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Project Summary

Environmental Assessment of NO_x Control on a Spark-Ignited, Large-Bore, Reciprocating Internal-Combustion Engine

C. Castaldini

This two-volume report gives emission results for a spark-ignited, large-bore, reciprocating, internal-combustion engine operating both under baseline (normal) conditions, and with combustion modification controls to reduce NO_x emissions to levels below the proposed new source performance standard (NSPS) for such engines. Exhaust gas measurements (in addition to continuous monitoring of criteria gas emissions) included total organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants (POMs), flue gas concentrations of 73 trace elements, and particulate matter. Exhaust NO_x emissions were reduced almost 50 percent, from a baseline level of 1,260 ng/J to 654 ng/J (730 to 420 ppm, corrected to 15 percent O_2 dry) by increasing the operating air/fuel ratio of the engine. Accompanying this reduction was a slight increase in engine efficiency. CO, methane, total hydrocarbon, and total semivolatile organic compound emissions were increased from 10 to 65 percent under low-NO_x operation. However, total nonvolatile organic emissions decreased 55 percent. The organic emissions for both tests consisted primarily of aliphatic hydrocarbons with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics. POMs were detected in concentrations below 4 μg/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 tests of the exhaust gas from a spark-ignited, large-bore, reciprocating, internal-combustion engine. Objectives of the tests were to measure exhaust gas emissions and evaluate the operating efficiency of the engine, both under baseline (normal) operating conditions, and with combustion modification controls to reduce NO_x emissions to levels below the proposed new source performance standards (NSPS) for such engines. 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 flue gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and flue gas concentrations of 73 trace elements; and Method 5 sampling for particulate.

Exhaust NO_x emissions were reduced almost 50 percent, from a baseline level of 1,260 ng/J to 654 ng/J by increasing the operating air/fuel ratio of the engine. Accompanying this reduction was a slight increase in engine efficiency. CO, methane, total hydrocarbon, and total semivolatile organic compound emissions were increased from 10 to 65 percent under low-NO_x operation. However, total nonvolatile organic emissions decreased 55 percent. Emissions of anthracene/phenanthrene and chrysene/benz(a) anthracene were 3 to 4 μg/dscm for both tests; levels of other POMs were less than detectable (2 μg/dscm). The organic emissions for both tests consisted primarily of aliphatic hydrocarbons with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics.

Summary and Conclusions

Test Engine

The test engine was a large-bore, turbocharged, 1,120-kW (1,500-Bhp) two-stroke, opposed-piston spark-ignited Model 37TDSB-1/8 engine manufactured by the Fairbanks Morse Engine Division of Colt Industries. Figure 1, a schematic of the engine, shows the turboblower arrangement for 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 from the lower cylinder ports drives the turbine of the turbocharger assembly. The fuel is ignited by spark ignition cells, arranged two per cylinder.

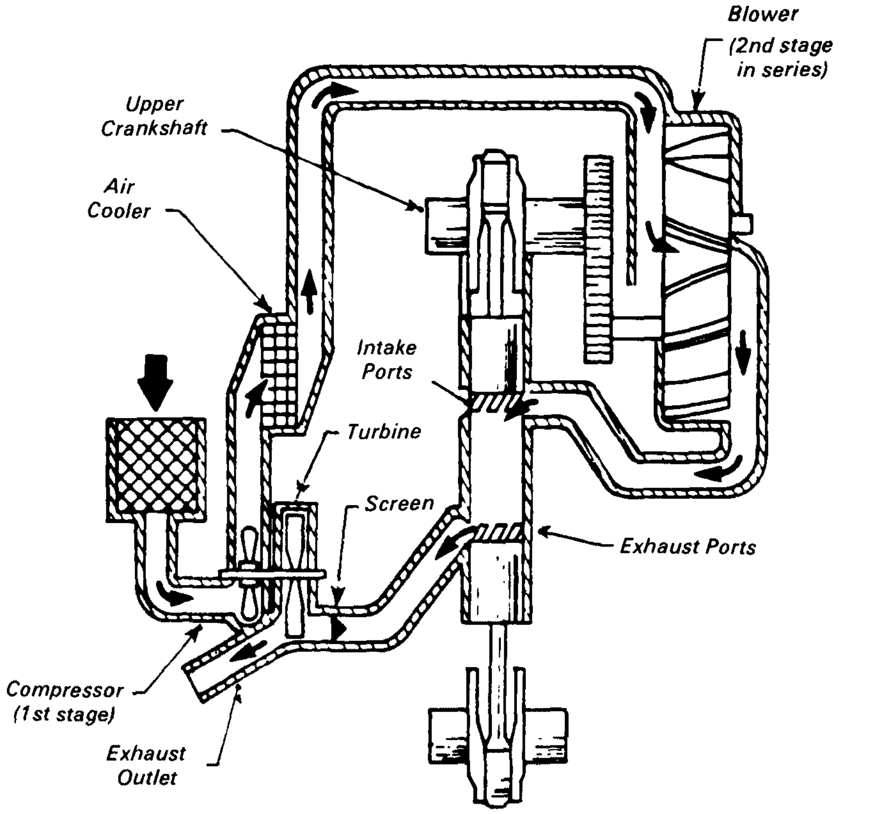

Figure 1. *Schematic of turboblower arrangement (courtesy of the Fairbanks Morse Division of Colt Industries).*

Engine Operation and Test Arrangements

The test program called for the analysis of flue gas samples collected during normal operation (baseline conditions) and with combustion modifications applied to lower NO_x emisisons. Table 1 summarizes the engine specifications and operating parameters during both the baseline and low-NO_x tests.

Since this engine design is usually marketed without the turbocharger and manifold air cooler existing on the test engine, it was necessary to reduce the effect of turbocharging during the baseline test. To reduce the effect of turbocharging, a portion of the combustion air was bypassed around the manifold air cooler. The resulting increase in combustion air temperature lowered the air mass flowrate, giving an air/fuel ratio which is more representative of the blower-scavenged design. The percent bypass air during the baseline tests was 16.4 percent, determined by the air flow control limits available on this test engine. Thus, baseline operation was as representative of normal blower-scavenged engine operation as could be achieved with the turbocharger in place.

The low-NO_x operation consisted of increasing the air/fuel ratio by eliminating the manifold air cooler bypass used during the baseline test and increasing the efficiency of the inlet manifold cooler. This modification reduced the inlet air temperature as well as increasing the air/fuel ratio. Engine power output was maintained nearly constant by decreasing fuel flow, while efficiency increased by about 0.4 percent during the low-NO_x test.

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 of exhaust gas emissions, all exhaust gas was measured at the engine muffler exit into the uninsulated exhaust stack. Emissions measurements included:

- Continuous monitoring for NO_x, NO, CO, CO_2, O_2, TUHC, and CH_4
- Source assessment sampling system (SASS) for trace element and organic emissions
- EPA Method 5 sampling for solid and condensable particulate mass emissions
- Grab sampling for onsite analysis of C_1 to C_6 hydrocarbons by gas chromatography
- Bosch smoke pot

In addition, samples of the engine lube oil were collected for analysis.

- Analyzing the lube oil and SASS train samples for 73 trace elements using spark source mass spectrometry (SSMS), supplemented by atomic absorption spectrometry (AAS)

Table 1. Spark Engine Design and Operating Parameters

Design Parameters (Engine Specifications)		
Model designation	38TDS8-1/8	
Configuration	2 stroke, O.P.	
Bore, m (in.)	0.206 (8-1/8)	
Stroke, m (in.)	0.254 (10) x 2	
No. of cylinders	6	
Displacement/cylinder m^3 ($in.^3$)	0.017 (1037)	
Compression ratio	9.7:1	
BMEP, kPa (psi)	731 (106)	
Power/cylinder at rpm, kW_t (Bhp)	186 (250) at 900	
Spark timing	4.5° before minimum volume (BMV)	
Lubricating oil	Pegasus 485	
Hours since overhaul	1050	
Operating Parameters	**Baseline**	**NO_x Control Test**
RPM (percent rating)	900 (100%)	900 (100%)
kW_t (Bhp) (percent rating)	1,117 (1,498) (99.8%)	1,123 (1,505) (100%)
kW_e (percent rating)	1,085 (97.8%)	1,091 (98.9%)
BMEP, kPa (psi)	731 (106)	731 (106)
Fuel flow, m^3/hr (ft^3/hr)	354 (12,492)	352 (12,426)
BSFC, g/kW-hr (lb/Bhp-hr)	217 (0.356)	215 (0.353)
Fuel rate, kW fuel/kW out (Btu/Bhp-hr)	2.91 (7413)	2.88 (7340)
Ignition timing	4.5° BMV	4.5° BMV
Compressor inlet air temp., K (°F)	302 (85)	302 (85)
Compressor outlet air temp., K (°F)	356 (181)	359 (187)
Manifold air cooling bypass, percent	16.4	0
Blower suction air temp., K (°F)	331 (136)	316 (110)
Blower discharger air temp., K (°F)	345 (161)	337 (146)
Blower discharge pressure, kPa (psig)	60 (8.7)	71 (10.3)
Air flow, kg/s (lb/min)	2.56 (338.3)	2.90 (383.4)
Fuel-air ratio	0.0271	0.0240
Combined cylinder exhaust temp., K (°F)	732 (858)	699 (799)
Turbine exhaust temp., K (°F)	652 (715)	617 (652)
Lube oil consumption, ml/s (gph)	0.45 (0.43)	0.45 (0.43)
Engine efficiency, percent	34.3	34.7
Average Ambient Atmospheric Conditions		
Outdoor temp. dry bulb, K (°F)	281 (46)	284 (51)
Barometric pressure, kPa (in. Hg)	98.2 (29.08)	98.6 (29.20)
Humidity, percent	60	62

- 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 sorbent module extract 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 analyses 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 exhaust sample 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 in both ng/J heat input and as mg/dscm of exhaust gas.

As noted in Table 2, NO_x emissions were decreased under low-NO_x operation to 654 ng/J from a baseline of 1,260 ng/J. This decrease in NO_x emissions was accompanied by increases in all relatively volatile combustible emissions, CO, TUHC, CH_4, and total semivolatile organics, although nonvolatile organic emissions decreased. Emission levels of the inorganic elements noted in Table 2 were relatively unchanged in going to low-NO_x operation from the baseline condition.

As a measure of the potential significance of emission levels for further monitoring and evaluation, Table 2 also lists occupational exposure guidelines for most pollutants in the table. The guidelines listed are generally either the time-weighted-average Threshold Limit Values (TLV) established by the American Conference of Governmental Industrial Hygienists, or the 8-hour time-weighted-average exposure limits estabalished by the Occupational Safety and Health Administration. These are noted only to aid in ranking emissions for further evaluation. In this respect, species emitted at levels several orders of magnitude higher than their guideline might warrant further consideration. Species emitted at levels significantly lower than their occupational exposure 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 the only pollutants emitted at levels which exceeded their respective guidelines were NO_x, CO, and Cu in the baseline test and NO_x, CO, Cu, Fe, and Cr in the low-NO_x test. The trace elements were emitted at levels at most a few times higher than their guidelines. In contrast, the criteria pollutants CO and NO_x were present in the exhaust at levels of almost one (CO) to well over two (NO_x) orders of magnitude higher than their guidelines. This suggests that NO_x emissions achieved may be the most significant change.

Analyses of SASS train samples for POM and other organic compounds (the semivolatile organic priority pollutant species) were performed. Only anthracene/phenanthrene and chrysene/benz(a)anthracene isomers were detected at levels above 2 µg/dscm. These were present at 3 to 4 µg/dscm levels for both tests.

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 sug-

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

Compound	Baseline Test: Per Heat Input (ng/J)	Baseline Test: Average Concentration (mg/dscm)	Low-NO_x Test: Per Heat Input (ng/J)	Low-NO_x Test: Average Concentration (mg/dscm)	Occupational Exposure Guideline[b] (mg/dscm)
Criteria Pollutant and Other Vapor Species					
NO_x (as NO_2)	1,260	1,900	654	976	6.0
CO	120	198	198	295	55
CH_4	293	480	323	482	
TUHC (as C_3H_8)	960	1,600	1,100	1,640	
Solid particulate	12.5	20	16.2	24.2	10.0[c]
Condensable particulate	7.3	12	7.5	11.2	(10.0[c], combined with above)
Total chromatographabale organics (C_1-C_{16})	1.3	2.1	1.6	2.4	
Total nonvolatile organics (>C_{16})	35	57.8	15	22.1	
Trace Elements					
Copper, Cu	0.15	0.25	0.18	0.27	0.10[d]
Iron, Fe	—	—[e]	1.1	1.6	1.0
Chromium, Cr	0.013	0.022	0.053	0.079	0.050
Phosphorus, P	0.0067	0.011	0.060	0.090	0.10
Silver, Ag	0.0010	0.0017	0.0046	0.0068	0.010
Potassium, K	>0.48	>0.80	>0.66	0.98	2.0[f]
Sodium, Na	>0.48	>0.80	>0.54	0.80	2.0[f]
Lead, Pb	0.012	0.020	0.0074	0.011	0.050[d]
Calcium, Ca	0.35	0.59	0.18	0.27	2.0
Selenium, Se	0.035	0.059	0.023	0.034	0.20
Cobalt, Co	—	—	0.018	0.027	0.10
Nickel, Ni	0.0014	0.023	0.0013	0.0019	0.10

[a]Exhaust O_2 and CO_2 levels were 12.1 and 4.9 percent, respectively, for the baseline test and 13.2 and 4.4 percent, respectively, for the low-NO_x test.
[b]Time-weighted-average, TLV, unless noted.
[c]For nuisance particulate.
[d]8-Hr time-weighted-average OSHA exposure limit.
[e]Dashes indicate the pollutant was not quantifiable.
[f]Ceiling limit.

gested that the exhaust gas organic for both tests was primarily aliphatic hydrocarbons, with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics (e.g., naphthalene and alkyl naphthalenes).

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

Table 3. *Bioassay Analysis Results*

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

[a]H = high toxicity; M = moderate toxicity.
[b]H = high mutagenicity;
M = moderate mutagenicity.

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C. Castaldini is with Acurex Corp., Mountain View, CA 94039.
***Robert E. Hall** is the EPA Project Officer (see below).*
The complete report consists of two volumes, entitled "Environmental Assessment of NO_x Control on a Spark-Ignited, Large-Bore, Reciprocating Internal-Combustion Engine:"
"Volume I. Technical Results," (Order No. PB 86-156 809/AS; Cost: $16.95)
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