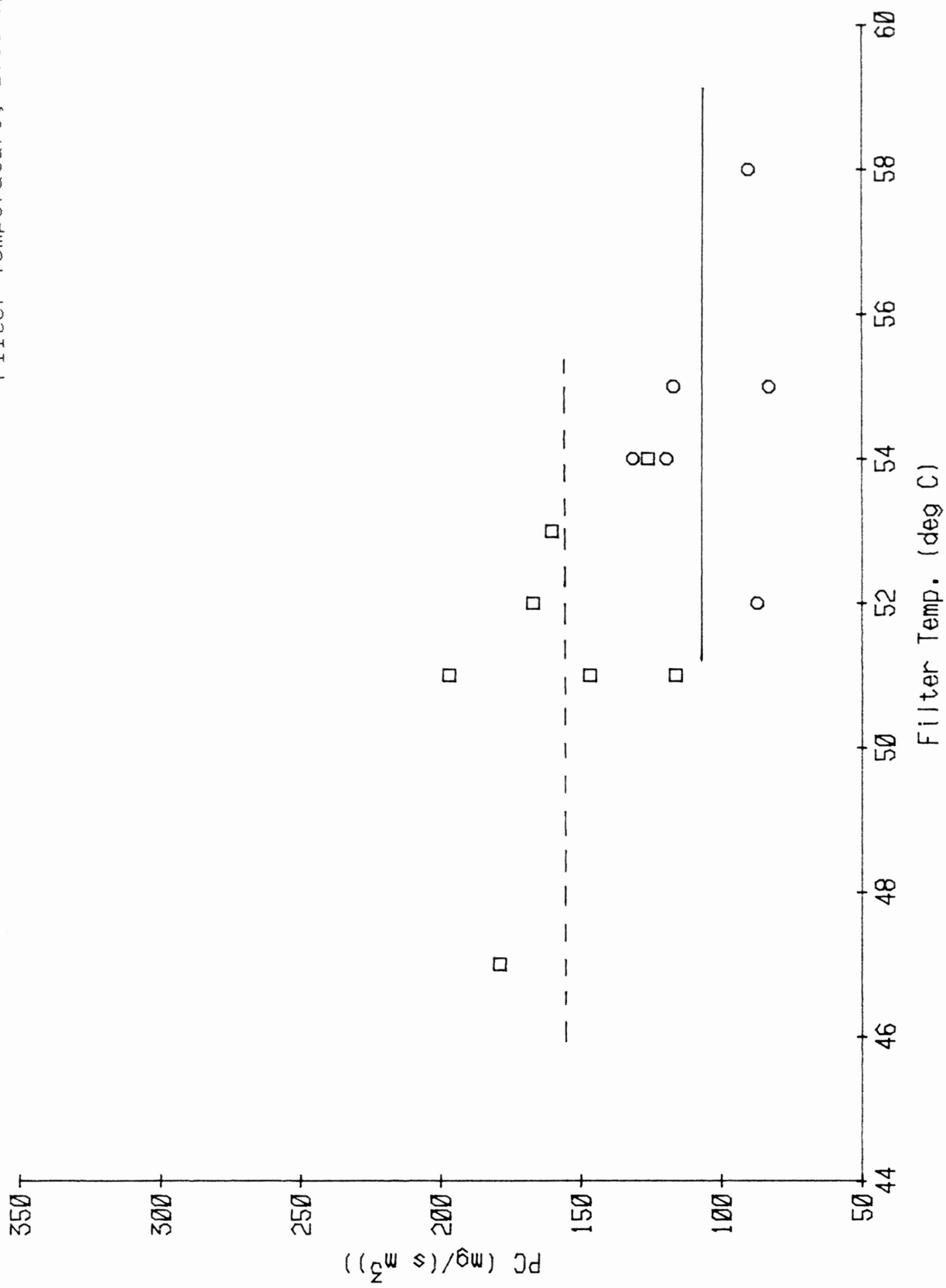


Figure 10 Variation of PC with Filter Temperature, 1600 rpm



Baseline: ○ — Modified: □ - -

Figure 11 Variation of PC with Filter Temperature, 1900 rpm

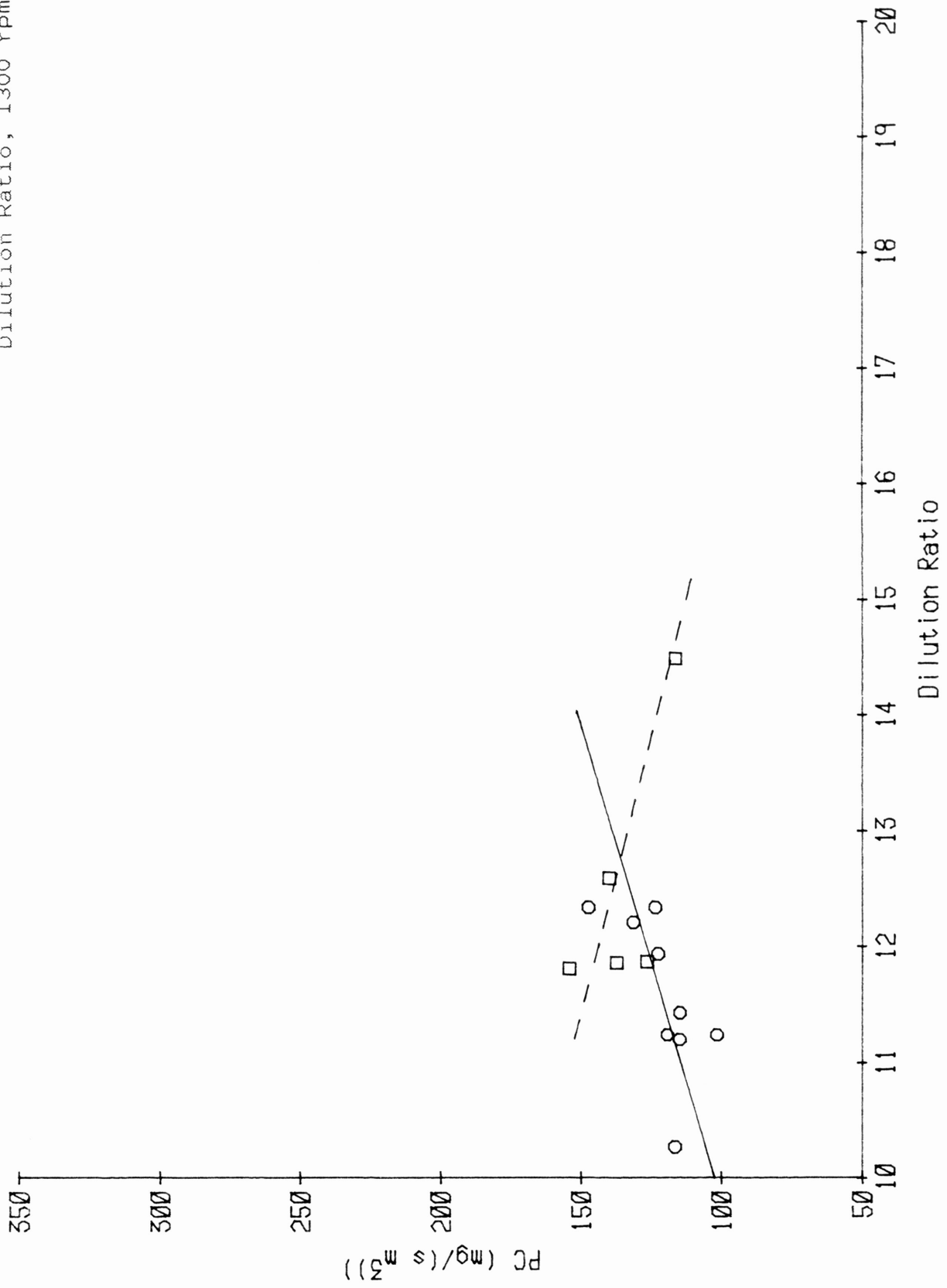


Baseline: o — Modified: □ - -

## VARIATION OF PC WITH DILUTION RATIO

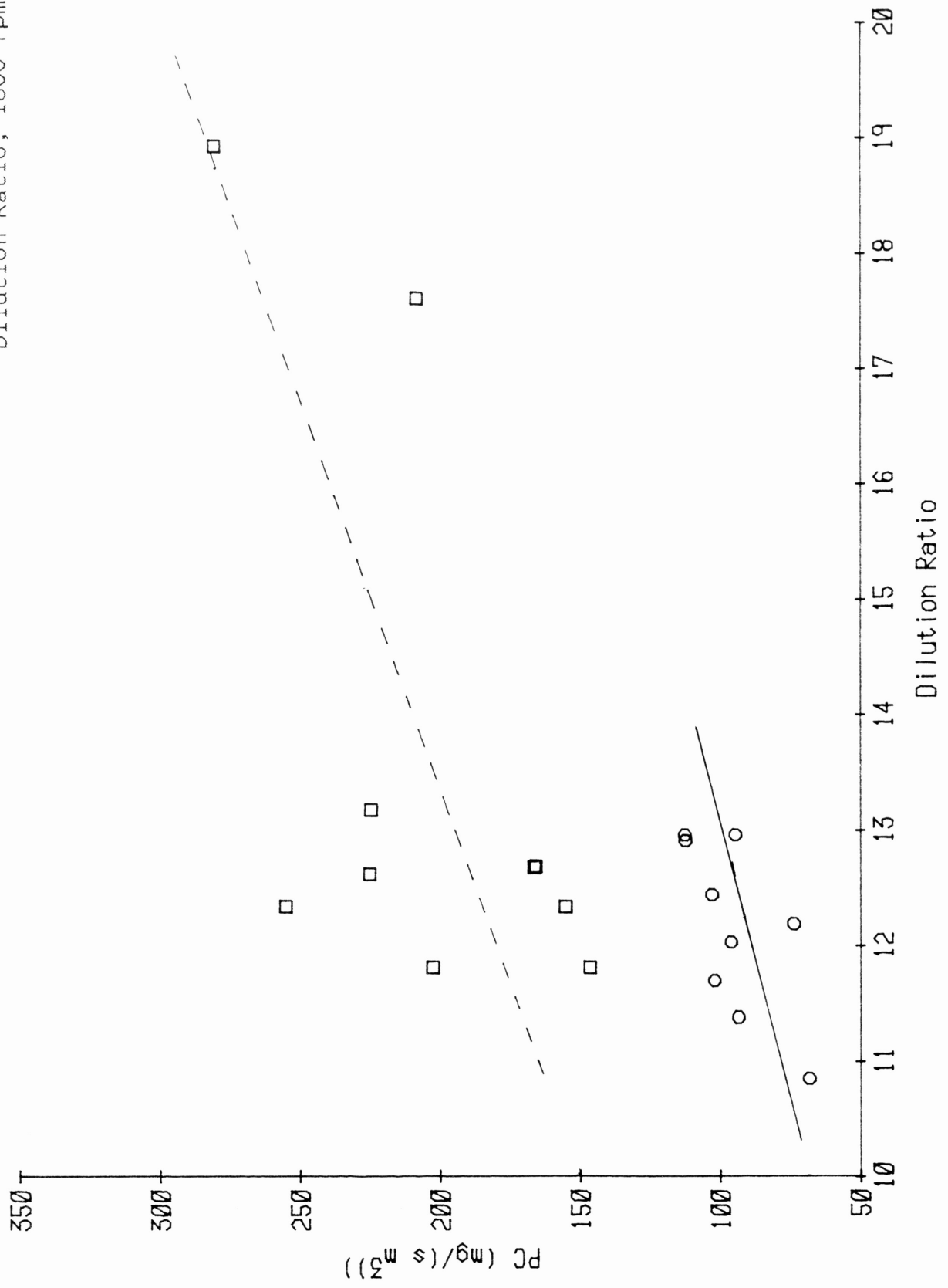
Figures 12 through 14 show the effect of dilution ratio on PC at 1300 rpm, 1600 rpm, and 1900 rpm, respectively. A strong dependence of PC on dilution ratio was observed for all three operating conditions for both fuels over the range of dilution ratios observed. Figure 12 depicts anomalous behaviour at 1300 rpm. While PC for the baseline fuel increases at a rate of  $12.00 \text{ mg/m}^3$  per unit increase in dilution ratio, modified fuel PC results decrease at a  $8.75 \text{ mg/m}^3$  rate per unit dilution ratio increase. No obvious explanation arises for the anomaly. Figures 13 and 14 yield rates that are in better agreement. PCs rise at rates of  $10.42 \text{ mg/m}^3$  for baseline and  $14.90 \text{ mg/m}^3$  for modified at 1600 rpm, and at rates of  $7.66 \text{ mg/m}^3$  for baseline and  $19.84 \text{ mg/m}^3$  for modified at 1900 rpm.

Figure 12 Variation of PC with  
Dilution Ratio, 1300 rpm



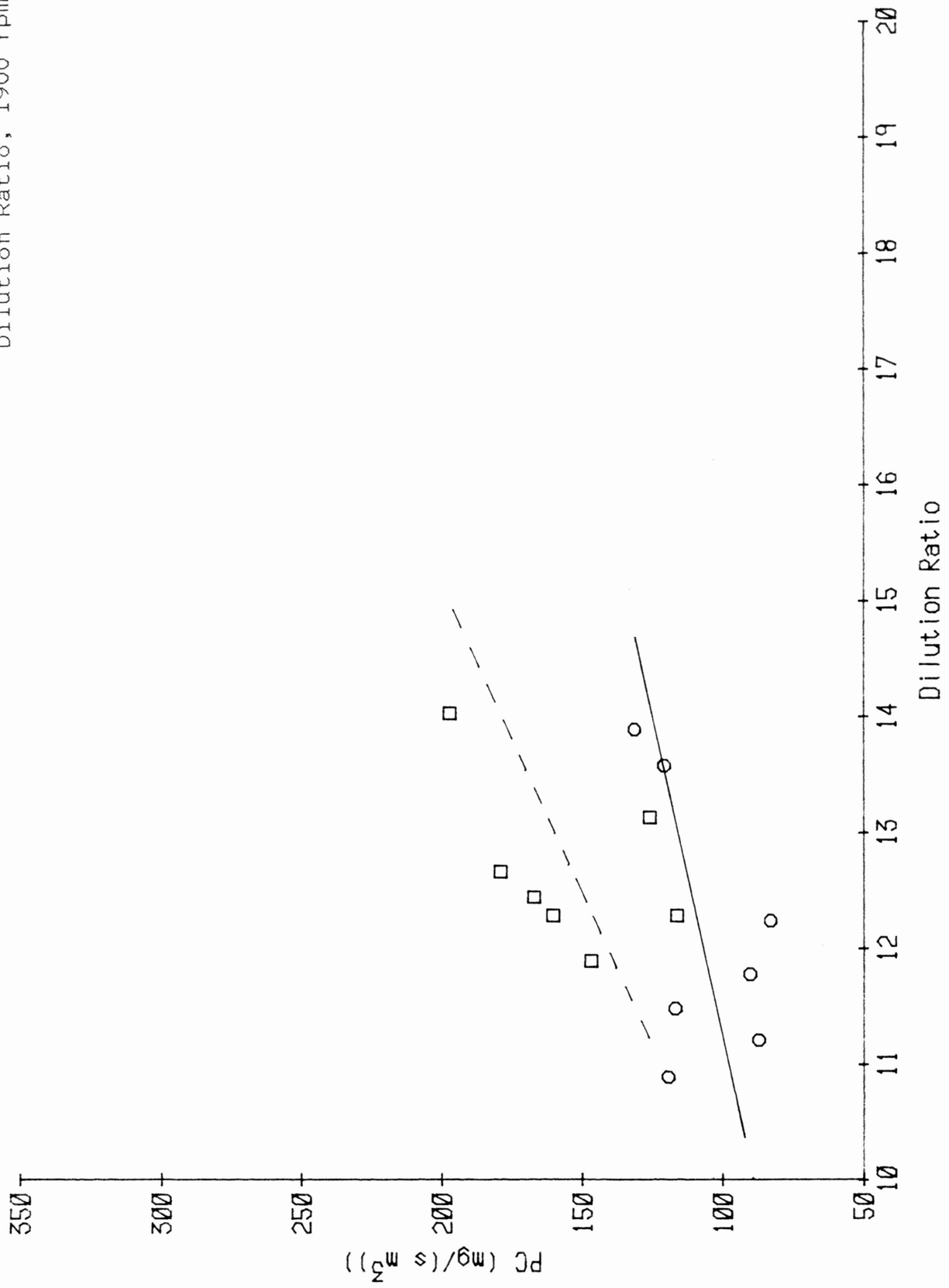
Baseline: ○ —      Modified: □ - -

Figure 13 Variation of PC with Dilution Ratio, 1600 rpm



Baseline: ○ — Modified: □ - -

Figure 14 Variation of PC with Dilution Ratio, 1900 rpm



Baseline: ○ — Modified: □ - -

## V. FINDINGS

The following list of findings summarizes the results and observations stemming from this investigation.

1. The additive-modified fuel exhibited increased particulate concentrations (PC), particulate emission rates (PER), specific particulate emissions (SPE), and particulate emission indices (PEI) over steady-state baseline fuel levels at all engine operating conditions tested.
2. PC for the modified fuel showed marked initial increase with strong time-dependent decay at 1600 rpm, while no transient response was observed for either fuel at 1300 rpm or 1900 rpm.
3. PC for baseline and modified fuels displayed opposing temperature dependence at 1600 rpm, while no temperature dependence was observed for either fuel at 1300 rpm or 1900 rpm.
4. PC for baseline and modified fuels displayed opposing dilution ratio dependence at 1300 rpm, while PC increased with increasing dilution ratio for both fuels at 1600 rpm and 1900 rpm.

## VI. CONCLUSIONS

The following list of conclusions is made based on the findings and observations from this investigation.

1. The additive-modified fuel detrimentally affects the particulate emissions and appears to be dependent on engine speed.
2. Although dilution ratio affects the particulate concentration, the excursions in dilution ratio could not entirely account for variations observed between particulate concentrations for baseline and modified fuels.



## VII. RECOMMENDATIONS

The following recommendations are made based on areas of uncertainty and deficiency encountered in this investigation.

1. Due to the temporary suspension of the project, the test matrix was unable to be completed. When research resumes, testing should continue on the modified fuel to determine steady-state characteristics of the particulate emissions obtained from long-term use.
2. The transient nature of the engine operation at 1600 rpm on the modified fuel should be investigated in an effort to identify the factors contributing to the phenomenon.
3. In order to better understand the reason for the increased particulate emissions obtained with the modified fuel, the loaded filters for both fuels should be subjected to electron micrography to determine any differences in particulate composition.
4. It would be beneficial to modify the existing dilution tunnel to provide greater control over dilution ratio and filter temperature.
5. Further research is needed to establish the effects of dilution ratio and filter temperature on particulate collection and measurement methods.

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## APPENDIX A: REDUCTION OF EXHAUST PARTICULATE DATA

The following relations were developed by Dr. J. A. Caton and were used in calculation of the results contained in the attached report.

### NOMENCLATURE

$[\text{CO}_2]_{e,d}$	- Raw exhaust $\text{CO}_2$ concentration, dry basis (Vol%)
$[\text{CO}_2]_{d,d}$	- Diluted exhaust $\text{CO}_2$ concentration, dry (Vol%)
$[\text{CO}_2]_{a,d}$	- Diluent air $\text{CO}_2$ concentration, dry (Vol%)
$[\text{CO}_2]_{e,w}$	- Raw exhaust $\text{CO}_2$ concentration, wet basis (Vol%)
$[\text{CO}_2]_{d,w}$	- Diluted exhaust $\text{CO}_2$ concentration, wet (Vol%)
$[\text{CO}_2]_{a,w}$	- Diluent air $\text{CO}_2$ concentration, wet (Vol%)
$[\text{H}_2\text{O}]_{e,d}$	- Raw exhaust water concentration, dry (Vol%)
$[\text{H}_2\text{O}]_{d,d}$	- Diluted exhaust water concentration, dry (Vol%)
$\text{DR}_{\text{dry}}$	- Dilution ratio, dry basis
$\text{DR}_{\text{wet}}$	- Dilution ratio, wet basis
$\Delta m$	- Particulate mass (mg)
$\Delta t$	- Time of collection period (min)
F	- Flowmeter reading ( $\text{ft}^3/\text{hr}$ )
$p_{\text{avg}}$	- Average pressure at flowmeter (in Hg vac)
$T_{\text{avg}}$	- Temperature at flowmeter (deg C)
$F_c$	- Corrected flow rate through filter ( $\text{s ft}^3/\text{hr}$ )
$F_{c,m}$	- Metric corrected flow rate ( $\text{s m}^3/\text{min}$ )

P	- Engine brake power (bhp)
$\dot{m}_f$	- Fuel mass flow rate (g/min)
AF	- Air-fuel mass ratio
$\dot{m}_e$	- Exhaust mass flow rate (g/min)
$\rho_{STP}$	- Density of exhaust gases at STP ( $\text{g}/\text{cm}^3$ )
$\dot{V}_e$	- Exhaust volume flow rate ( $\text{s m}^3/\text{min}$ )
PC	- Exhaust particulate concentration ( $\text{mg}/\text{s m}^3$ )
PER	- Particulate emission rate (mg/min)
SPE	- Specific particulate emission (g/bhp·hr)
PEI	- Particulate Emission Index (g·part./kg·fuel)

## MEASUREMENTS

$[\text{CO}_2]_{e,d}$	$\Delta m$	$p_{avg}$	P
$[\text{CO}_2]_{d,d}$	$\Delta t$	$T_{avg}$	$\dot{m}_f$
$[\text{CO}_2]_{a,d}$	F		$\rho_{STP}$

## CALCULATIONS

Determination of Dilution Ratio:

$$DR_{dry} = \frac{[\text{CO}_2]_{e,d} - [\text{CO}_2]_{a,d}}{[\text{CO}_2]_{d,d} - [\text{CO}_2]_{a,d}}$$

Assume

$$[\text{CO}_2]_{a,w} = [\text{CO}_2]_{a,d}$$

From stoichiometric considerations,

$$[\text{CO}_2]_{e,w} = (0.996 - [\text{CO}_2]_{e,d}/116) * [\text{CO}_2]_{e,d}$$

$$[\text{H}_2\text{O}]_{e,d} = 0.909 [\text{CO}_2]_{e,d}$$

$$[\text{H}_2\text{O}]_{d,d} = [\text{H}_2\text{O}]_{e,d} / \text{DR}_{\text{dry}}$$

$$[\text{CO}_2]_{d,w} = \frac{100 [\text{CO}_2]_{d,d}}{100 + [\text{H}_2\text{O}]_{d,d}}$$

Then

$$\text{DR}_{\text{wet}} = \frac{[\text{CO}_2]_{e,w} - [\text{CO}_2]_{a,w}}{[\text{CO}_2]_{d,w} - [\text{CO}_2]_{a,w}}$$

Corrected Flow Rate through Filter:

$$F_c = F \left[ \frac{273}{T_{\text{avg}} + 273} \right]^{1/2} \left[ \frac{p_{\text{avg}} + 29.92}{29.92} \right]^{1/2}$$

$$F_{c,m} = F_c / 2118.88$$

Exhaust Volume Flow Rate:

From stoichiometry,

$$\text{AF} = \frac{14.46}{0.0125 + 0.0647 [\text{CO}_2]_{e,d}}$$

$$\dot{m}_e = (\text{AF} + 1) \dot{m}_f$$

$$\dot{V}_e = \dot{m}_e / (\rho_{STP} 10^6)$$

Results:

$$PC = \left[ \frac{\Delta m}{F_{c,m} * \Delta t} \right] DR_{wet}$$

$$PER = PC * \dot{V}_e$$

$$SPE = 0.06 PER / P$$

$$PEI = PER / \dot{m}_f$$