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Fuel Additive and Engine Operation Effects on Diesel Soot Emissions

By H. William Zeller

U.S. DEPARTMENT OF THE INTERIOR
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UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

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CONTENTS

ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere, standard	L	liter
°C	degree Celsius	lb	pound
cfm/hp	cubic foot per minute per horsepower	mg/hp-min	milligram per horsepower-minute
cSt	centistokes	mg/m^3	milligram per cubic meter
°F	degree Fahrenheit	mg/min	milligram per minute
gal	gallon	pct	percent
h	hour	r/min	revolution per minute
hp	horsepower	vol pct	volume percent
in H_2O	inch of water	wt pct	weight percent

FUEL ADDITIVE AND ENGINE OPERATION EFFECTS ON DIESEL SOOT EMISSIONS

By H. William Zeller[1]

ABSTRACT

The Bureau of Mines performed laboratory research into the effects of a barium-based fuel additive (the "postflame" type) on diesel particulate matter (DPM) emissions. The 5.6-L, six-cylinder test engine is typical of types certifiable for use in underground mines. Test parameters consisted of additive concentration and engine loads, speed, and air intake restriction. DPM emissions, including condensed volatiles, were measured gravimetrically. Also measured were gaseous emissions including carbon monoxide, nitrogen oxides, and hydrocarbons.

The fuel additive was effective, reducing DPM up to 75 pct, when used at a concentration of 0.09 wt pct (one-fourth of the concentration recommended by the manufacturer). The additive was most effective at the highest fuel-air ratios, reducing DPM from 400 mg/m^3 for untreated fuel to 120 mg/m^3. At light loads, 25 pct of full rated, no DPM reductions were measured. Based on these results, the additive is recommended for use in diesel fuel, at a concentration of 0.09 wt pct, to power underground mining equipment as long as certain conditions are met: that a beneficial DPM reduction is verified, that the minimum required quantity of additive is used, and that potential adverse effects such as increased nitrogen oxides are checked.

[1]Physical scientist, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

Diesel-powered equipment is widely used in underground mining because of its high productivity potential and flexibility compared with electric-powered equipment. Unfortunately, diesel engines emit particulates consisting of insoluble carbonaceous agglomerates, adsorbed soluble organic compounds, and traces of other substances such as sulfates and metals. Although diesel particulate matter (DPM) levels are not specifically regulated in underground mines, DPM adds to the general dust level and aggravates efforts to comply with respirable dust standards.

To help mine operators comply with dust standards and to reduce potential occupational health problems (*1*)[2] arising from exposure to DPM emissions, the Bureau of Mines is conducting research on improved DPM control methods to supplement current controls such as ventilation, engine maintenance, and operator work practices. The emphasis, to date, has been on the evaluation of the diesel particulate filter (DPF) for coal and noncoal mines (*2-3*). However, even if successful, the DPF can be used on inby equipment in coal mines only as part of an integrated exhaust cooling and filtering system, which is currently still under development (*3*).

To provide the mining industry with alternatives to the DPF, other DPM controls, such as fuel additives, are being evaluated by the Bureau. Additives can be classified according to the problems they are designed to correct. "Preflame" additives are designed to correct problems that occur prior to burning (that is, storage stability, flow in cold weather, water contamination) and include dispersants, pour-point depressants, and emulsifiers. "Flame" additives promote complete burning of fuel in the combustion chamber and include atomizers and combustion catalysts. "Postflame" additives are designed to reduce engine deposits, smoke, and emissions.

The Bureau selected a barium-based, postflame product because earlier research by others (*4-6*) generally concluded that barium was more effective for reducing diesel soot than fuel additives such as iron or calcium compounds. The additive tested is a commercial product, Lubrizol 565 (see appendix). Prior research on postflame fuel additives by the Bureau and others was reviewed by Zeller (*7-8*).

The general objective of this work was to determine the effectiveness of a barium-based fuel additive for reducing DPM emissions. Specific objectives were as follows: (1) Determine the optimum additive concentration for minimum DPM emissions, (2) evaluate the effect of the additive on individual components of engine exhaust, (3) determine the extent of any adverse effects of the additive, and (4) compare the results with those from earlier tests on a different engine (*7-8*).

In this report, the effects of the additive on DPM emissions are examined first. Then, effects on the following specific exhaust components are examined: (1) solid diesel particulate matter (SDPM), (2) volatile diesel particulate matter (VDPM), (3) gas-phase hydrocarbons (GPHC), and (4) total exhaust hydrocarbons (TEHC), which are defined as the sum of the VDPM and the GPHC in the exhaust. Both the volatile and gas-phase hydrocarbons are considered because they contain the carcinogenic and mutagenic compounds that may have adverse health effects on workers exposed to diesel exhaust (*1*). The effects of the additive on both carbon monoxide (CO) and nitrogen oxides (NO_x) are also reported. Finally, the results for DPM emissions are compared with those from a different engine tested with the same additive.

ACKNOWLEDGMENTS

The author gratefully acknowledges the contributions of Carl Anderson, physical scientist, Twin Cities Research Center, who did the special programming required for the engine control system, and Robert G. Vandenbos, electronics technician, Twin Cities Research Center, who ensured the proper operation and calibration of the exhaust emissions measuring instruments and associated data acquisition systems.

APPARATUS AND PROCEDURES

The Bureau's Diesel Emissions Research Laboratory consists of three adjoining rooms: the control room, the engine test cell, and the emissions room. Figure 1 shows the general layout of the laboratory and identifies the major hardware used or available for this study. Details of this facility have been published (*7*).

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

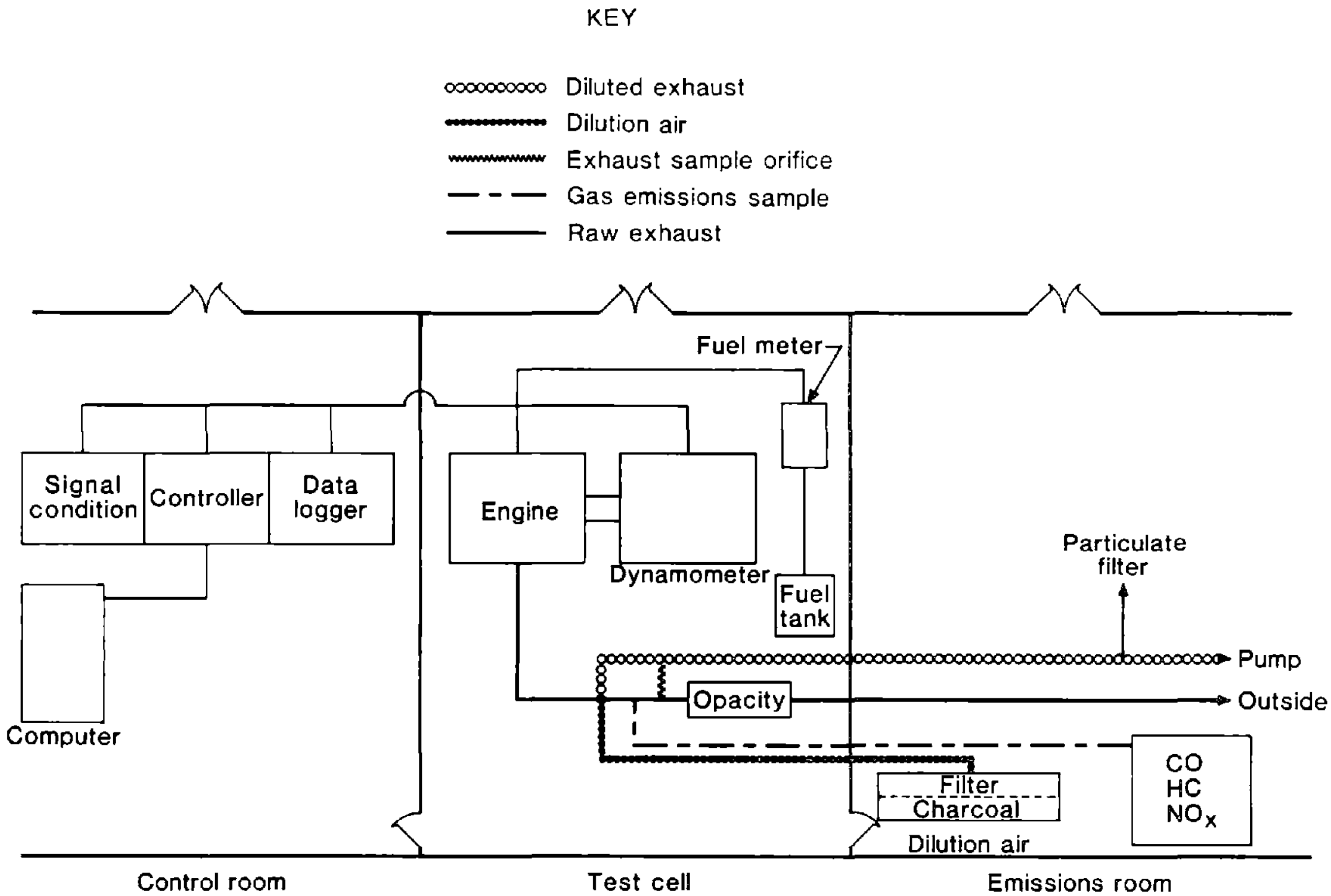

Figure 1.–Diesel engine emissions research laboratory.

ENGINE TEST CONDITIONS

Most of the results presented in this report were obtained from tests conducted on a Deutz[3] F6L 912W six-cylinder, four-cycle, diesel engine. Versions of this indirect-injected, naturally aspirated, air-cooled, 5.6-L engine are certified for underground coal mine use by the U.S. Mine Safety and Health Administration (MSHA) and are rated for 82 hp at 2,300 r/min. The engine complied with factory specifications for power, fuel consumption, and gaseous emissions. For the purpose of comparing different engines, selected results from previous tests (*7-8*) on a Caterpillar 3304 engine are also presented. The Caterpillar engine is generally similar to the Deutz engine except that it is water cooled and has four cylinders instead of six.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

Engine loads were applied by an eddy-current universal dynamometer and were controlled by a microprocessor system that maintains precise speed (±1 r/min) and load (±0.1 pct). A data acquisition system recorded up to 48 analog inputs from various transducers such as thermocouples and pressure transducers.

All the tests were conducted at steady-state conditions. The engine was started and brought to normal operating temperature before any test sequence was begun. Changes in intake air density affect the fuel-air ratio to the extent that DPM emissions from some engines, operated at or near peak torque loads, can increase about 10 pct for each 1 pct decrease in the air intake density (*7*). For this reason, controls on the engine intake system are used for maintaining air intake conditions. The manual temperature and automatic pressure controls can maintain engine air intake density to within ±0.5 pct of set values.

Three air intake conditions or restrictions were adopted. At an air temperature of 77° F (25° C), the small, medium, and large intake restrictions are respectively equivalent to pressure drops into the engine of 8, 28, and 53 in H_2O from 1 atm. In practice, both the temperature and pressure of the engine intake air were controlled to maintain air densities equivalent to the temperature-pressure combinations listed. Note that the small-restriction condition is equivalent to the Society of Automotive Engineers (SAE) (*9*) recommended power test conditions for dry air. All emissions data reported here are adjusted to SAE conditions of temperature and pressure.

Engine exhaust back pressures are controlled by a combination of a butterfly valve and an exhaust fan. Most engine tests were conducted with only a few inches of water back pressure. A few tests were conducted at back pressures up to 40 in H_2O, the engine manufacturer's rated maximum (*10-11*).

FUEL, OIL, AND ADDITIVE MIXING

All the tests were conducted with the same batch of No. 2-D fuel. No chemical analysis for this fuel is available. The crankcase oil was SAE 30 weight and was changed at 100-h intervals.

The additive was premixed, by weight, with the fuel in 55-gal drums prior to testing. Between runs involving different fuel mixtures, the engine fueling system was drained to prevent fuel used in prior tests from influencing the results of subsequent tests. Any residual old fuel remaining in the system after draining was purged by operating the engine for at least 1 h using the new fuel mixture.

EMISSIONS MEASUREMENT

Approximately 3 pct of the raw exhaust was diluted and transported to the sampling section (fig. 1) where the DPM was collected on fluorocarbon-coated, glass-fiber filters. Dilution was always sufficient to maintain filter temperatures below 125° F. The volatile particulate on the filters was determined gravimetrically after treatment in a vacuum oven at a temperature of 392° F. Measurements of nitrogen oxides, carbon monoxide, and gas-phase hydrocarbons were made on undiluted exhaust transported through a heated (350° F) line (fig. 1).

RESULTS AND ANALYSIS

PARTICULATE EMISSIONS

The two largest components of DPM are the solid fraction, composed mainly of carbon and sulfate for untreated fuels, and the volatile fraction, which is derived from fuel and engine lubricant. For barium-treated fuel, the solid DPM also contains barium compounds. In the following sections, the effects of engine operating parameters on DPM are presented followed by an examination of the effects of barium on total DPM and on the two main fractions–solid and volatile.

Diesel Particulate Matter

Untreated Fuel

DPM emissions from diesel engines depend on many variables, including speed, torque or load, and air intake conditions. Figure 2 compares the average DPM mass concentration for the Deutz engine at four loads, one intake condition, and one speed. Other speed and intake conditions produce similar plots. Figure 2 shows that the lowest DPM concentrations (40 mg/m^3) are measured at 75 pct of full load and that lower or higher loads increase DPM. The maximum emission level (115 mg/m^3) occurs at full load.

DPM emissions are plotted for full-torque conditions at four speeds and three intake conditions (fig. 3). The overall range of emissions is almost 7:1 (60 to 400 mg/m^3). At fixed intake conditions, speed variations produce about a 3.5:1 range of DPM emissions, while at fixed speed, the intake conditions shown have about a 2:1 effect on the DPM emissions.

All the data in figures 2 and 3, plus additional results, are displayed more concisely in a single chart (fig. 4), plotting emissions against fuel-air ratio. Some of the scatter is caused by experimental error, but most of the observed spread is attributable to engine speed effects.

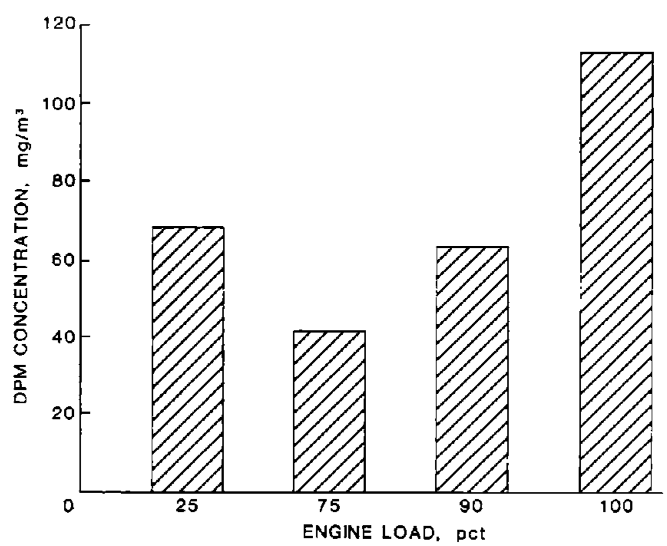

Figure 2.–DPM emissions from Deutz engine for untreated fuel, 2,300 r/min, and medium intake restriction.

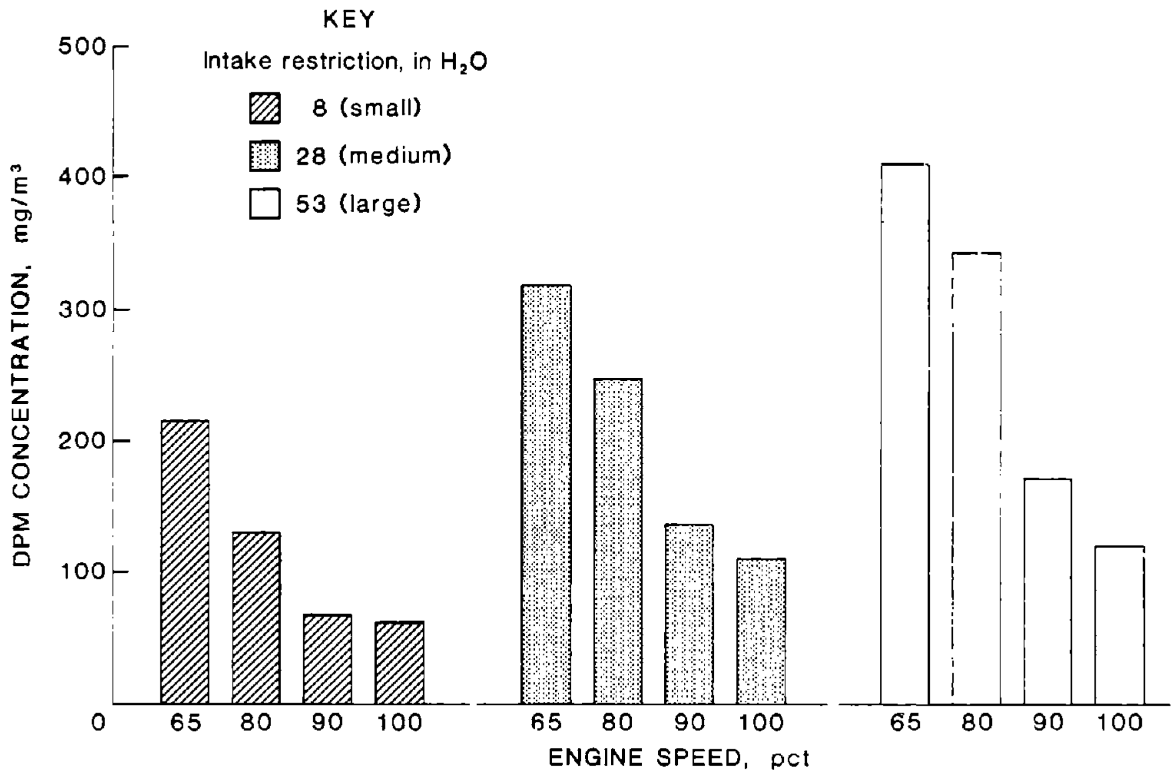

Figure 3.–DPM emissions from Deutz engine for untreated fuel, full load, four speeds, and three intake restrictions.

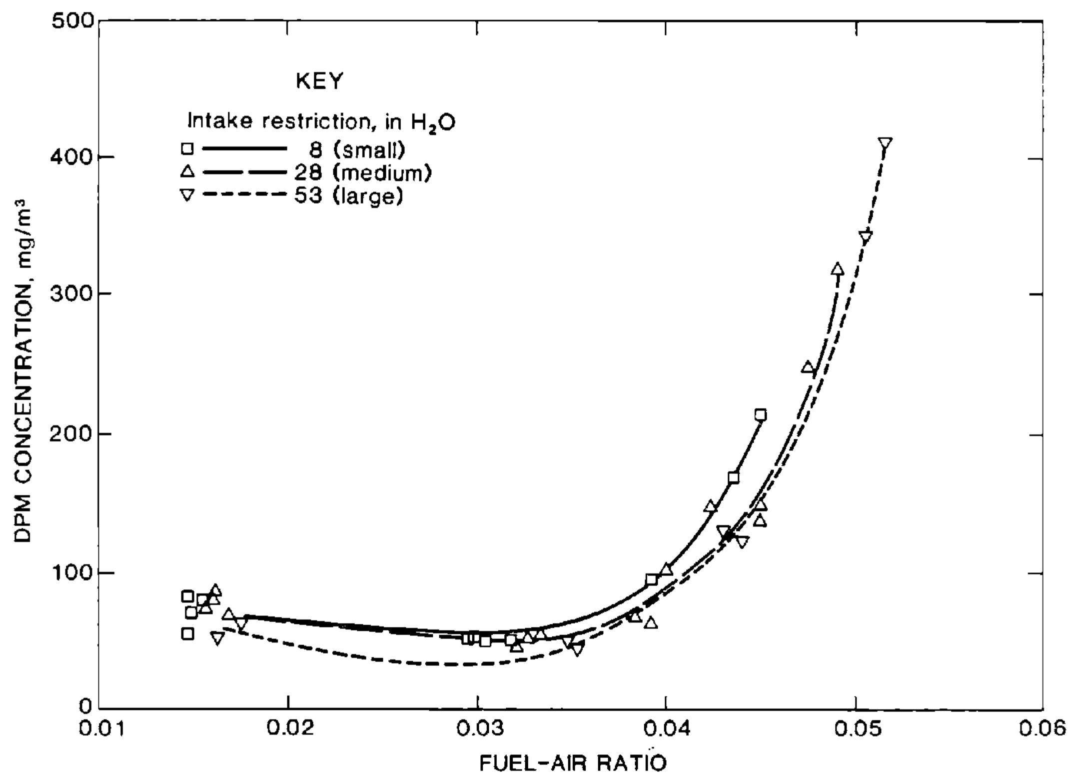

Figure 4.–DPM emissions from Deutz engine as function of fuel-air ratio for untreated fuel.

For fuel-air ratios less than 0.04, the DPM emissions range between 40 and 100 mg/m^3, with minimum emissions measured for the fuel-air range between about 0.03 and 0.035. The rapid increase in DPM emissions for fuel-air ratios greater than about 0.04 emphasizes the importance of maintaining fuel-air ratios as low as possible. This can be accomplished by proper maintenance of the engine's air and fuel systems and by not lugging the engine.

The mine ventilation required for certified engines of this type is 85 cfm/hp (*10-11*), which will dilute the exhaust by about 40:1. Applying this dilution factor to the measured emissions (figs. 2-4) indicates that the in-mine DPM levels produced by this engine will range between 1 and 10 mg/m^3. It is clear that this engine can contribute significantly to mine dusts.

Barium-Treated Fuel

The data in figure 5, which were obtained from a Caterpillar engine (*7*), illustrate two important results of using barium-treated fuel: first, barium compounds represent a substantial fraction of DPM, especially at high additive concentrations in the fuel, and second, the non-barium fraction (carbon, sulfates, and volatiles) at each of the engine loads is nearly independent of additive concentration, which suggests that the additive might effectively reduce DPM at even lower concentrations than the 0.18-wt-pct level shown.

Experiments were conducted on the Deutz engine to determine the optimum concentration required to minimize DPM emissions. The results (fig. 6) are for additive concentrations between 0.0 and 0.36 wt pct, engine speeds of 90 and 100 pct of full-rated, engine torques from 25 to 100 pct of full torque, and the medium intake restriction.

Examination of these results leads to the following observations: (1) Even the minimum additive level tested, 0.02 wt pct, reduced DPM levels, compared with untreated fuel, (2) the most effective concentration for minimum DPM emissions under the test conditions was 0.09 wt pct, (3) most of the results obtained for 0.18 and 0.36 wt pct at full engine speed indicate that these levels are too high because DPM emissions are greater than those for 0.09 wt pct.

In order to better illustrate overall trends, DPM emissions are plotted against fuel-air ratios in figure 7 for treated and untreated fuel (at different engine intake conditions, engine speeds, and engine loads). Comparing untreated-fuel results with those for the 0.09-wt-pct additive level indicates that the barium additive is not useful at fuel-air ratios smaller than about 0.02. The effectiveness as measured by DPM reduction from the untreated-fuel condition clearly improves with increasing fuel-air ratio. Also, for fuel-air ratios between 0.03 and about 0.045, DPM emissions for the 0.09-wt-pct treatment do not exceed 50 mg/m^3 while DPM levels for untreated fuel range up to 250 mg/m^3. Only at the highest fuel-air ratios tested do the results suggest that additive levels of 0.18 and 0.36 wt pct may be slightly more effective than the 0.09-wt-pct treatment.

Solid Particulate Fraction

The SDPM fraction is the material remaining on the sample filters after vacuum-oven treatment. The values of SDPM for untreated fuel (fig. 8) show how the solid fraction, in this case mostly carbon and sulfates, increases uniformly with increasing fuel-air ratio. Because the contribution of volatiles to DPM at fuel-air ratios greater than 0.03 is small, the SDPM and DPM emissions plots are similar at high fuel-air values.

To illustrate the effect of barium treatment on the particulate solids fraction, SDPM is plotted in figure 9 for one engine speed condition and three additive concentration levels. By restricting the plot to one speed, the trends for each fuel condition are clearly delineated. These data emphasize that most of the SDPM reduction attributable to the additive occurs at high fuel-air ratios; for example, a 75-pct reduction (340 to 80 mg/m^3) was obtained at the 0.05 fuel-air ratio. No solids reduction is observed for the lowest fuel-air ratios of about 0.016.

Generally, the minimum SDPM levels were measured for an additive concentration of 0.09 wt pct. At some fuel-air ratios between 0.03 and 0.035, the 0.36-wt-pct additive concentration produced slightly greater emissions than those measured for untreated fuel.

Volatile Particulate Fraction

The VDPM mass concentration ranged from 60 mg/m^3 at low fuel-air ratios to near zero at high fuel-air ratios (fig. 10). At fuel-air ratios less than 0.02, the minimum VDPM levels are for the lowest speed tested. This result agrees with that of others who found that, at light loads, lubricating oil emissions tend to increase with increasing engine speed (*12*).

The full engine speed results (fig. 11) show that the barium-additive treatment results in reduced VDPM emissions. In a later section, "Hydrocarbon Emissions," it is shown that the gas-phase hydrocarbons are either unchanged or increased slightly with the fuel treatment. Consequently, it is suggested that the VDPM reduction is caused by the large SDPM reductions (fig. 9), which in turn reduce the particulate surface available for hydrocarbon adsorption and condensation.

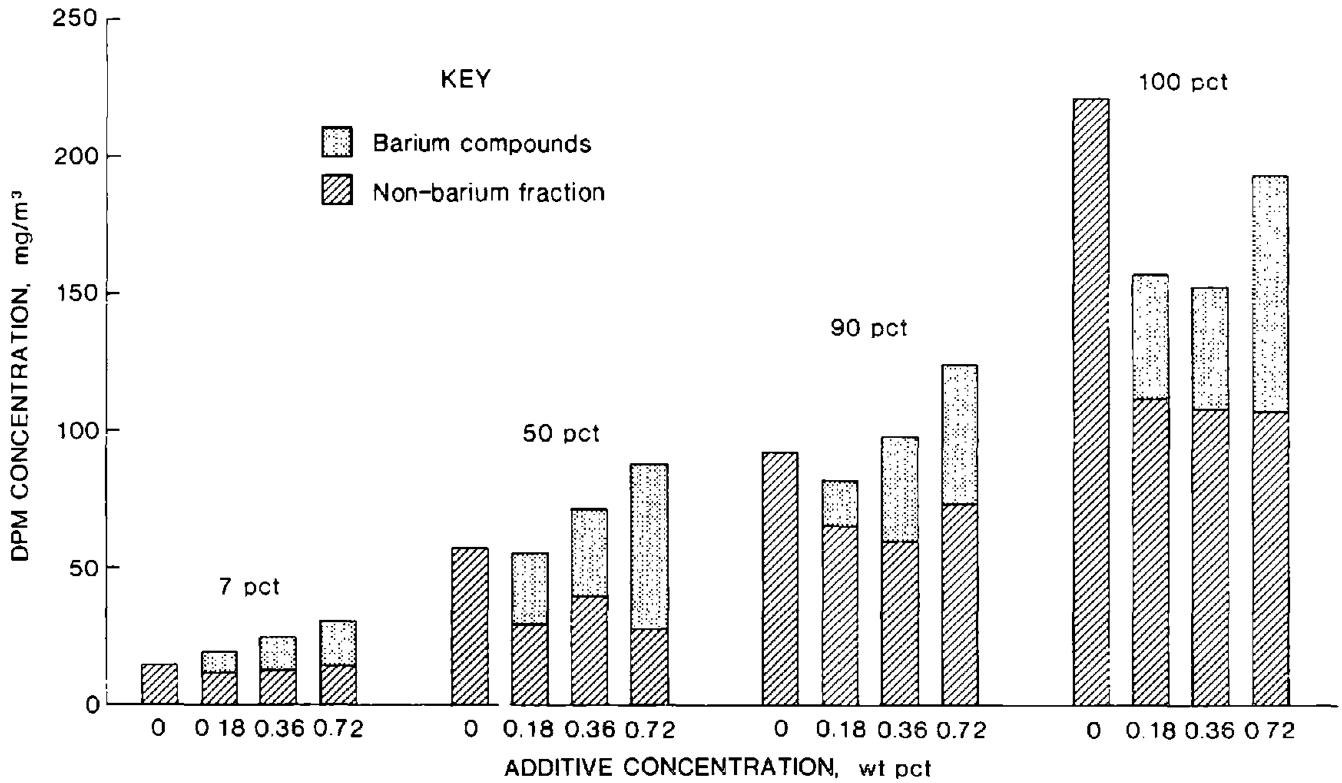

Figure 5.–Effect of barium fuel additive on DPM constituents from Caterpillar engine at 1,200 r/min and 7, 50, 90, and 100 pct of full load.

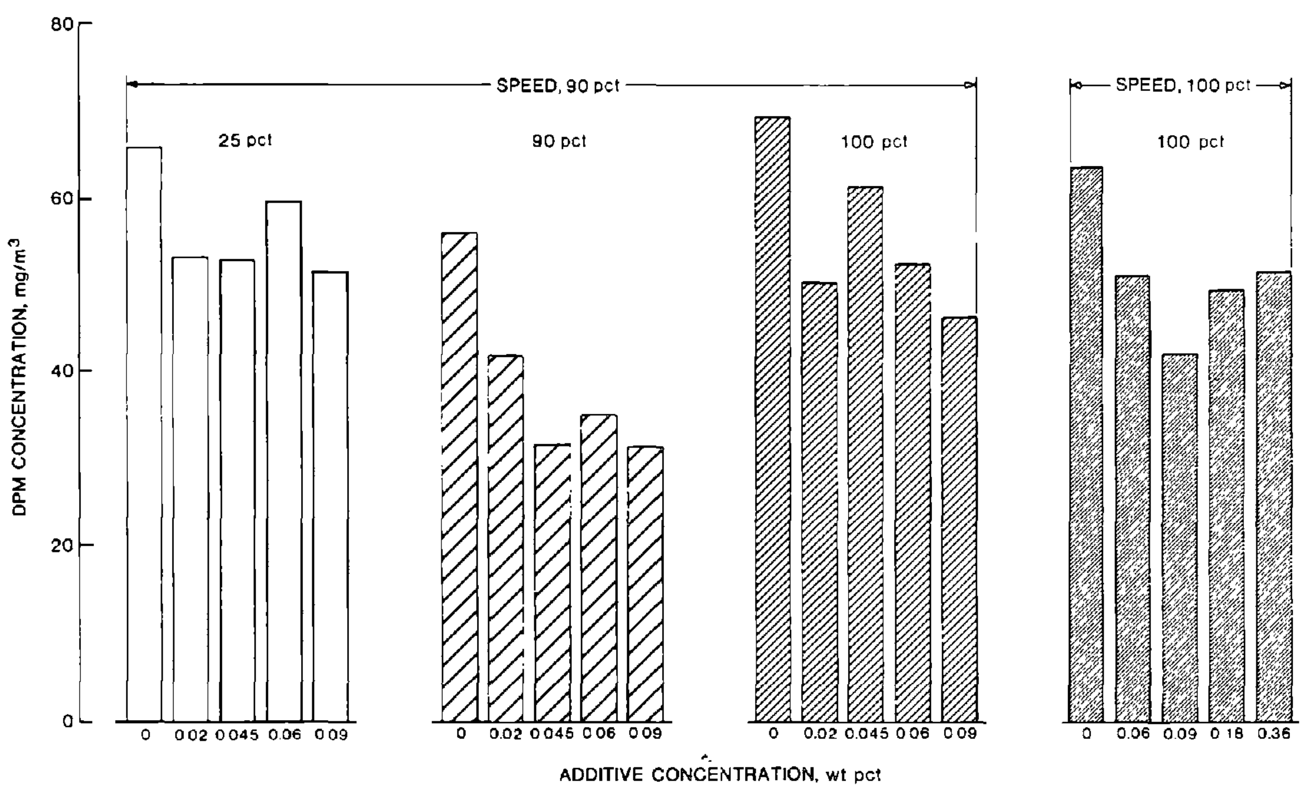

Figure 6.–Effect of additive concentration on DPM emissions from Deutz engine at two speeds and 25, 90, and 100 pct of full load.

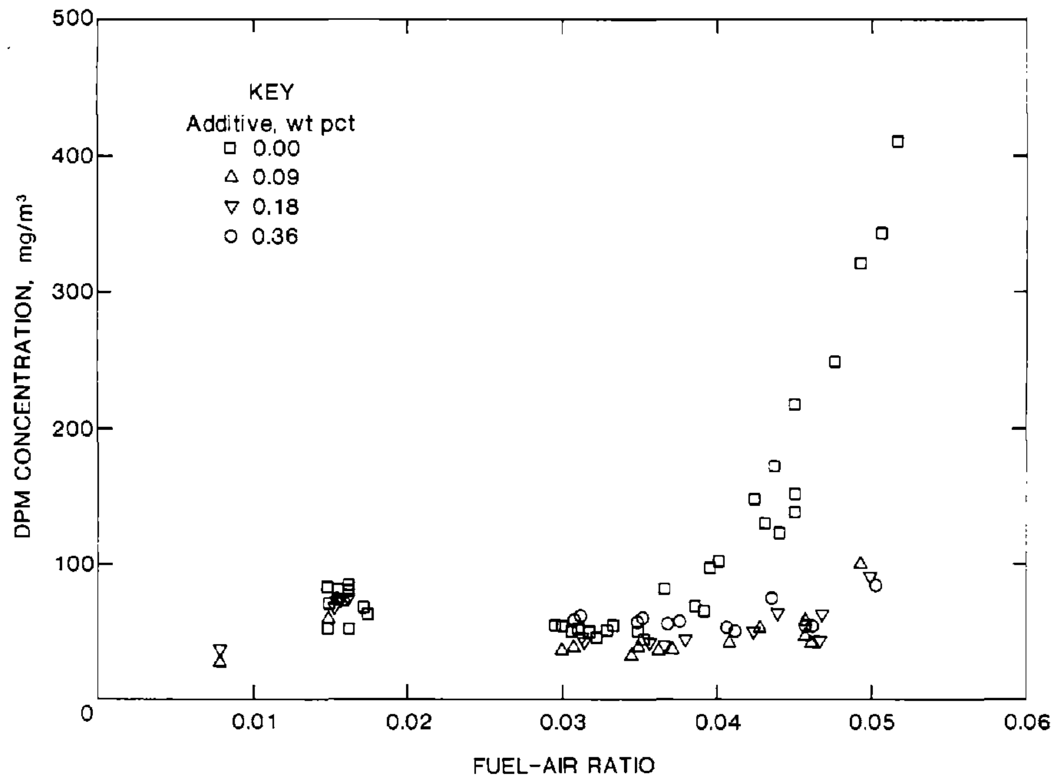

Figure 7.-Additive effect on DPM emissions from Deutz engine at different fuel-air ratios.

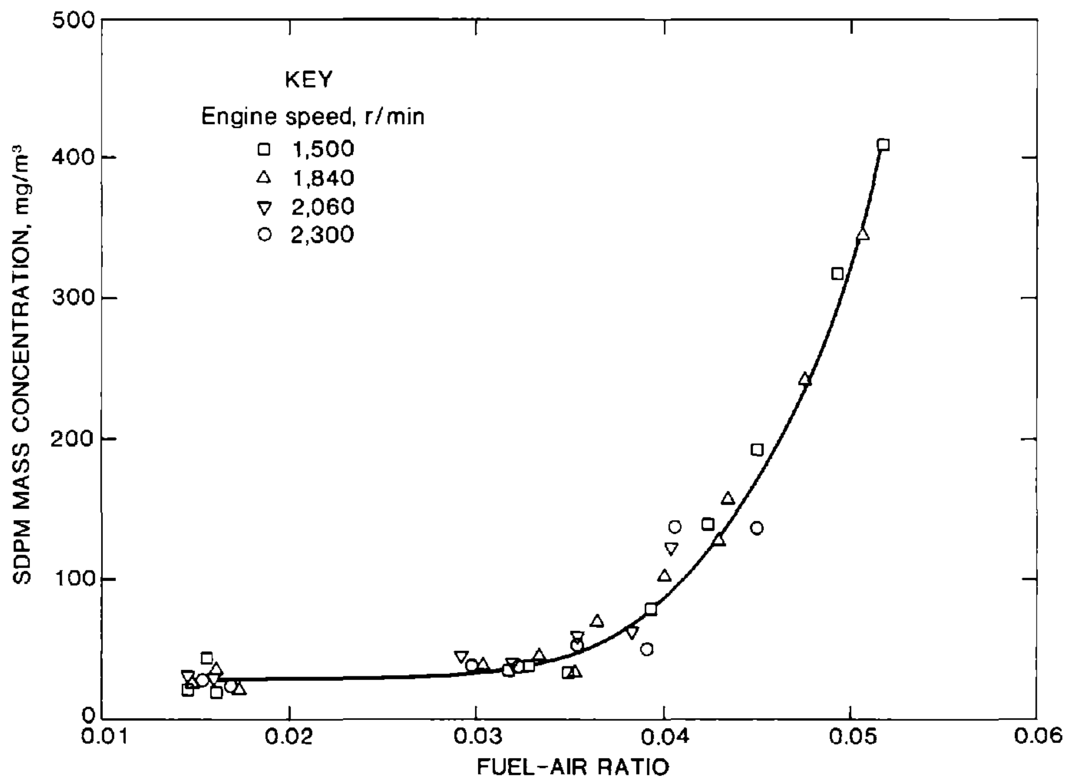

Figure 8.-SDPM emissions from Deutz engine for untreated fuel.

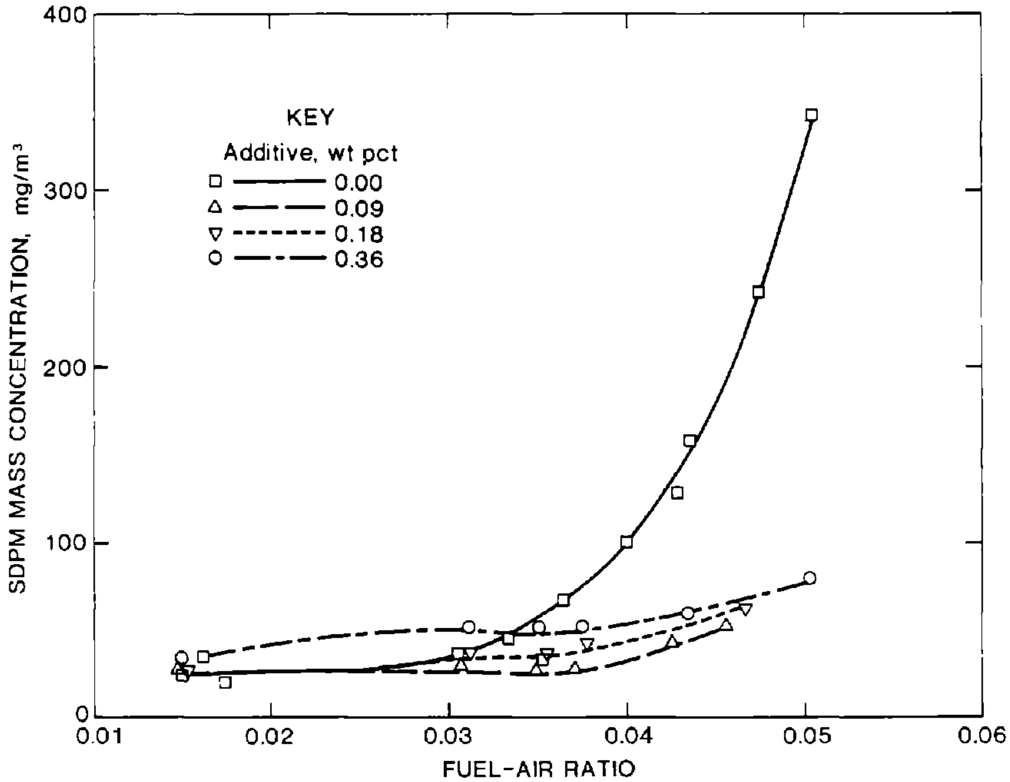

Figure 9.-Additive effect on SDPM emissions from Deutz engine at 80 pct of rated speed.

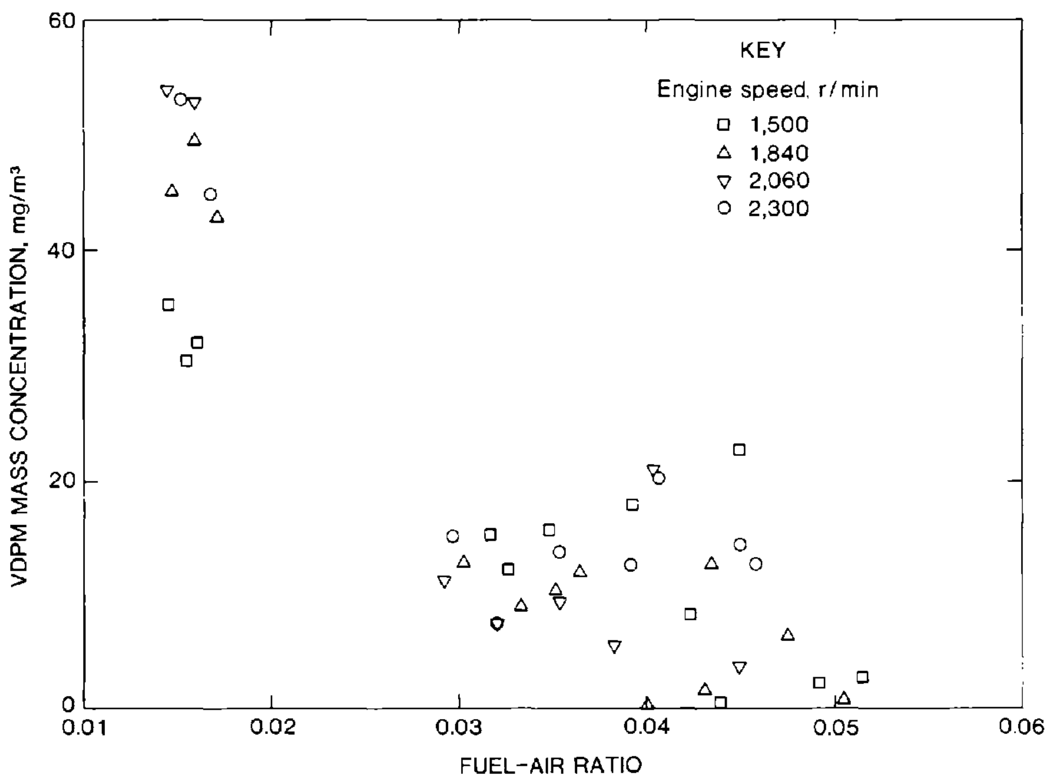

Figure 10.-VDPM emissions from Deutz engine for untreated fuel.

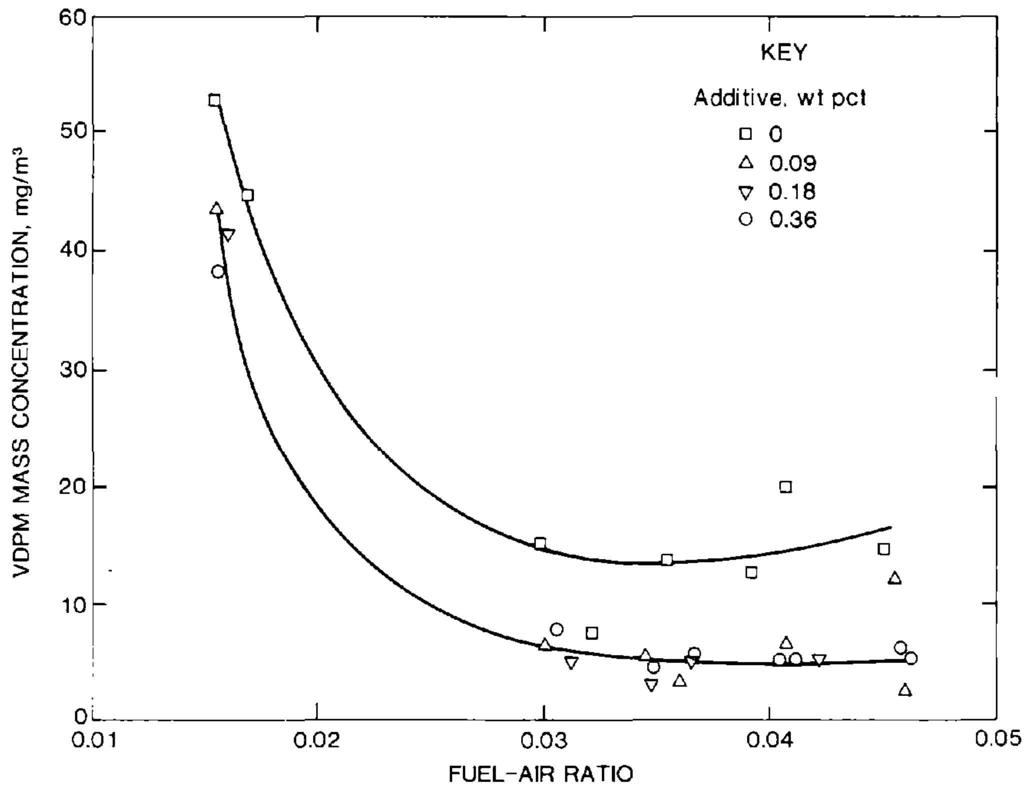

Figure 11.–Additive effect on VDPM from Deutz engine at full speed.

Comparison of Solid and Volatile Fractions

The results (fig. 12) for full engine speed and the small intake restriction were selected to illustrate the relative levels of the solid and volatile particulate components for both treated and untreated fuels. For the Deutz engine and for both treated and untreated fuel, the solid fraction (SDPM) is the main component of DPM for fuel-air ratios greater than about 0.025, while at smaller fuel-air ratios the volatile fraction (VDPM) is the main constituent of DPM. The most obvious effect of the additive is reduction of the solid component, although, as noted in previous sections, some volatile reduction also occurs.

Also (fig. 12), for treated fuel (0.09 wt pct), the nearly constant level of SDPM between 30 and 40 mg/m³, in conjunction with the results in figure 6, suggests a minimum DPM level and maximum effectiveness of DPM reduction using barium. At full load, the barium rate into the engine, for 0.09-wt-pct additive in the fuel, is 52 mg/min. If all the barium is emitted as barium sulfate (7) in the exhaust, the concentration is about 25 mg/m³, the major portion of the SDPM emitted. There are other unknown substances in this commercial additive that may also be emitted as solid components in the exhaust. The point is that the composition of the additive may be a significant limiting factor in DPM reduction; therefore, it is important to use only sufficient additive to achieve the required or desired effectiveness.

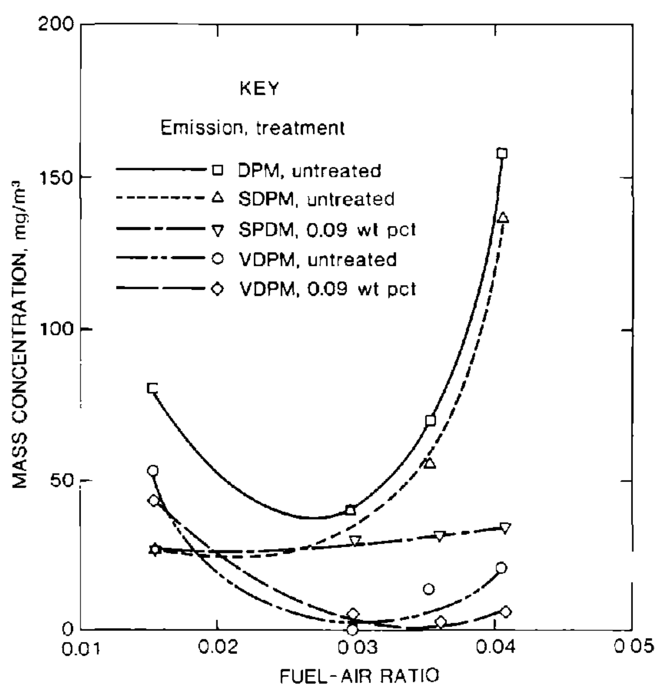

Figure 12.–Comparison of solid and volatile particulates from Deutz engine at full speed for small intake restriction.

HYDROCARBON EMISSIONS

Gaseous Hydrocarbons

The untreated-fuel GPHC mass concentration emissions are plotted (fig. 13) for all test conditions. The range of GPHC concentrations (plotted as methane equivalent) is large–between 10 and 80 mg/m^3. There will be no attempt to identify trends, because of the complex interactions among engine speed, engine load, and engine intake conditions. An additional complicating factor is the probability that a substantial fraction of the GPHC originates from the engine lubricating oil, especially at light loads and high speeds (*12*).

GPHC emissions for both treated and untreated fuels are plotted in figure 14, where the untreated-fuel data are the same as those plotted in figure 13. It is apparent that the main effect of the additive is to reduce the overall range of the GPHC emissions, especially at fuel-air ratios greater than 0.025. The minimum GPHC level observed for treated fuel is about 25 mg/m^3, compared with the minimum of about 10 mg/m^3 observed for untreated fuel. The increase in GPHC for treated fuel can be explained by referring back to figure 11, which showed that the condensed volatiles, or VDPM, were decreased, on the average, by barium-treated fuel. Consequently, it follows that if the exhaust hydrocarbons do not condense on the particulate fraction, then they must remain in the gas phase as observed. What is not explained is why the GPHC levels for treated fuel (fig. 14) decrease with increasing additive concentration. Additive effects on exhaust hydrocarbons are examined further in the following section.

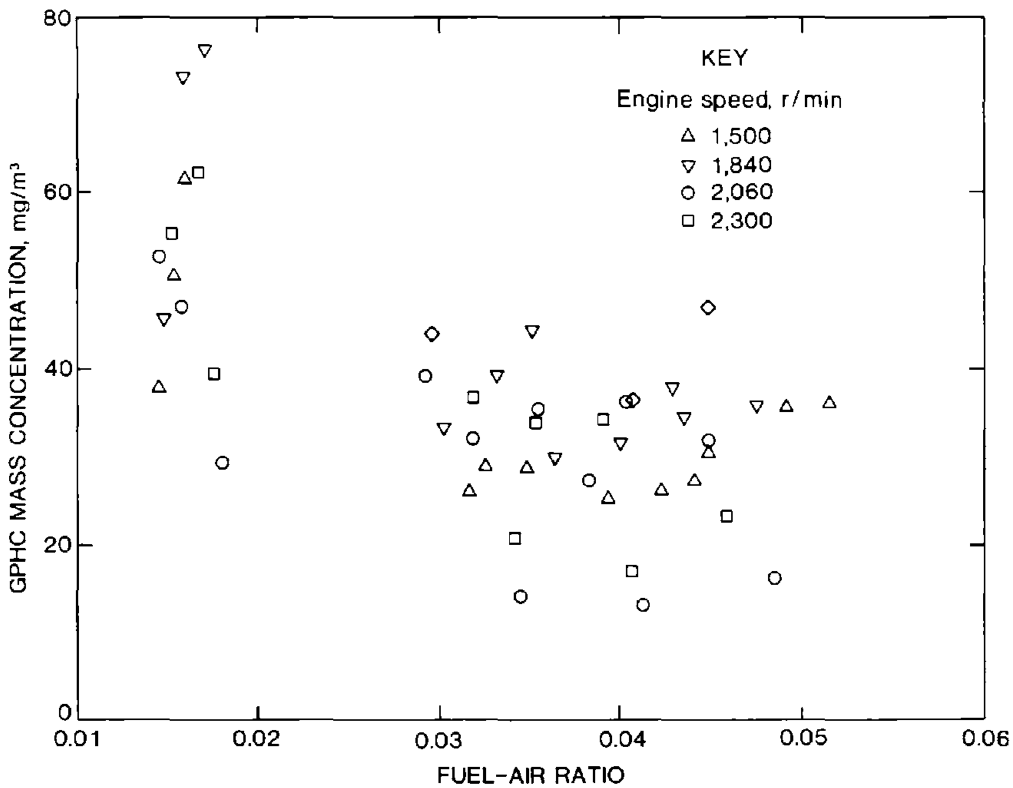

Figure 13.–GPHC concentrations (plotted as methane equivalent) from Deutz engine for untreated fuel.

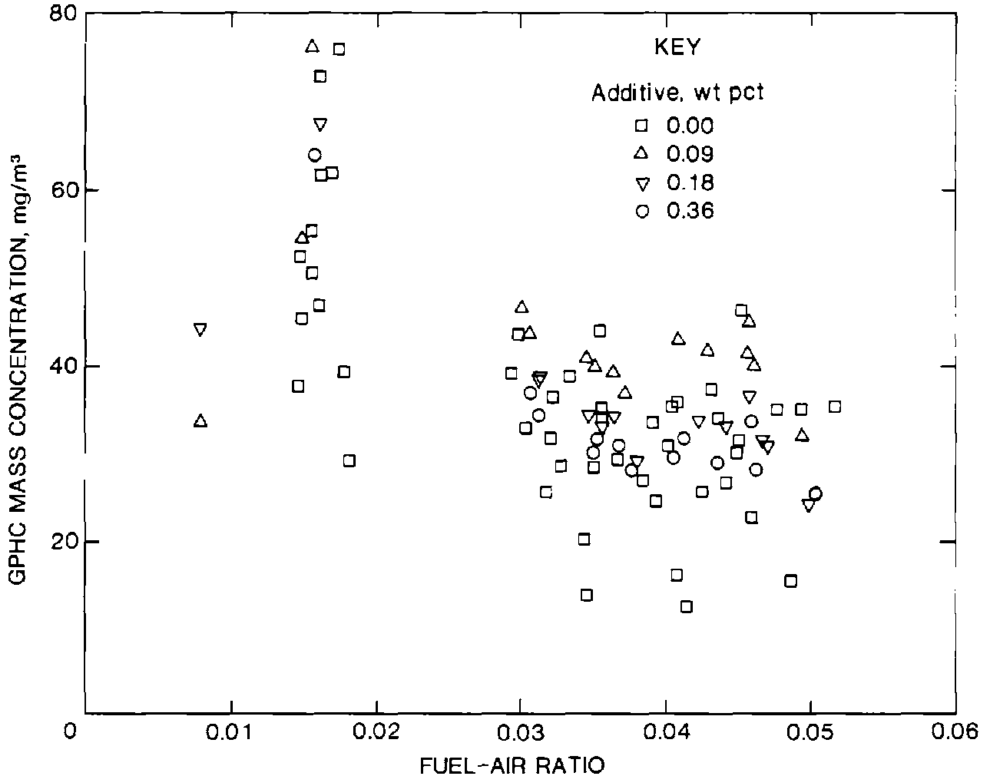

Figure 14.–GPHC concentrations (plotted as methane equivalent) for different additive concentrations and for all Deutz engine conditions.

Total Exhaust Hydrocarbons

Diesel exhaust is a complex, dynamic system in which the physical and chemical properties of the species present continuously change with time. For the purpose of this discussion, the following are assumed: (1) The diluted exhaust, from which the filter sample is extracted, is representative of the state of the VDPM in the exhaust pipe; that is, adsorption, desorption, and condensation are fully quenched at the instant of dilution; (2) the heated gas sampling line provides a representative GPHC sample to the instruments. If these conditions are met, then an estimate of TEHC is determined as follows:

$$\text{TEHC} = \text{VDPM} + \text{GPHC},$$

when expressed in consistent units such as mass concentration.

Calculated values of TEHC are plotted (fig. 15) against fuel-air ratio. No strong trends are apparent. Of more interest are the treated-fuel levels of TEHC for full-speed conditions (fig. 16) along with untreated-fuel data also for full-speed conditions; all three intake conditions are plotted here. There are two observations. First, the average TEHC levels do not appear to be substantially changed when all treated-fuel results are compared with all untreated-fuel data. Additive effects on TEHC are not significant relative to the reductions measured for SDPM (fig. 9). On the other hand, looking only at the treated-fuel results, TEHC levels appear to decrease with increasing additive concentration, as a result of the decrease in GPHC levels with increasing barium concentration.

TOXIC GASEOUS EMISSIONS

Nitrogen Oxides

Nitrogen oxide emissions for different speeds, loads, intake restrictions, and additive treatments are plotted against fuel-air ratio (fig. 17). In general, nitrogen oxide formation increases with temperature and with the availability of oxidizing agents during combustion. For example, combustion temperature is related directly to fuel-air ratio and in-cylinder oxygen concentration is related inversely to fuel-air ratio. As a result, some of the nitrogen oxide emission plots (fig. 17) peak at about a fuel-air ratio of 0.04.

For untreated fuel, the lowest nitrogen oxide levels of about 100 mg/m^3 were measured for the largest restriction (minimum oxygen) and low fuel-air ratios corresponding to minimum temperatures. The highest levels for untreated fuel, around 800 mg/m^3, were for the smallest intake restriction (higher oxygen levels) and high fuel-air ratios (high temperatures).

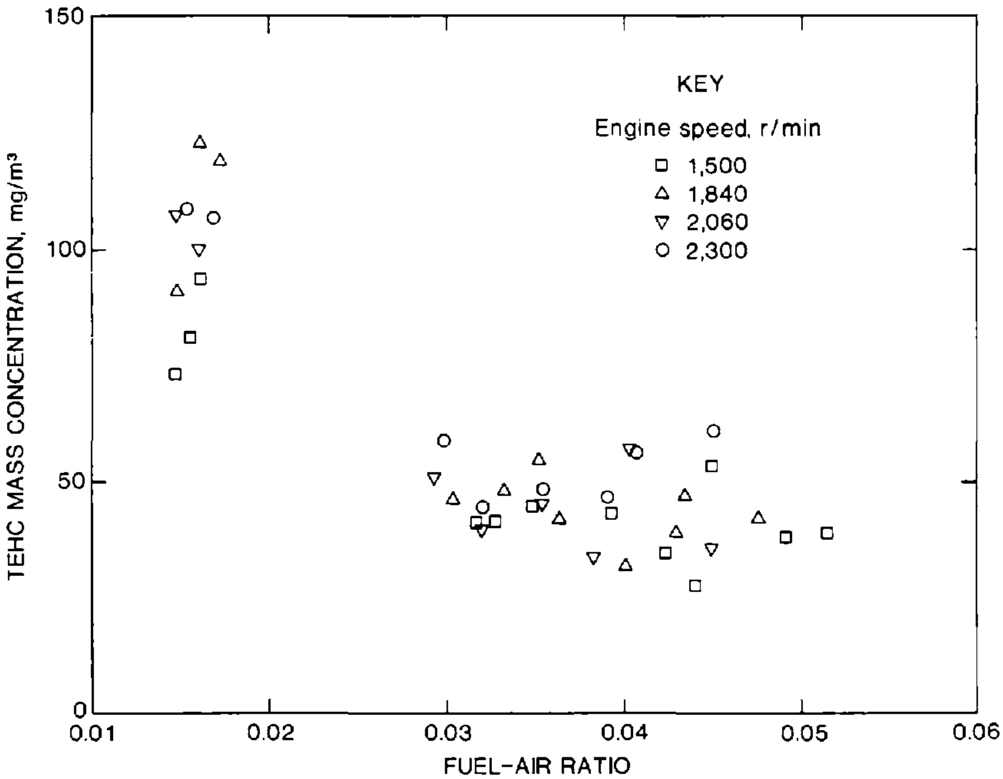

Figure 15.-TEHC concentrations for untreated fuel and all Deutz engine conditions.

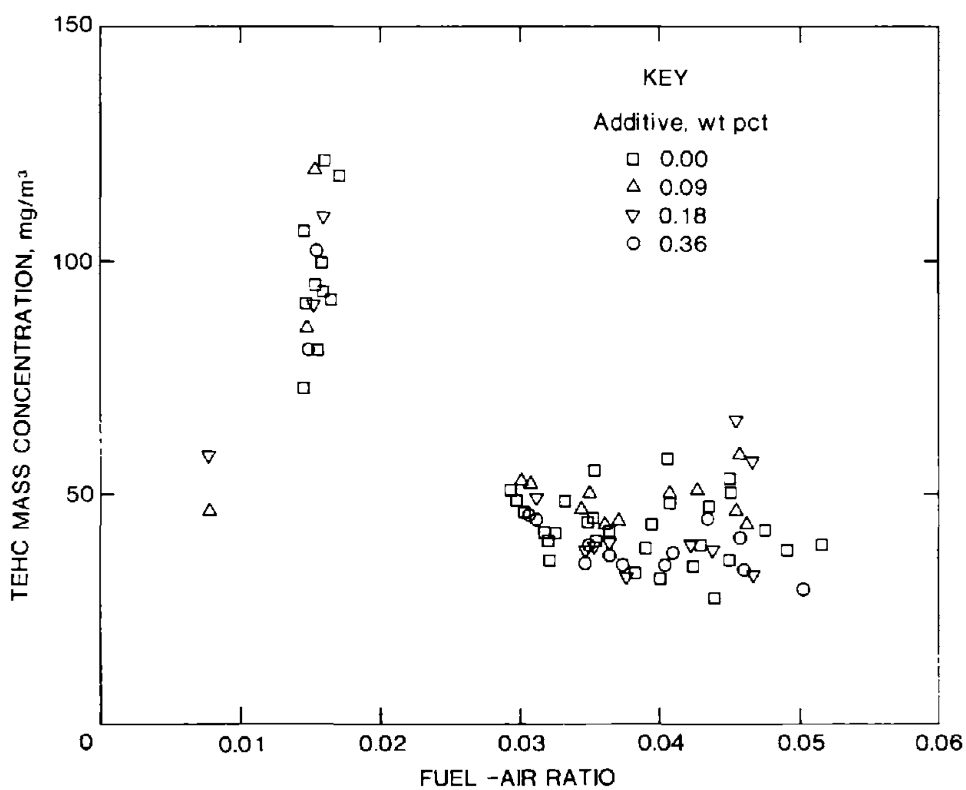

Figure 16.-TEHC concentrations from Deutz engine for treated fuel at full speed.

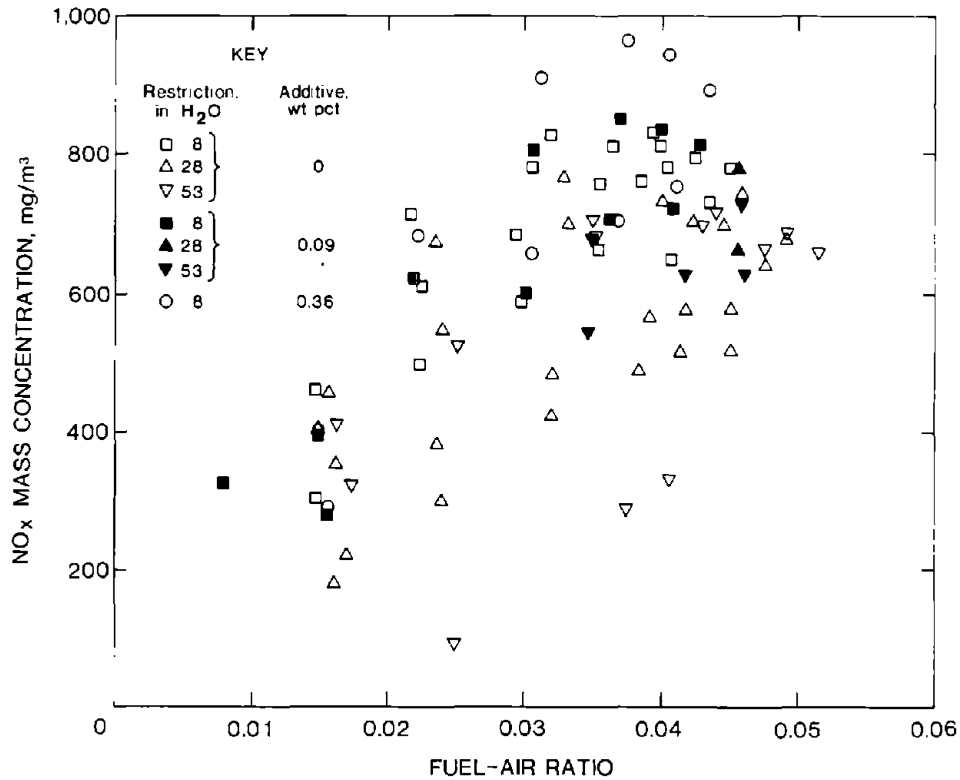

Figure 17.–Comparison of nitrogen oxide concentrations from Deutz engine for treated and untreated fuels.

Overall, the treated-fuel nitrogen oxide levels were greater than those measured for untreated fuel at the same fuel-air ratios. The 0.36-wt-pct additive treatment and small restriction produced the highest nitrogen oxide levels for a given fuel-air ratio. This general increase in nitrogen oxide levels for treated fuels is assumed to be the result of the oxidizing effect of barium. These results again emphasize the importance of not using any more additive in the fuel than necessary for DPM reduction.

Carbon Monoxide

The carbon monoxide exhaust emissions are plotted (fig. 18) against fuel-air ratio. The effect of the additive on carbon monoxide levels is mixed, which suggests that the additive will produce neither positive nor negative effects on carbon monoxide in the exhaust.

ENGINE COMPARISON

The purpose of this section is a limited comparison of the DPM emissions from two different engines: the Deutz engine tested in this research and a Caterpillar 3304 engine evaluated earlier (*7-8*). The comparison is limited because test data for the Caterpillar engine are available only for low-speed tests at 1,200 r/min or 67 pct of the full-rated speed (1,800 r/min) for that engine.

The DPM emissions for untreated fuel (fig. 19) are expressed in power-specific mass rate to help account for the differences in the test loads and speeds for the two engines. Over the full range of fuel-air ratios, the Caterpillar engine emissions are smaller than those from the Deutz engine, including the full-speed Deutz engine data.

DPM emissions are shown in figure 20 for a fuel treatment of 0.18 pct (the smallest concentration data available for the Caterpillar engine) for both engines, plus 0.09-wt-pct additive results for the Deutz engine. The data show that for treated fuel the Deutz engine emits less DPM at most fuel-air ratios. In other words, the additive appears to be more effective for the Deutz engine, with the qualification that this result may be related to the fact that the speed of the Deutz engine was greater–1,840 r/min (80 pct of full-rated speed) compared with 1,200 r/min for the Caterpillar engine (67 pct of full-rated speed). If the two engines could be compared at the same speeds, the results might be different.

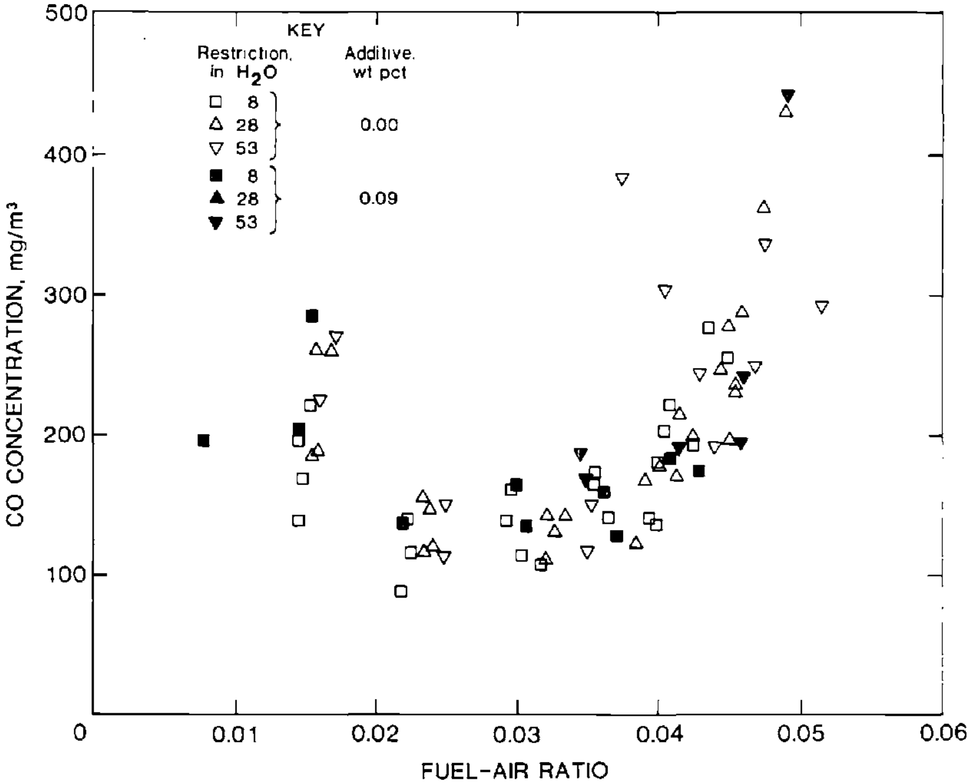

Figure 18.-Comparison of carbon monoxide concentrations from Deutz engine for treated and untreated fuels.

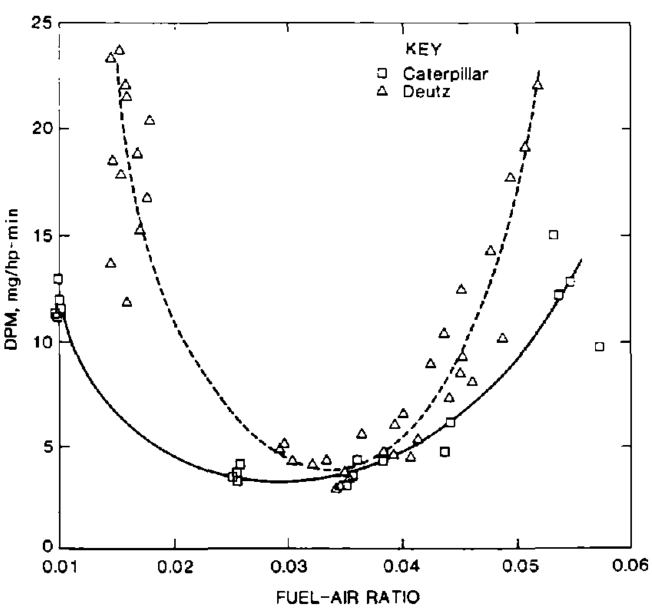

Figure 19.-Comparison of DPM from Deutz and Caterpillar engines for untreated fuel.

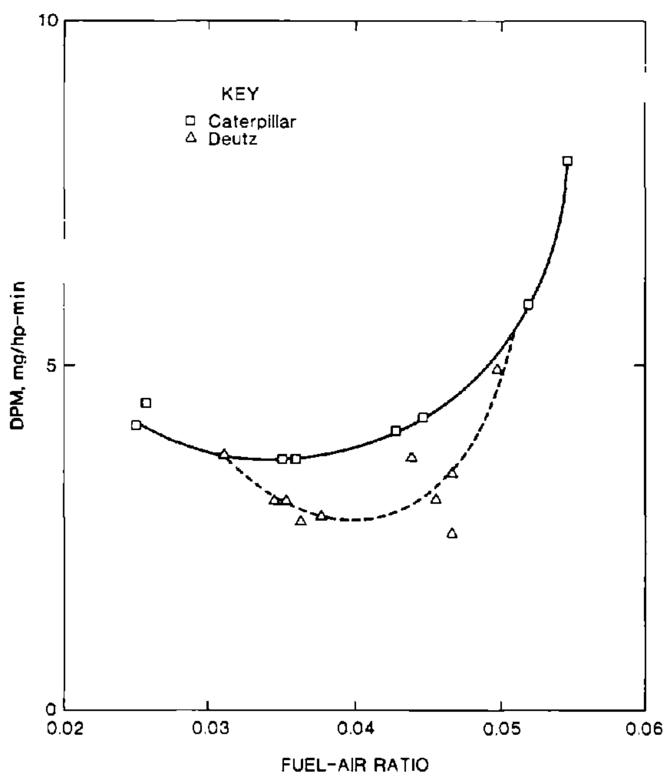

Figure 20.-Comparison of DPM from Deutz and Caterpillar engines for treated fuel.

CONCLUSIONS AND RECOMMENDATIONS

At fuel-air ratios between 0.01 and 0.052, the DPM emissions of the Deutz engine ranged between 35 and 420 mg/m^3. For fuel-air ratios up to about 0.04, the maximum DPM levels measured were less than about 120 mg/m^3, a result that emphasizes the importance of operation at high speed with minimum intake restrictions (clean air filters) in order to maintain low fuel-air ratios.

The DPM emissions from the Deutz engine were compared with those from a Caterpillar engine. For untreated-fuel operation, the DPM levels from the Caterpillar engine were less than those from the Deutz engine over the entire range of fuel-air ratios tested.

For maximum DPM reduction over the entire range of fuel-air ratios, the most effective additive concentration evaluated was 0.09 wt pct. Only at the maximum fuel-air ratios tested did the manufacturer's recommended concentration of 0.36 wt pct seem to impart a marginal additional benefit in reducing DPM compared with the 0.09-wt-pct treatment. Additive concentrations as low as 0.02 wt pct were observed to produce some DPM reductions.

The effect of the additive on nitrogen oxide and carbon monoxide emissions was complex. Overall, nitrogen oxide levels tended to increase while carbon monoxide levels remained within the untreated-fuel range. Because emission levels of both these gases are well within acceptable limits for the tested conditions and because the changes are small, the effect of the additive on nitrogen oxide should be considered in mine applications but is not expected to be a problem for well-maintained engines and properly ventilated mines.

This barium-based additive is recommended for reducing DPM emissions from diesel-powered equipment used in underground mines if the following conditions are met:

1. The additive reduces excessive particulate levels and is used mainly in equipment having heavy work-duty cycles involving substantial periods of full or near-full load operation.
2. The additive is used at the minimum concentration required to produce the measured DPM reduction observed. Based on results in this report, the suggested concentration is 0.09 wt pct.
3. Potential adverse effects such as unacceptable nitrogen oxide increases should be checked.

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APPENDIX.–ADDITIVE SPECIFICATIONS

Supplier:

Lubrizol Corp.
29400 Lakeland Blvd.
Wickliffe, OH 44092

Type: Lubrizol 565

Recommended concentration: 0.36 wt pct or 0.25 vol pct (or 1,075 lb per 1,000 barrels of fuel)

Physical and chemical properties:

Specific gravity at 60° F		1.22
Viscosity at 100° C	cSt	9.62
Barium content	wt pct	20-25
Sulfur content	wt pct	0.25-0.50
Nitrogen content	wt pct	0.4-0.6