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Project Summary

Environmental Assessment of NO_x Control on a Compression-Ignition, Large-Bore, Reciprocating Internal-Combustion Engine

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The report gives emission results from field testing of the exhaust gas from a large-bore, compression-ignition reciprocating engine burning diesel fuel. An objective of the tests was to evaluate the operating efficiency of the engine with combustion modification NO_x control to reduce emissions to below the proposed NO_x new source performance standard (NSPS) of 600 ppm at 15 percent O_2 dry. Engine NO_x emissions were reduced 31 percent (from 825 to 571 ppm) at 15 percent O_2 with 3.5° of fuel injection timing retard. This reduction was accompanied by a 1 percent loss in engine efficiency. CO emissions decreased slightly (from 119 to 90 ppm). Total unburned hydrocarbons remained relatively unchanged (25 ppm), as did particulate emissions (35 ng/J) and total organic emissions (55 ng/J). Volatile organics (boiling point $<$ about 100° C) accounted for the largest fraction of the total organic. Naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were the only organic priority pollutants detected in both tests at levels below 70 micrograms/dscm.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in two separate volumes of the same title (see Project Report ordering information at back).

Introduction

This report describes emission results obtained from field testing of the exhaust gas from a large-bore, dual-fuel, compression-ignition, reciprocating internal-combustion (IC) engine burning distillate oil (diesel fuel). Objectives of the tests were to measure exhaust gas emissions and to evaluate the operating efficiency of the engine under baseline or normal operating conditions and with combustion modification NO_x control to reduce emissions to below the proposed NO_x New Source Performance Standard (NSPS) of 600 ppm at 15 percent O_2. Emission measurements included continuous monitoring of exhaust gas emissions; source assessment sampling system (SASS) sampling of the exhaust gas with subsequent laboratory analysis of samples to give total exhaust gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and exhaust gas concentrations of 73 trace elements; Method 5 sampling for particulate; Method 8 sampling for SO_2 and SO_3; and grab sampling of fuel and engine lubricating oil for inorganic composition determinations.

Engine NO_x emissions were reduced 31 percent (from 825 to 571 ppm) at 15 percent O_2 with the control approach tested (3.5° of fuel injection timing retard). This reduction was accompanied by a 1 percent loss in engine efficiency (from 36.3 to 35.3 percent). CO emissions decreased slightly (from 119 to 90 ppm) at 15 percent O_2 under controlled operation. Total unburned hydrocarbon emissions remained relatively unchanged (at about 25 ppm, as propane) at 15 percent O_2, as did particulate emissions at about 35 ng/J heat input. Total organic emissions also remained relatively unchanged at about 55 ng/J. Volatile organics (boiling point less than about 100°C) accounted for the largest fraction of the total organic.

Of the 58 semivolatile organic priority pollutants analyzed, only naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were detected in the uncontrolled engine exhaust at levels of 7 to 70 µg/dscm. Levels of these in the controlled engine exhaust were lower, being less than 1 to 50 µg/dscm.

Summary and Conclusions

Test Engine

The test engine was a turbocharged 1,565 kW (2,100-Bhp), two-stroke, opposed-piston, compression-ignition Model 38TDD8-1/8 engine manufactured by the Fairbanks Morse Engine Division of Colt Industries. Figure 1, a schematic of the engine, shows the turboblower arrangement of the inlet combustion air and the opposed-piston design. The combustion air is drawn into the turbocharger where it is compressed and discharged through an air cooler to the positive-displacement lobe-type blower. The blower, driven by the upper engine crankshaft, discharges the air directly to the cylinders through the engine intake manifold. The air/fuel mixture is compressed between the two pistons which work vertically toward each other in each cylinder. The upper and lower pistons drive separate crankshafts interconnected by a vertical drive. Hot exhaust gas leading from the lower cylinder ports drives the turbine of the turbocharger assembly. The fuel is ignited by the heat of compression.

Engine Operation and Test Arrangements

The test program called for the analysis of exhaust gas samples collected (1) during uncontrolled or baseline operation, and (2) with fuel injection retard to lower NO_x emissions to or below the level of the proposed NSPS. Table 1 summarizes the engine specifications, operating parameters, and atmospheric conditions during both tests.

For the baseline test, fuel injection timing was set at the normal setting for this engine, 16° before minimum volume (RMV). Combustion modification NO_x control consisted of retarding the fuel injection timing from 16 to 10.5° BMV. The effect of 5.5° retard on the operation of the engine was a loss in efficiency of about 1.0 percent. This efficiency loss is clearly identifiable by the increase in fuel flow required to maintain rated power output. The air flow was also increased during the low-NO_x tests as indicated by the increase in blower discharge pressure. However, the fuel/air ratio during the low-NO_x test decreased about 8 percent from the baseline level. Blower discharge and engine exhaust gas temperatures remained nearly constant while there was a small reduction in temperature at the turbine outlet of the turbocharger.

Emission Measurements and Results

The sampling and analysis procedures used in this test program conformed to a modified EPA level 1 protocol. Except for continuous monitoring to exhaust gas emissions, all exhaust gases were measured at the exit of the engine muffler into the uninsulated exhaust stack. Emission measurements included:

- Continuous monitoring for NO_x, NO, CO, CO_2, O_2, and TUHC
- Source Assessment Sampling System (SASS) for trace elements and organic emissions
- EPA Method 5 for solid and condensible particulate mass emissions
- EPA Method 8 for SO_2 and SO_3 emissions
- Grab sample for onsite analysis of C_1 to C_6 hydrocarbons by gas chromatography (GC)
- Bosch smoke spot

In addition, samples of the engine lubricating oil and the diesel fuel oil were collected for analysis.

The analysis protocol included:

- Analyzing the fuel/lube oil, and SASS train samples for 73 trace elements using spark source mass spectrometry (SSMS), supplement-

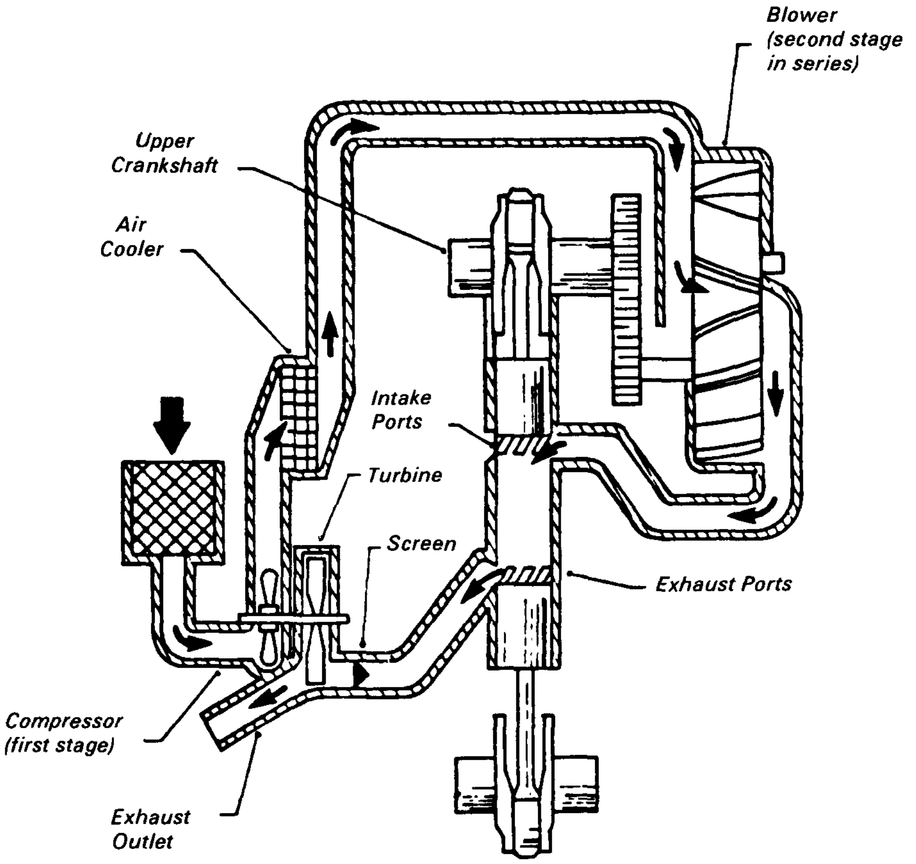

Figure 1. *Schematic of turboblower arrangement (courtesy of Fairbanks Morse Division of Colt Industries).*

ed by atomic absorption spectrometry (AAS)

- Analyzing SASS train samples for total organic content in two boiling point ranges: 100 to 300°C by total chromatographable organics (TCO) analysis and >300°C by gravimetry (GRAV)
- Analyzing the SASS train samples for 58 semivolatile organic species including many POM compounds
- Performing infrared (IR) spectrometry analysis of organic sample extracts
- Performing liquid chromatography (LC) separation of selected sample extracts with subsequent TCO, GRAV, and IR analysis of LC fractions
- Performing direct insertion probe and batch inlet low resolution mass spectrometry (LRMS) of selected sample extracts

Bioassay tests were also performed on the SASS organic sorbent module extract to estimate this sample's potential toxicity and mutagenicity.

Table 2 summarizes exhaust gas emissions measured in the test program. Emissions are presented as ng/J heat input and as mg/dscm of exhaust.

As noted in Table 2, NOx emissions were reduced with fuel injection retard to 1,040 ng/J from a baseline of 1,490 ng/J. CO emissions were also decreased slightly. TUHC, particulate, and total semivolatile organic emissions were relatively unchanged; nonvolatile organic emissions increased with low-NOx operation.

As a measure of the potential significance of the emissions levels for further monitoring evaluation, Table 2 also lists occupational exposure guidelines for most pollutants noted in the table. The guidelines listed are generally either time-weighted-average Threshold Limit Values (TLV) established by the American Conference of Governmental Industrial Hygienists, or the 8-hr time-weighted-averaged exposure limits established by the Occupational Safety and Health Administration. These are noted only to aid in ranking the emissions for evaluation. In this respect, pollutants emitted at levels several orders of magnitude higher than their guideline might warrant further consideration, while species emitted at levels significantly lower than their guideline might be considered of lesser concern. Only elements emitted at levels exceeding 10 percent of their guideline are noted in Table 2.

Table 2 shows that several trace elements were emitted at levels up to eight times their respective guidelines. For comparison, emissions of the gaseous pollutants CO, SO_2, and SO_3 were at levels ranging from 2 to 20 times their guidelines; NOx emissions were at levels over 300 times its guideline. These comparisons suggest that the NOx control achieved may be the most significant change.

Analyses of SASS train samples for POM and other organic compounds (the semivolatile organic priority pollutants species) were performed. Only naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were detected in the baseline test exhaust gas at levels of 7 to 70 µg/dscm. Levels of these compounds in the low-NOx test exhaust gas were lower, from less than 1 to 50 µg/dscm.

SASS train organic extract samples were subjected to LC fractionation, with TCO, GRAV, IR, and LRMS analysis of LC fractions, in attempts to elucidate the chemical character of the exhaust gas organic material. These analyses suggested that the exhaust gas organic for both tests was primarily aliphatic hydrocarbons with some esters, carboxylic acids, phenols, mercaptans,

Table 1. *Compression Ignition Engine Design and Operating Parameters*

Engine Design Parameters Specifications		
Model designation	*38TDD8-1/8*	
Engine configuration	*2-stroke, opposed-piston*	
Bore/stroke, m (in.)	*0.206/0.254 (8-1/8/10) x 2*	
Number of cylinders	*6*	
Displacement/cylinder, m^3 (in.^{3})	*0.017 (1.037)*	
Compression ratio	*11:1*	
BMEP, MPa (psia)	*1.01 (148.5)*	
kW/cylinder (Bhp/cylinder) rpm	*261 (350) at 900 rpm*	
Injection timing	*16° before minimum volume (BMV)*	
Lubricating oil	*Mobil 446*	
Lubricating oil consumption, ml/s (gph)	*0.37 (0.35)*	
Fuel oil	*No. 2*	
Hours since last overhaul	*30*	
	Baseline	*Low-NO$_x$*
Engine Operating Parameters		
RPM (percent rating)	*900 (100%)*	*900 (100%)*
kW$_t$ (Bhp) (percent rating)	*1566 (2100) (100%)*	*1567 (2101) (100%)*
Generator output, kW$_e$ (percent rating)	*1503 (9.8%)*	*1505 (99.8%)*
Fuel flow, g/s (lb/hr)	*97.7 (775)*	*101 (798)*
BSFC, g/kW-hr (lb/Bhp-hr)	*225 (0.37)*	*231 (0.38)*
Fuel rate, kW$_t$ in/kW$_t$ out (Btu/Bhp-hr)	*2.75 (7009)*[a]	*2.84 (7218)*[a]
Injection timing	*16.0° BMV*	*10.5° BMV*
Cylinder firing pressure, MPa (psig)	*9.02-9.23 (1320-1350)*	*8.20-8.34 (1200-1220)*
Compressor inlet air temp., K (°F)	*305 (89)*	*291 (65)*
Compressor outlet air temp., K (°F)	*417 (292)*	*414 (286)*
Blower suction temp., K (°F)	*324 (124)*	*327 (130)*
Blower discharge temp., K (°F)	*338 (149)*	*340 (153)*
Blower discharge pressure, kPa (psig)	*150 (22.0)*	*176 (25.7)*
Air flow, kq/s (lb/min)	*4.05 (535)*	*4.52 (598)*
Fuel/air ratio	*0.02414*	*0.02223*
Combined cylinder exhaust temp., K (°F)	*757 (903)*	*754 (898)*
Turbine exhaust temp., K (°F)	*636 (686)*	*625 (665)*
Engine efficiency, percent	*36.3*	*35.3*
Average Ambient Atmospheric Condition		
Ambient temperature—dry bulb, K (°F)	*304 (88)*	*290 (63)*
Barometric pressure, kPa (in. Hg)	*97.3 (28.82)*	*98.2 (29.07)*
Relative humidity, percent	*37*	*45*

[a] *Heat input accounts for the heating value of lube oil burned by the engine.*

Table 2. *Summary of Exhaust Gas Emissions*[a]

Compound	Baseline Test (ng/J Heat Input)	Baseline Test (mg/dcsm)	Low-NO_x (ng/J Heat Input)	Low-NO_x (mg/dscm)	Occupational Exposure Guideline (μg/dscm)[b]
Criteria Pollutants and Other Vapor Species					
NO_x (as NO_2)	1,490	1,940	1,040	1,230	6.0
CO	130	170	98	117	55
TUHC (as C_3H_8)	45	59	42	50	—[c]
SO_2	44	57	95	113	5.0
SO_3	11	14	19	23	1.0
Solid particulate	29.5	38.4	36.6	43.7	10.0[d]
Condensible particulate	3.3	4.5	—[e]	—	
Total semivolatile organics (C_1-C_{16})	1.1	1.5	1.2	1.4	—[c]
Total nonvolatile organics (>C_{16})	3.5	4.6	12.2	14.5	—[c]
Trace Elements					
Phosphorus, P	>0.61	>0.79	0.045	0.054	0.10
Copper, Cu	0.062	0.081	0.34	0.40	0.10[f]
Iron, Fe	0.020	0.026	0.92	1.1	1.0
Silver, Ag	0.0085	0.011	<0.0017	<0.0020	0.010
Potassium, K	>1.1	>1.4	>0.60	>0.72	2.09
Sodium, Na	>0.63	>0.82	>0.55	>0.65	2.09
Calcium, Ca	>0.54	>0.70	—	—	2.0
Aluminum, Al	0.53	0.69	0.010	0.012	2.0
Zinc, Zn	0.065	0.085	0.23	0.27	1.0
Chromium, Cr	0.0020	0.0026	0.010	0.012	0.050
Lead, Pb	0.0007	0.0009	0.0072	0.00087	0.050[f]
Nickel, Ni	0.012	0.015	0.0034	0.0041	0.10
Selenium, Se	0.020	0.026	0.023	0.027	0.20

[a] *Exhaust O_2 and CO_2 levels were 13.7 and 5.3 percent, respectively, for the baseline test and 14.3 and 5.0 percent, respectively, for the low-NO_x test.*
[b] *Time-weighted-average TLV unless noted.*
[c] *No occupational exposure guideline applicable.*
[d] *For nuisance particulate.*
[e] *Sample lost.*
[f] *8-Hr time-weight-average OSHA exposure limit.*

and low-molecular-weight fused-ring aromatics (e.g. naphthalene and alkyl naphthalenes).

Bioassay tests were performed on the organic sorbent module extract from the SASS trains for both tests. The health effects bioassay tests performed were the Ames mutagenicity assay, and the CHO cytotoxicity assay. The results of these assays are summarized in Table 3. The results suggest that the exhaust gas under both baseline and low-NOx operation is of moderate to high toxicity and moderate mutagenicity. This is a typical bioassay response for combustion source SASS train XAD-2 extract.

Table 3. *Bioassay Analysis Results*

Sample	Test	Bioassay Analysis CHO[a]	Bioassay Analysis Ames[b]
XAD-2 Extract	Baseline	H	M
XAD-2 Extract	Low-NO_x	H/M	M

[a] *H = High toxicity, M = Moderate toxicity.*
[b] *M = Moderate mutagenicity.*

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The complete report consists of two volumes entitled "Environmental Assessment of NO_x Control on a Compression-Ignition, Large-Bore, Reciprocating, Internal-Combustion Engine:"

"Volume I. Technical Results," (Order No. PB 86-155 819/AS; Cost: $16.95, subject to change).

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