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Project Summary

Environmental Assessment of a Reciprocating Engine Retrofitted with Selective Catalytic Reduction

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This report describes emission results obtained from field testing of a gas-fired lean-burn reciprocating internal combustion engine retrofitted with a selective catalytic reduction (SCR) system for NO_x reduction. Two series of tests were performed: a comprehensive test program to characterize catalyst inlet and outlet exhaust gas composition at a catalyst NO_x reduction performance target of greater than or equal to 80 percent; and a 15-day exhaust monitoring program to measure the catalyst performance under typical engine operating conditions.

Emission measurements during the comprehensive test program included continuous monitoring of flue gas emissions; source assessment sampling system (SASS) sampling of the exhaust gas with subsequent laboratory analysis of samples to give solid particulate emissions, total organics in two boiling point ranges, compound category information within these ranges, and specific quantitation of the semivolatile organic priority pollutants; VOST sampling for volatile organic emissions at the catalyst outlet; modified EPA Method 6 sampling systems for NH_3 and total cyanides; and exhaust gas grab samples for N_2O analysis by gas chromatography. Emission measurements during the 15-day monitoring program were limited to continuous monitoring of exhaust gas species.

Comprehensive test results indicated that during the 1-day test the NO_x reduction performance of the catalyst was maintained relatively constant at 81 percent. NO_x emissions at the catalyst inlet ranged from 2,200 to 2,600 ppm, as measured at 11.2 percent O_2 (2,400 ppm average). At the catalyst outlet, NO_x ranged from 330 to 560 ppm, also at about 11.2 percent O_2 (445 ppm average).

CO emissions averaged 245 ppm at the catalyst inlet and 225 ppm at the outlet. Hydrocarbon emission data were not available for the comprehensive tests; however, emission results obtained during the extended emission testing indicated emissions in the range of about 1,500 to 1,800 ppm at both the inlet and outlet. Total organic (C_{6+}) emissions were apparently reduced across the catalyst from 4.9 to 1.5 mg/dscm (20 to 6.2 mg/bhp-hr). Emissions of two polynuclear aromatic hydrocarbon (PAH) species, naphthalene and phenanthrene, and a nitrophenol were quantitated. Again, catalyst inlet levels were higher than outlet levels. Outlet PAH emissions were at or below 0.4 µg/dscm (about 1.6 µg/bhp-hr).

During the extended 15-day performance test, the NO_x reduction performance was also maintained relatively constant at about 80 percent. Only occasionally and briefly did NO_x reduction fall below 80 percent. These brief low catalyst performance periods were attributed to engine load surges and an occasional malfunction in the NH_3 injection flowrate.

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

In California, the South Coast Air Quality Management District (SCAQMD) continues to be in nonattainment of both federal and state NO_2 standards. Stationary reciprocating internal combustion engines (ICEs) are estimated to contribute about 14 percent of the NO_x (about 59 Mg/day (65 tons/day)) from all stationary sources and 5.1 percent of total NO_x emissions in the basin. In 1979, the California Air Resources Board (CARB) proposed a control strategy for ICEs that called for retrofit of these sources with nonselective and selective gas treatment catalysts (NSCR and SCR, respectively). The proposed SCAQMD rule 1110 called for demonstration of 90 percent NO_x reduction or an emissions limit of 0.28 µg/J (0.75 g/bhp-hr) of heat output. Following this proposed rule, there has been a sustained R&D effort to demonstrate the capability of commercially available NSCR and SCR catalysts and identify problems in their application. In September 1984, a modified version of this rule was adopted by SCAQMD calling for 80 percent NO_x reduction demonstration with subsequent 70 percent reduction from existing lean-burn engines. The retrofit schedule calls for 80 percent of all existing lean-burn engines with capacity greater than 500 hp in the South Coast Air Basin to be controlled by December 31, 1987. The remaining lean-burn engines (all above 50 hp) are to be controlled by December 31, 1994.

This report describes the results of comprehensive emission tests and 15-day extended monitoring tests of a lean-burn reciprocating engine retrofitted with an SCR system. Emissions were measured at both the inlet and outlet of the catalyst to quantitate both NO_x reduction performance and the impact of the catalyst on other pollutants.

The tests were performed on an Ingersoll-Rand 412 KVS (2,000-hp) four-stroke, turbocharged gas compressor engine owned and operated by Southern California Gas Company (SoCal). In April 1984, the engine was retrofitted with an Englehard SCR catalyst system. A similar system was previously tested on a slipstream of the engine and found capable of 90 percent NO_x reduction. The catalyst, based on a proprietary metal oxide formulation, has an upper temperature limit of 427 °C (800 °F). The slipstream tests by SoCal had shown that 90 percent NO_x reduction was achieved using an NH_3/NO injection rate of 1.0 (molar ratio) and an exhaust temperature of about 400 °C (750 °F).

Summary and Conclusions

Engine Operation

The test program called for the evaluation of NO_x reduction performance of the catalyst and its effect on organic and inorganic gaseous pollutants during 1 day of comprehensive tests with the engine NH_3 injection rate adjusted for NO_x reduction of greater than 80 percent at constant power output. In addition, the test program called for a continuous 15-day emission monitoring program to evaluate the NO_x control capability with the engine operating under typical conditions with varying load and NH_3 injection rate.

Table 1 summarizes engine operating characteristics during the comprehensive tests. Engine load was maintained relatively constant, at about 1,270 kW (1,700 hp), throughout this portion of the test program. Brake-specific fuel consumption was 9.4 MJ/kWh (6,600 Btu/bhp-hr) based on fuel lower heating value. This is at the low end of representative four-stroke turbocharged engines. The NH_3 injection rate ranged from about 4.4 to 4.9 l/s (565 to 620 scfh), representing an NH_3/NO molar ratio of about 1.0. The NH_3 injection rate was controlled by a feedback system which monitored NO_x at the engine outlet and set NH_3 injection rate to maintain a target NO_x reduction of 80 percent.

Note that, prior to the test period, problems were experienced with the NH_3 control system, specifically the NO_x analyzer and the NH_3 control valve.

Emission Measurements and Results — Comprehensive Tests

The sampling and analysis procedures used in this test conformed to a modified EPA Level 1 protocol. The exhaust gas measurements included the following at both the catalyst inlet and outlet:

- Continuous monitoring for O_2, CO_2, CO, NO/NO_x, NH_3, and TUHC.
- SASS sampling.
- VOST sampling for volatile organics.
- Modified EPA Method 6 train sampling for NH_3 and total cyanide.
- Gas grab sample for N_2O determination.

The analysis protocol included:

- Analyzing SASS train samples for

Table 1. *Engine Operation — Comprehensive Tests*

Parameter	*Range*	*Average*
Ambient		
Dry bulb temperature, °C (°F)	*22 to 33 (72 to 92)*	*29 (84)*
Wet bulb temperature, °C (°F)	*19 to 21 (67 to 72)*	*20 (68)*
Relative humidity, percent	*45 to 55*	*50*
Barometric pressure, kPa (in. Hg)	—	*96.2 (28.5)*
Engine Operation		
Engine load, kW_t (bhp)[a]	—	*1270 (1700)*
Fuel flow, m^3/h (scfh)	—	*327 (11,550)*
Heat input, MW (million Btu/hr)[b]	—	*3.29 (11.2)*
Specific fuel consumption, kJ/kWh (Btu/bhp-hr)[b]	—	*9390 (6610)*
Air manifold pressure, kPa (psig)	*25 to 28 (3.6 to 4.0)*	*26.5 (3.85)*
Air manifold temperature, °C (°F)	*68 to 70 (154 to 158)*	*69 (156)*
Engine speed, rpm	*320 to 333*	*325*
Exhaust manifold temperature, °C (°F)	*380 to 382 (716 to 720)*	*380 (718)*
Catalyst/NH_3 System		
Catalyst inlet temperature, °C (°F)	*390 to 400 (740 to 750)*	*396 (745)*
Catalyst outlet temperature, °C (°F)	*344 to 382 (652 to 720)*	*362 (683)*
NH_3 flowrate, l/s (scfh)	*4.44 to 4.88 (565 to 620)*	*4.64 (590)*
Gas Compressor		
Suction pressure, MPa (psig)	—	*4.02 (583)*
Interstage pressure, MPa (psig)	—	*7.86 (1,140)*
Discharge pressure, MPa (psig)	—	*18.87 (2,898)*
Suction temperature, °C (°F)	*26 to 35 (78 to 95)*	*29 (85)*
Interstage temperature, °C (°F)	*88 to 93 (180 to 200)*	*91 (195)*
Discharge temperature, °C (°F)	*107 to 118 (225 to 245)*	*113 (235)*

[a]Engine load obtained from engine performance curves.
[b]Heat input based on low heating value (LHV) of natural gas. Specific fuel consumption based on LHV of fuel.

total organic content in two boiling point ranges: 100 to 300 °C by total chromatographable organics (TCO) analysis, and greater than 300 °C by gravimetry (GRAV).

- Analyzing the SASS train sorbent module extract for 58 semivolatile organic species including many of the PAH compounds.
- Performing infrared (IR) spectrometry analysis of organic sample extracts.
- Analyzing VOST traps for 34 volatile organic priority pollutant species.

Table 2 summarizes emissions measured at the engine muffler outlet (catalyst inlet) and the catalyst outlet. Continuous monitored emissions (O_2, CO_2, CO, NO/NO_x, and TUHC) were measured upstream of the NH_3 injection, located upstream at the engine muffler. Emissions are presented in milligrams per dry standard cubic meter, nanograms per Joule heat input, and milligrams per brake horsepower-hour shaft output.

As shown in Table 2, NO_x emissions were reduced 81 percent on the average, from 2,760 to 513 ng/J (19.2 to 3.57 g/bhp-hr). Actually, NO_x reductions did not vary significantly from this average throughout the test, indicating a relatively constant NO_x reduction performance of the catalytic system.

NH_3 emissions measured at the catalyst outlet with an extractive sampling system averaged 39 ng/J (0.27 g/bhp-hr), corresponding to a volumetric gas concentration of 93 ppm. NH_3 emissions, also measured at this location by a continuous monitoring system, confirmed these results. Total cyanide increased significantly across the catalyst to a concentration of 2.4 mg/dscm at the catalyst outlet. Both TCO and GRAV organics were apparently reduced by the catalyst by about 46 and 82 percent, respectively. This performance coincides with relatively low CO levels that were also measured at the catalyst outlet. Solid particulate emissions were not detectable within the accuracy of the analytical procedure.

Table 3 summarizes the emissions of volatile and semivolatile organic compounds detected by GC/MS analyses of VOST traps and SASS sorbent extract samples. Volatile organics were measured only at the catalyst outlet. These data show benzene and toluene as the principal compounds with concentrations of about 900 and 250 μg/dscm, respectively, at the catalyst outlet. Other volatiles detected were xylenes, chlorobenzenes, and ethylbenzenes with concentrations below 100 μg/dscm. Naphthalene and 2-nitrophenol were the major semivolatile organics detected at the catalyst inlet. Their concentrations of 8.4 and 5.3 μg/dscm, respectively, were reduced at the outlet to undetectable levels (≤0.4 μg/dscm).

Emission Measurements and Results — 15-Day Monitoring

The sampling and analysis protocol for this portion of the test program consisted of continuous monitoring of inlet and outlet exhaust gas for O_2, CO_2, CO, NO/NO_x, NH_3, and TUHC with certification of NO_x analyzer readings using EPA Method 7. Since both engine power output and NH_3 injection rate were not restricted to specified ranges, the data obtained can be considered reflective of typical operating practice. Figures 1 through 6 summarize emission results. Each data point in these figures represents an hourly average. The data indicate relatively steady engine operation with exhaust O_2 levels at about 11 percent and CO_2 at about 5.5 percent. NO_x emissions ranged between 1,200 and 1,600 ppm corrected to 15 percent O_2 at the inlet and about 100 to 400 ppm at 15 percent O_2 at the catalyst outlet. NO_x reduction efficiency translates to nearly constant 80 percent as shown in Figure 3. The two data points indicating reduced or no NO_x reduction were generally caused by an occasional loss of NH_3 flow or a surge in engine load. These

Table 2. Summary of Exhaust Gas Emissions

	Catalyst inlet[a]			Catalyst outlet[a]		
Specie	mg/dscm	ng/J	mg/bhp-hr	mg/dscm	ng/J	mg/bhp-hr
NO_x (as NO_2)	4,630	2,760	19,200	860	513	3,570
CO	287	171	1,190	265	158	1,100
NH_3[b]				65	39	270
Total cyanide (as CN)	0.007	0.004	0.03	2.4	1.4	10
N_2O[c]	180	108	750	79	47	327
Total chromatographable organics (C_7 to C_{16})	1.7	1.0	7.0	0.9	0.54	3.7
Total GRAV organics (C_{16+})	3.2	1.9	13	0.6	0.34	2.4

[a]Average exhaust gas O_2 and CO_2 were 11.2 and 5.5 percent, respectively, at both catalyst inlet and outlet.
[b]NH_3 emissions at the engine outlet were not measured by wet chemical analysis.
[c]N_2O emissions were measured after the comprehensive test period. Catalyst inlet and outlet NO_x during these tests were similar to levels measured during the comprehensive tests.

Table 3. Volatile and Semivolatile Organic Emissions

Compound	Catalyst Inlet (μg/dscm)	Catalyst Outlet (μg/dscm)
Volatile organics:[a]		
Benzene	NA[b]	915
Chlorobenzene		61
Chloroethane		1.8
1,1,dichloroethane		1.5
Ethylbenzene		20
Tetrachloroethane		2.4
Toluene		247
Acetone		17
Total xylenes		85
Semivolatile organics:		
Naphthalene	8.4	0.4
Phenanthrene	0.4	<0.4
2-Nitrophenol	5.3	<0.4
Di-n-butyl phthalate[c]	3.1	5.5
Bis(2-ethylhexyl)phthalate[c]	1.9	1.0

[a]Volatile organic emissions measured only at the catalyst outlet. Values presented are blank corrected average of two measurements.
[b]NA = Not available. No measurements for volatile organics performed at the catalyst inlet.
[c]Suspected contaminants, commonly found in laboratory blanks.

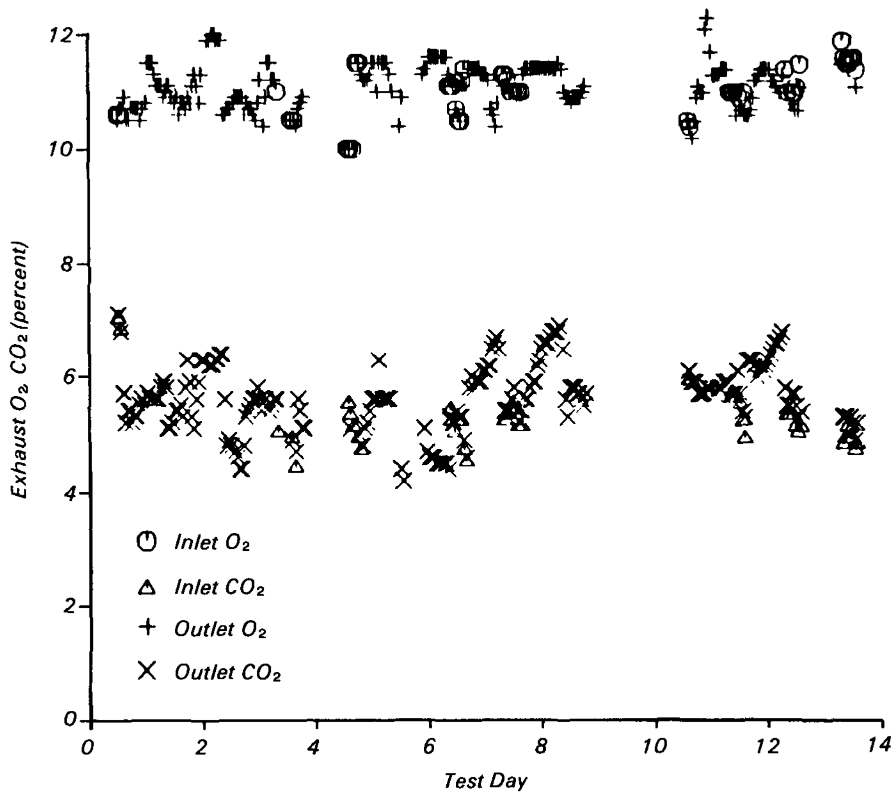

Figure 1. *Exhaust O_2 and CO_2 for the extended continuous monitoring period.*

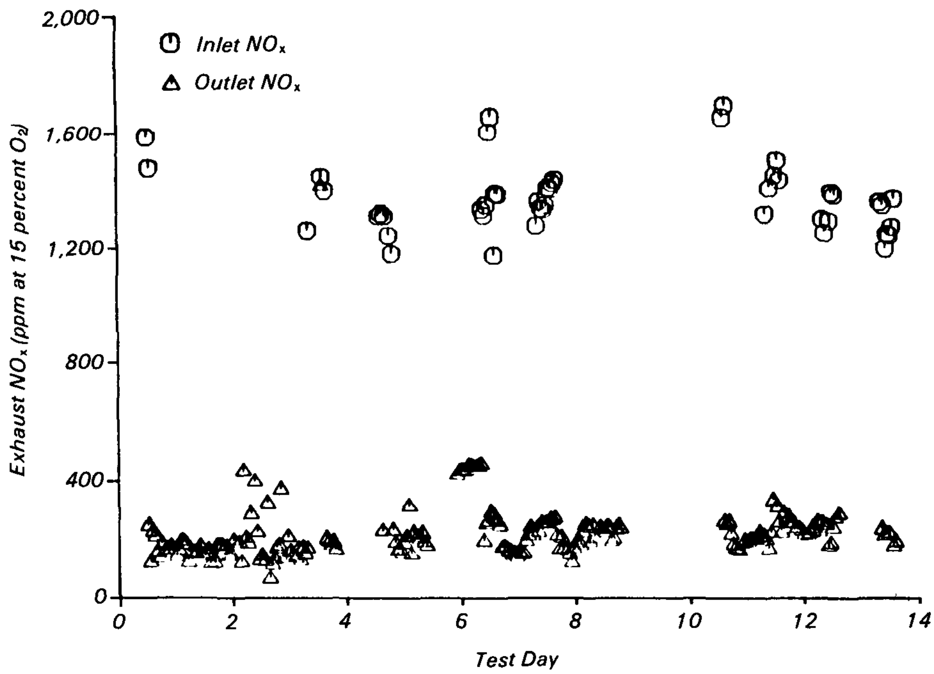

Figure 2. *Exhaust NO_x levels for the extended continuous monitoring period.*

episodes were infrequent and generally brief. Periods of no data are indicative of engine shutdown due to a lubricating system problem. NH_3 emissions at the catalyst outlet, Figure 4, ranged typically between zero and 150 ppm. These data were collected by using two NO_x analyzers, one equipped with a molybdenum and one with a stainless steel converter, respectively. NH_3 was determined by the difference between the $NO+NO_2+NH_3$ and $NO+NO_2$ readouts of the two online instruments. Combustible emissions were 100 to 300 ppm for CO and 750 to 1,250 ppm for TUHC.

Summary

Emission test of a lean-burn reciprocating internal combustion engine retrofitted with a SCR NO_x control system suggest that NO_x emission reduction of 80 percent can be maintained with good control on NH_3 injection rate at relatively constant engine load. The catalyst was found to slightly reduce CO emissions including detected organic compounds. NH_3 breakthrough emissions ranged generally between zero and 150 ppm corrected to 15 percent O_2. Measurements by wet chemical methods support these levels. Total cyanides increased by 3 orders of magnitude across the catalyst to a level of 1.4 ng/J at the catalyst outlet.

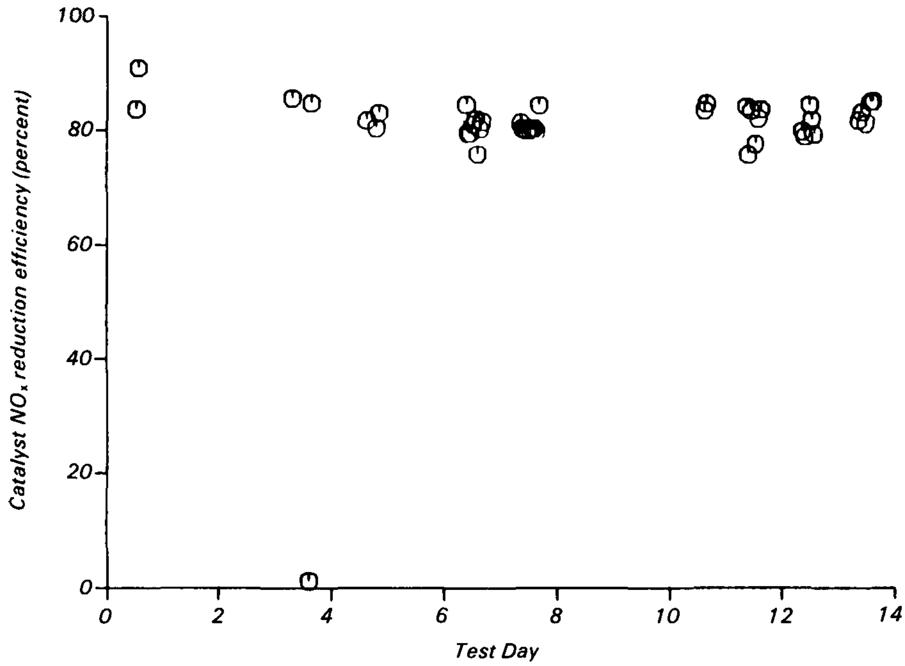

Figure 3. *Catalyst NO_x reduction efficiency for the extended monitoring period.*

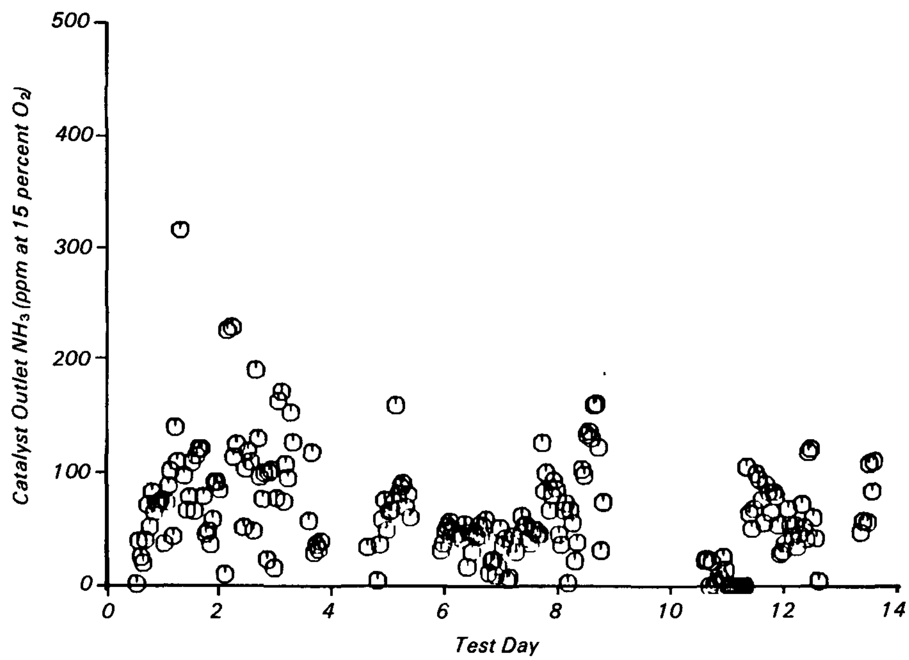

Figure 4. *Catalyst outlet NH_3 emissions for the extended continuous monitoring period.*

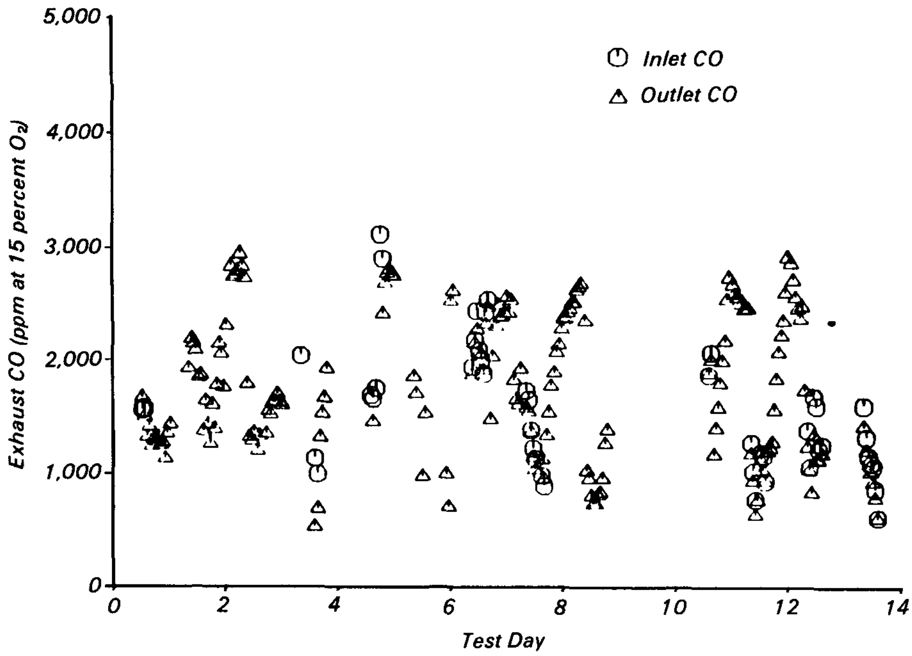

Figure 5. *Exhaust CO levels for the extended continuous monitoring period.*

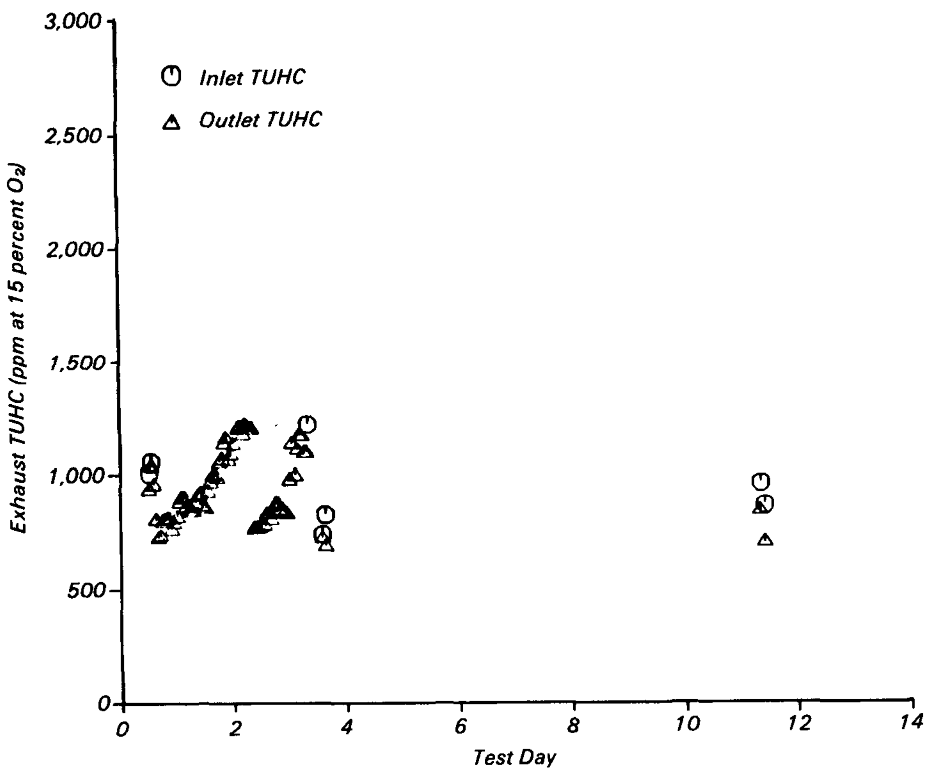

Figure 6. *Exhaust hydrocarbon levels for the extended continuous monitoring period.*

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The complete report consists of two volumes, entitled "Environmental Assessment of a Reciprocating Flame Retrofitted with Selective Catalytic Reduction:"
"Volume I. Technical Results," (Order No. PB 86-183 779/AS; Cost: $11.95)
"Volume II. Data Supplement," (Order No. PB 86-183 787/AS; Cost: $11.95)

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