United States
Environmental Protection
Agency

EPA-600/7-84-073a

July 1984

EPA

Research and Development

ENVIRONMENTAL ASSESSMENT OF
A RECIPROCATING ENGINE
RETROFITTED WITH NONSELECTIVE
CATALYTIC REDUCTION
Volume I. Technical Results

Prepared for

Office of Air Quality Planning and Standards

Prepared by

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

EPA REVIEW NOTICE

This report has been reviewed by the participating Federal Agencies, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/7-84-073a
July 1984

ENVIRONMENTAL ASSESSMENT OF A RECIPROCATING ENGINE RETROFITTED WITH NONSELECTIVE CATALYTIC REDUCTION

Volume I
Technical Results

by

C. Castaldini and L. R. Waterland
Acurex Corporation
Energy & Environmental Division
555 Clyde Avenue
P.O. Box 7555
Mountain View, California 94039

Contract No. 68-02-3188

EPA Project Officer:

R.E. Hall
Combustion Research Branch
Energy Assessment and Control Division
Industrial Environmental Research Laboratory
Research Triangle Park, North Carolina 27711

Prepared for:

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, DC 20460

ABSTRACT

The two-volume report describes results obtained from testing a rich-burn reciprocating internal combustion engine retrofitted with a nonselective catalytic reduction system (NSCR) for NO_x reduction. A comprehensive test program was performed to characterize catalyst inlet and outlet organic and inorganic emissions at optimum catalyst NO_x reduction performance, followed by a 15-day exhaust emission monitoring program to measure the catalyst performance under typical engine operating conditions. Over the 1-day comprehensive test period, the NO_x reduction performance of the catalyst ranged between 54 and 81 percent, with an average of 70 percent. NO_x emissions averaged 1700 ppm at the catalyst inlet and 550 at the catalyst outlet. Catalyst inlet CO and TUHC concentrations averaged 14,600 ppm and 115 ppm, respectively. These inlet combustible concentrations were the result of engine operation at an air/fuel ratio near or slightly below the stoichiometry required for efficient NO_x reduction. Catalyst outlet CO and TUHC levels were reduced to 13,200 ppm and 125 ppm, respectively. Total organic emissions were also reduced by the catalyst from 15.5 to 2.1 mg/dscm. Ammonia and cyanide levels increased by factors of 15 and 450, respectively, across the catalyst. Over the 15-day monitoring period, NO_x reduction performance was mostly in the 0 to 40 percent range. Only occasionally did NO_x reduction exceed 90 percent. During these periods of better performance, CO and TUHC emissions at the inlet were as high as 1 percent and 0.1 percent, respectively.

CONTENTS

FIGURES

TABLES

ACKNOWLEDGMENTS

This test was performed in cooperation with Southern California Gas Company (SoCal). Appreciation is greatly extended to G. Gardetta and W. Matlock of SoCal. Special recognition and thanks are extended to the Acurex field test crew of Bruce DaRos, Regan Best, Pete Kaufmann, Greg Nicoll, and Sherman Smith under the supervision of Howard Mason, the project leader at the site.

SECTION 1

INTRODUCTION

This report describes and presents results for a set of environmental assessment tests performed for the Industrial Environmental Research Laboratory/Research Triangle Park (IERL/RTP) of EPA under the Combustion Modification Environmental Assessment (CMEA) program, EPA Contract No. 68-02-3188. The CMEA started in 1976 with a 3-year study the NO_x Control Technology Environmental Assessment (NO_x EA, EPA Contract No. 68-02-2160), having the following objectives:

- Identify potential multimedia environmental effects of stationary combustion sources and combustion modification technology
- Develop and document control application guidelines to minimize these effects
- Identify stationary source and combustion modification R&D priorities
- Disseminate program results to intended users

During the first year of the NO_x EA, data and methodologies for the environmental assessment were compiled. Furthermore, priorities for the schedule and level of effort for developing emission data for the various source/fuel/control combinations were identified. This effort revealed major data gaps, particularly for noncriteria pollutants (organic emissions and trace elements) for virtually all combinations of stationary combustion

sources and combustion modification techniques. Consequently, a series of seven environmental field test programs was undertaken to fill these data gaps. The results of these tests are documented in seven individual reports (References 1-1 through 1-7) and in the NO_x EA final report summarizing the entire 3-year effort (Reference 1-8).

The current CMEA program has, as major objectives, the continuation of multimedia environmental field tests initiated in the original NO_x EA program. These new tests, using standardized sampling and analytical procedures (Reference 1-9) are aimed at filling remaining data gaps and addressing the following priority needs:

- Advanced NO_x controls
- Alternate fuels
- Secondary sources
- EPA program data needs
  - -- Residential oil combustion
  - -- Wood firing in residential, commercial, and industrial sources
  - -- High interest emissions determination (e.g., listed and candidate hazardous air-pollutant species)
- Nonsteady-state operations

In California, the South Coast Air Quality Management District (SCAQMD) continues to be in nonattainment of both federal and state NO_2 standards. Reciprocating internal combustion engines (ICE's) in this district are estimated to contribute 14 percent of the NO_x (about 59 Mg/day (65 tons/day)) from all stationary sources and 5.1 percent of the total NO_x emissions in the basin (References 1-10 and 1-11). Furthermore, since acid precipitation in noncoal-burning regions such as the SCAQMD is being increasingly attributed

to NO_x emissions from sources with low stacks, reciprocating ICE's are being viewed as possibly contributing to the acid rain problem.

In 1979, the California Air Resources Board (CARB) proposed a control strategy for ICE's that called for retrofit of these sources with nonselective and selective gas treatment catalysts (NSCR and SCR, respectively). In keeping with this CARB strategy, the SCAQMD passed rule 1110 calling for demonstration tests of NSCR and SCR technologies for engine NO_x control. Southern California Gas Company (SoCal) has conducted several performance tests to evaluate NSCR and SCR catalysts for their applicability in reducing NO_x from SoCal operated ICE's. In addition to the problem of sustained NO_x reduction performance, several environmental concerns associated with this technology have been documented (Reference 1-12). In the case of NSCR, for example, the formation of ammonia and cyanide gases by the catalyst has been highlighted. For SCR, breakthrough ammonia and N_2O formation are also concerns.

In response to these concerns, a rich-burn reciprocating ICE operated by SoCal and retrofitted with a commercially available NSCR system was selected for testing under the CMEA program. The objective of the tests was to quantify multimedia emissions (including organics, inorganics, as well as, ammonia and cyanides) at the inlet and outlet of the NSCR catalytic reactor. In addition to these tests, NO_x reduction performance of the NSCR was monitored continuously over 15 days under typical operating conditions.

Table 1-1 lists all the tests performed in the CMEA program, outlining the source tested, fuel used, combustion modifications implemented and the level of sampling and analysis performed in each case. Results of these test programs are discussed in separate reports.

TABLE 1-1. COMPLETED TESTS DURING THE CURRENT PROGRAM

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Spark-ignited natural-gas-fueled reciprocating internal combustion engine	Large-bore, 6-cylinder, opposed piston, 186 kW (250 Bhp)/cyl, 900 rpm, Model 38TDS8-1/8	-- Baseline (pre-NSPS) -- Increased air-fuel ratio aimed at meeting proposed NSPS of 700 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Compression-ignition diesel-fueled reciprocating internal combustion engine	Large-bore, 6-cylinder opposed piston, 261-kW (350 Bhp)/cyl, 900-rpm, Model 38TDD8-1/8	-- Baseline (pre-NSPS) -- Fuel injection retard aimed at meeting proposed NSPS of 600 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Low-NO_x residential condensing heating system furnished by Karlsons Blueburner Systems Ltd. of Canada	Residential hot water heater equipped with M.A.N. low-NO_x burner, 0.55 ml/s (0.5 gal/hr) firing capacity, condensing flue gas	Low-NO_x burner design by M.A.N.	Furnace exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Waste water	New test
Rocketdyne/EPA low-NO_x residential forced warm air furnace	Residential warm air furnace with modified high pressure burner and firebox, 0.83 ml/s (0.75 gal/hr) firing capacity	Low-NO_x burner design and integrated furnace system	Furnace exhaust: -- SASS -- Method 8 -- Controlled condensation -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel	New test

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Pulverized coal-fired utility boiler, Conesville station	400-MW tangentially fired; new NSPS design aimed at meeting 301 ng/J NO_x limit	ESP inlet and outlet, one test	ESP inlet and outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2 Coal Bottom ash ESP ash	Exxon Research and Engineering (ER&E) conducting corrosion tests
Nova Scotia Technical College industrial boiler	1.14 kg/s steam (9,000 lb/hr) firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with limestone injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, CO_2, CO, NO_x Fuel	Envirocon performed particulate and sulfur emission tests
Adelphi University industrial boiler	1.89 kg/s steam (15,000 lb/hr) hot water firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with Na_2CO_3 injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas Sample (C_1-C_6 HC) -- Continuous O_2, CO_2, NO_x, CO Fuel	Adelphi University
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-oil (COM)	-- Baseline test only with COM	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Continuous O_2, CO_2, NO_x, TUHC, CO -- N_2O grab sample Fuel	PETC and General Electric (GE)

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
TOSCO Refinery vertical crude oil heater	2.54 Ml/day (16,000 bbl/day) natural draft process heater burning oil/refinery gas	-- Baseline -- Staged combustion using air injection lances	Heater outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO, CO_2, HC -- N_2O, grab sample Fuel oil Refinery gas	KVB coordinated the staged combustion operation and continuous emission monitoring
Mohawk-Getty Oil industrial boiler	8.21 kg/s steam (65,000 lb/hr) watertube burning mixture of refinery gas and residual oil	-- Baseline -- Ammonia injection using the noncatalytic thermal deNO_x process	Economizer outlet: -- SASS -- Method 5, 17 -- Controlled condensation -- Gas Sample (C_1-C_6 HC) -- Ammonia emissions -- N_2O grab sample -- Continuous O_2, NO_x, CO, CO_2 Fuels (refinery gas and residual oil)	Mohawk-Getty Oil
Industrial boiler	2.52 kg/s steam (20,000 lb/hr) watertube burning woodwaste	-- Baseline (dry wood) -- Green wood	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO Fuel Flyash	North Carolina Department of Natural Resources, EPA IERL-RTP
Industrial boiler	3.16 kg/s steam (29,000 lb/hr) firetube with refractory firebox burning woodwaste	-- Baseline (dry wood)	Outlet of cyclone particulate collector: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO Fuel Bottom ash	North Carolina Department of Natural Resources, EPA IERL-RTP

TABLF 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Enhanced oil recovery steam generator	15-MW (50 million Btu/hr) steam generator burning crude oil equipped with MHI low-NO_x burner	-- Performance mapping -- Low NO_x operation	Steamer outlet -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO, CO_2 -- N_2O grab sample Fuel	Getty Oil Company, CE-Natco
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-water slurry (CWS)	-- Baseline test only with CWS	Boiler outlet -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Collector hopper ash	PETC
Internal combustion engine -- nonselective NO_x catalyst	(610 kW (818-hp) Waukesha engine equipped with DuPont NSCR catalyst	-- Low-NO_x with catalyst -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- Grab sample N_2O -- Continuous O_2, CO_2, NO_x TUHC Fuel	Southern California Gas Company
Industrial boiler	180 kg/hr steam (400 lb/hr) stoker-fired with a mixture of coal and plastic waste	-- Baseline (coal) -- Coal and plastic waste	Boiler outlet -- SASS -- VOST -- Method 5/8 -- HCl -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Cyclone ash	Vermont Agency of Environmental Conservation

TABLE 1-1. (concluded)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Industrial boiler	7.6 kg/s steam (60,000 lb/hr watertube retrofit for coal water slurry firing	-- Baseline (CWS)	Boiler outlet -- SASS -- VOST -- Method 5/8 -- Grab sample (C_1-C_6 HC) -- Grab sample (N_2O) -- Continuous NO_x, CO, CO_2, O_2, TUHC, SO_2 Fuel	EPRI, DuPont
Enhanced oil recovery steam generator	15-MW (50 million Btu/hr) steam generator burning crude oil, equipped with the EPA/EER low-NO_x burner	-- Low NO_x -- 30-day emissions monitoring	Steamer outlet -- SASS -- VOST -- Method 5/8 -- Controller condensation -- Anderson monitors -- Grab sample (C_1-C_6 HC) -- Grab sample (N_2O) -- Continuous NO_x, CO, CO_2, O_2, SO_2 Fuel	Chevron U.S.A., EERC

REFERENCES FOR SECTION 1

1-1. Larkin, R. and E. B. Higginbotham, "Combustion Modification Controls for Stationary Gas Turbines: Volume II. Utility Unit Field Test," EPA-600/7-81-122b, NTIS PB82-226473, July 1981.

1-2. Higginbotham, E. B., "Combustion Modification Controls for Residential and Commercial Heating Systems: Volume II. Oil-fired Residential Furnace Field Test," EPA-600/7-81-123b, NTIS PB82-231175, July 1981.

1-3. Higginbotham, E. B. and P. M. Goldberg, "Combustion Modification NO_x Controls for Utility Boilers: Volume I. Tangential Coal-fired Unit Field Test," EPA-600/7-81-124a, NTIS PB82-227265, July 1981.

1-4. Sawyer, J. W. and E. B. Higginbotham, "Combustion Modification NO_x Controls for Utility Boilers: Volume II. Pulverized-coal Wall-fired Unit Field Test," EPA-600/7-81-124b, NTIS PB82-227273, July 1981.

1-5. Sawyer, J. W. and E. B. Higginbotham, "Combustion Modification NO_x Controls for Utility Boilers: Volume III. Residual-oil Wall-fired Unit Field Test," EPA-600/7-81-124c, NTIS PB82-227281, July 1981.

1-6. Goldberg, P. M. and E. B. Higginbotham, "Industrial Boiler Combustion Modification NO_x Controls: Volume II. Stoker Coal-fired Boiler Field Test -- Site A," EPA-600/7-81-126b, NTIS PB82-231085, July 1981.

1-7. Lips, H. I. and E. B. Higginbotham, "Industrial Boiler Combustion Modification NO_x Controls: Volume III. Stoker Coal-fired Boiler Field Test --Site B," EPA-600/7-81/126c, NTIS PB82-231093, July 1981.

1-8. Waterland, L. R., et al., "Environmental Assessment of Stationary Source NO_x Control Technologies -- Final Report," EPA-600/7-82-034, NTIS PB82-249350, May 1982.

1-9. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

1-10. Bartz, D., et al., "Control of Oxides of Nitrogen from Stationary Sources in the Sixth Coast Air Basin," KVB, Inc., Irvine, California, September 1974.

1-11. "Draft Air Quality Management Plan," South Coast Air Quality Management District, El Monte, California, October 1978.

1-12. Khakbiz, S., "Engineering Report -- DuPont Non-Selective System at Honor Rancho," Southern California Gas Company Engineering Job M-82-35, April 1983.

SECTION 2

SOURCE DESCRIPTION AND OPERATION

The tests were performed on a four-stroke, naturally aspirated Waukesha electric generator engine equipped with a PR-5 DuPont NSCR catalyst. This engine is located at the SoCal Honor Rancho underground storage field near Valencia, California. Table 2-1 summarizes the engine model specifications. The PR-5 DuPont catalyst, installed in November 1982 and having an initial operating life (per vendor information) of about 4,000 hr, is a platinum-rhodium-based formulation with an upper operating temperature limit of 788°C (1,450°F). The catalyst, located downstream of the engine silencer, was designed to reduce NO_x emissions by 90 percent or greater, and thereby meet SCAQMD rule 1110 of 0.28 µg/J (heat output), as NO_2 (0.75 g/Bhp-hr). Reducing gases, H_2, TUHC, and CO, in the exhaust gas react with NO_x in the presence of this noble metal catalyst to reduce both NO and NO_2. The NSCR chemical reaction process has been suggested to be as follows (Reference 2-1):

1. $CH_4 - 4NO_2 \rightarrow CO_2 + 4NO + 2H_2O$
2. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
3. $CH_4 + 4NO \rightarrow CO_2 + 2N_2 + 2H_2O$
4. $2CO + 2NO \rightarrow 2CO_2 + N_2$
5. $2H_2 + 2NO \rightarrow 2H_2O + N_2$

The NSCR process then requires fuel-rich engine operation or the addition of reducing agents in the flue gas upstream of the catalyst. To

TABLE 2-1. ENGINE MODEL SPECIFICATIONS[a]

Manufacturer	Waukesha
Model	L7042 GU
Strokes	4
Air charging	Naturally aspirated
Number of cylinders	V-12
Bore	0.238 m (9.375 in.)
Stroke	0.216 m (8.50 in.)
Displacement/cyl	9.62 l (587 $in.^3$)
Compression ratio	10:1
BMEP	703 kPa (102 psi)
Bhp/cyl @ rpm	50.7 kW (68 Bhp) @ 900 rpm
Generator output (electrical)	610 kW
BSFC	10,200 kJ/kWh (7,200 Btu/Bhp-hr)
Lubricating oil consumption	70 l/kWh (1.37 gal/Bhp-hr)

[a]Engine operating performance is based on continuous operation, ambient conditions of 99.2 kPa (29.38 in. Hg) and 29°C (85°F) and a natural gas fuel (lower heating value) of 33.5 MJ/m^3 (900 Btu/ft^3).

provide for an adequate concentration of reducing agents in the exhaust gas the engine often has to be operated with an air-to-fuel ratio (A/F) richer than that necessary for minimum fuel consumption. SoCal experience with the test engine has shown that A/F in the range of 17.2 to 17.4 is required to reduce NO_x emissions by 90 percent or more (Reference 2-2). Since the engine is not equipped with an automatic A/F controller, several manual adjustments are required to maintain this narrow range of A/F, especially during engine load changes. During normal operation, fluctuating demands are imposed on the engine generator and thus engine horsepower. This in turn causes changes in A/F and NO_x concentrations in the exhaust gas, often resulting in decreased catalyst performance.

During the CMEA tests, exhaust emissions (NO_x, O_2, CO, CO_2, and TUHC) were measured on a continuous basis for a period of 15 days during normal engine operating conditions (fluctuating loads and A/F). In addition, a comprehensive emission test program was performed over a 1-day period during which engine load and A/F were tightly controlled for catalyst NO_x reduction of greater than 80 percent. Table 2-2 summarizes the engine operation and ambient atmospheric conditions during this 1-day comprehensive testing period.

As noted, the comprehensive test program was performed at approximately 78 percent of rated load. Engine horsepower was most conveniently measured by the generator output, which corresponds to 1.45 times the generator kilowatts. Engine load oscillated about 60 hp (10 percent) over the test period with probable effects on A/F. Specific fuel consumption measured 12,300 kJ/kWh (8,660 Btu/Bhp-hr) based on the lower heating value of the fuel gas. This fuel consumption was well above the engine manufacturer

TABLE 2-2. ENGINE OPERATION

Parameter	Range	Average
Ambient		
Dry bulb temperature, °C (°F)	26 to 29 (79 to 85)	29 (84)
Wet bulb temperature, °C (°F)	20 to 22 (68 to 71)	22 (71)
Relative humidity, percent	--	52
Barometric pressure, kPa (in. Hg)	--	96.4 (28.55)
Engine Operation		
Generator output, kW	415 to 455	425
Engine load, kW_t (Bhp)[a]	448 to 492 (601 to 660)	459 (616)
Fuel flow, m^3/h (scfh)	--	156 (5,509)
Heat input, MW (million Btu/hr)[b]	--	1.56 (5.33)
Specific fuel consumption, KJ/kWh (Btu/Bhp-hr)[b]	--	12,300 (8,660)
Air manifold pressure		
• L, kPa (in. Hg vac)	14 to 16 (4.1 to 4.6)	15 (4.4)
• R, kPa (in. Hg vac)	14 to 16 (4.1 to 4.8)	15 (4.5)
Speed, rpm	900 to 910	905
Catalyst inlet temperature, °C (°F)	533 to 536 (991 to 997)	535 (995)
Catalyst output temperature, °C (°F)	534 to 561 (994 to 1,042)	552 (1,025)
Gas Analysis, Percent Volume[c]		
O_2	--	0.073
N_2	--	1.119
CO_2	--	0.890
CH_4	--	90.119
C_2H_6	--	6.294
C_3H_8	--	1.247
iso-C_4H_{10}	--	0.094
n-C_4H_{10}	--	0.106
iso-C_5H_{12}	--	0.029
n-C_5H_{12}	--	0.029
C_{6+}	--	0.003
HHV, MJ/m^3 (Btu/ft^3)[d]		39.9 (1,072)
LHV, MJ/m^3 (Btu/ft^3)[d]		36.0 (968)

[a]Horsepower not a measured value -- calculated from generator output times 1.45
[b]Based on lower heating value
[c]Based on data supplied by SoCal
[d]Calculated heating value

specifications. Exhaust gas temperature across the catalyst increased about 17°C (30°F) on the average reflecting the exothermic oxidation reaction promoted by the catalyst.

REFERENCES FOR SECTION 2

2-1. Chehaske, J. T., "NO_x Flue Gas Treatment," presented at the Seminar on Emissions and Air Quality At Natural Gas Pipeline Installations, San Antonio, Texas, November 12, 1980.

2-2. Khakbiz, S., "Engineering Report -- DuPont Non-Selective System At Honor Rancho," Southern California Gas Company Engineering Job M-82-35, April 8, 1983.

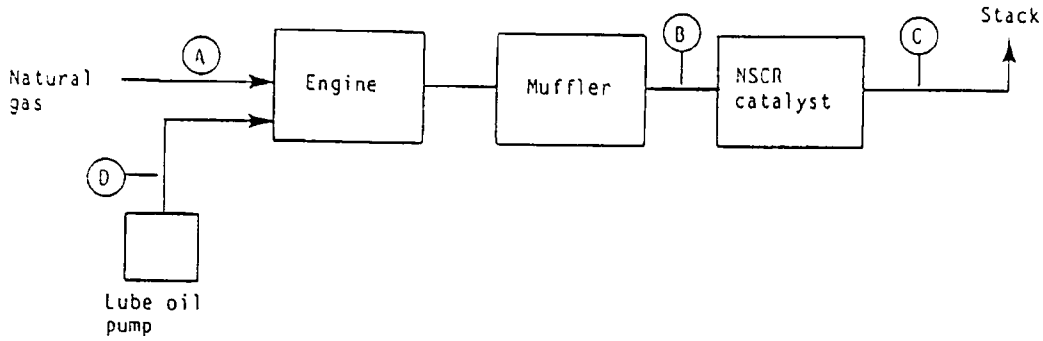
SECTION 3

EMISSION RESULTS

The objectives of this test program were: (1) to measure engine exhaust emissions during a 15-day test period to evaluate the continuous performance of the catalyst, utilizing continuous NO_x and other gas emission analyzers, and (2) to perform comprehensive tests over a 1-day period to measure the effect of the catalyst on inorganic and organic emissions including the possible formation of nitrogen compounds, such as NH_3 and HCN. Emission measurements were performed in cooperation with SoCal, owner and operator of the test facility, whose field crew and equipment included an emission monitoring laboratory with operating staff.

3.1 SAMPLING PROTOCOL

Figure 3-1 illustrates a schematic of the test site highlighting the sampling locations, sampling and analytical test matrix, and the test team performing the sampling and evaluation. As indicated, continuous monitoring of flue gas was performed both upstream and downstream of the catalytic reactor utilizing both heated and unheated sample lines. The sampling and gas conditioning system for this test program included continuous monitors for O_2, CO_2, CO, NO, NO_x, and TUHC. The continuous monitors were operated throughout a 15-day test period while engine load fluctuated according to generator demand. Certification of the NO_x analyzer readings was performed twice during this 15-day test period using standard EPA Method 7 protocol.



Sample Location	Type of Sample	Analyses[a]	Test Number
A -- Natural gas to engine	Grab sample -- Fuel	Gas chromatography for composition; heating value, specific gravity	SoCal
B -- Catalyst inlet	Extractive Sample -- Continuous Monitors	O_2, CO_2, CO, TUHC, NO, NO_x,	
	Sampling train -- SASS	Particulate by gravimetry, inorganics by SSMS and semi- and nonvolatile organics by EPA Method 625	Acurex
	Sampling train -- Modified Method 6	NH_3 by selective ion	Acurex
	Sampling train -- Modified Method 6	HCN by selective ion	Acurex
	Grab sample -- Gas bomb	N_2O by GC/ECD	Acurex
	Grab sample -- Method 7 flasks	NO_x	Acurex
C -- Catalyst outlet	Same as location B except no Method 7 taken		Acurex
D -- Lube oil pump	Grab sample -- Lube oil	Inorganics	Acurex

[a]Measurement and analysis techniques used are discussed in detail in Appendix A.

Figure 3-1. Sampling sites and analysis test matrix.

The source assessment sampling system (SASS), the NH_3, and the HCN, sampling trains were operated during 1 day of tests at both the inlet and outlet of the catalytic converter. Simultaneous inlet and outlet samples were performed to measure any change in the organic and inorganic composition of the exhaust gas across the catalyst. These measurements were performed while engine load was maintained constant and A/F was adjusted for effective NO_x reduction by the catalyst.

Figure 3-2 illustrates the actual test activity schedule. The following sections summarize the emission results. Sections 3.2 through 3.4 present emission results obtained during the comprehensive tests that took place on June 7, 1983. Section 3.5 summarizes results of continuous emission measurements and EPA Method 7 certification tests performed over the 15-day test period. Details of the sampling and analysis procedures used are discussed in Appendix A.

3.2 CRITERIA POLLUTANT AND OTHER VAPOR SPECIES EMISSIONS

Table 3-1 summarizes gaseous and particulate emissions measured during the 1-day comprehensive tests performed at the beginning of the 15-day continuous monitoring period. Exhaust O_2 was essentially undetected (reported as 0.1 percent dry). This indicates that the air-fuel mixture was near or below stoichiometric conditions, about 17.2 A/F weight basis.

Figures 3-3 and 3-4 show the variation in exhaust gas O_2 and CO_2 concentrations over the comprehensive test day (June 7, 1983). As indicated in the O_2 chart (Figure 3-3), prior to the start of the tests exhaust O_2 was reading approximately 0.8 percent. At about 9:00 a.m. the A/F was adjusted for richer burning conditions with exhaust O_2 dropping essentially to zero.

Test activity	June 1983															
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
• Continuous monitors (inlet/outlet)	Δ															Δ
• Comprehensive tests (inlet/outlet)																
-- SASS		Δ														
-- NH_3		Δ														
-- HCN		Δ														
-- N_2O			Δ													
• Method 7 certification tests (inlet)			Δ												Δ	

Figure 3-2. Test activity schedule

TABLE 3-1. CRITERIA AND OTHER GAS SPECIES EMISSIONS -- COMPREHENSIVE TESTS

Pollutant[a]	Catalyst Inlet			Catalyst Outlet		
As measured by continuous gas analyzers, range (average)						
O_2, percent dry	-- (0.1)			-- (0.1)		
CO_2, percent dry	9.8 to 10.5 (10.2)			9.8 to 10.6 (10.2)		
CO, ppm dry[b]	13,750 to 15,500 (14,600)			12,000 to 14,000 (13,200)		
NO_x, ppm dry	1,650 to 1,850 (1,700)			300 to 800 (550)		
TUHC, ppm dry as CH_4	140 to 370 (215)			80 to 200 (125)		
Corrected average gaseous emissions:	ppm[c]	ng/J[d]	g/Bhp-hr[e]	ppm[c]	ng/J[d]	g/Bhp-hr[e]
CO	4,270	1,210	12.2	3,860	1,030	10.4
NO_x[f]	486	770	7.79	157	250	2.53
TUHC[g]	61	34	0.33	36	20	0.20
NH_3	8.9	5.2	0.05	140	82	0.82
Total cyanide[h]	0.005	0.005	5.1×10^{-5}	2.3	2.2	0.022
Solid particulate mass emissions:						
-- SASS solid	--	0.309	0.003	--	0.303	0.003

[a]Appendix A discusses continuous monitor analyses used, sample gas conditioning system, particulate sampling equipment, and other sampling trains and procedures.
[b]CO emission data provided by SoCal.
[c]Corrected to 15 percent O_2, dry.
[d]On heat input basis, lower heating value.
[e]Shaft output basis.
[f]As NO_2
[g]As CH_4
[h]As HCN

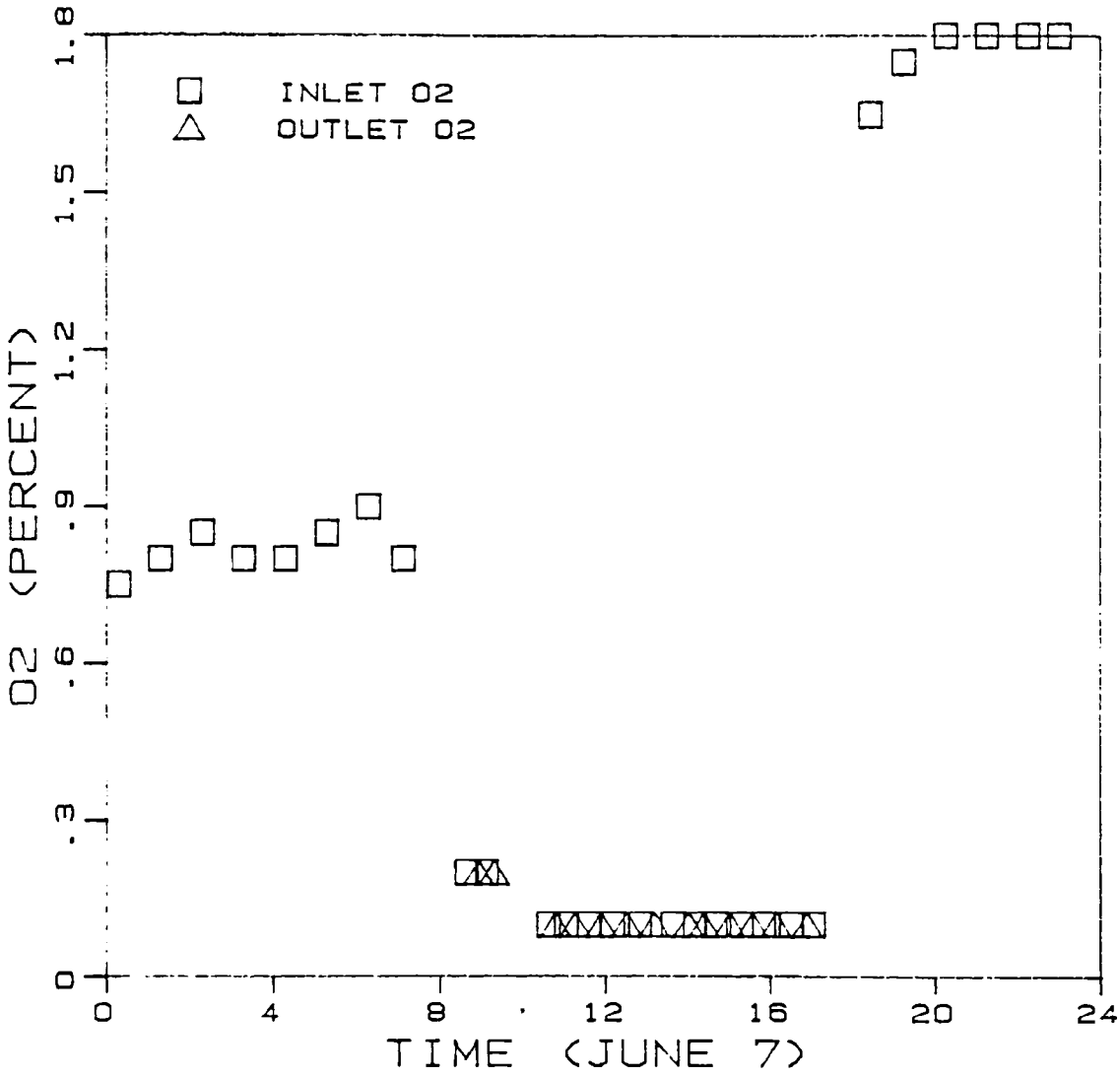


Figure 3-3. Exhaust gas O_2 during comprehensive tests.

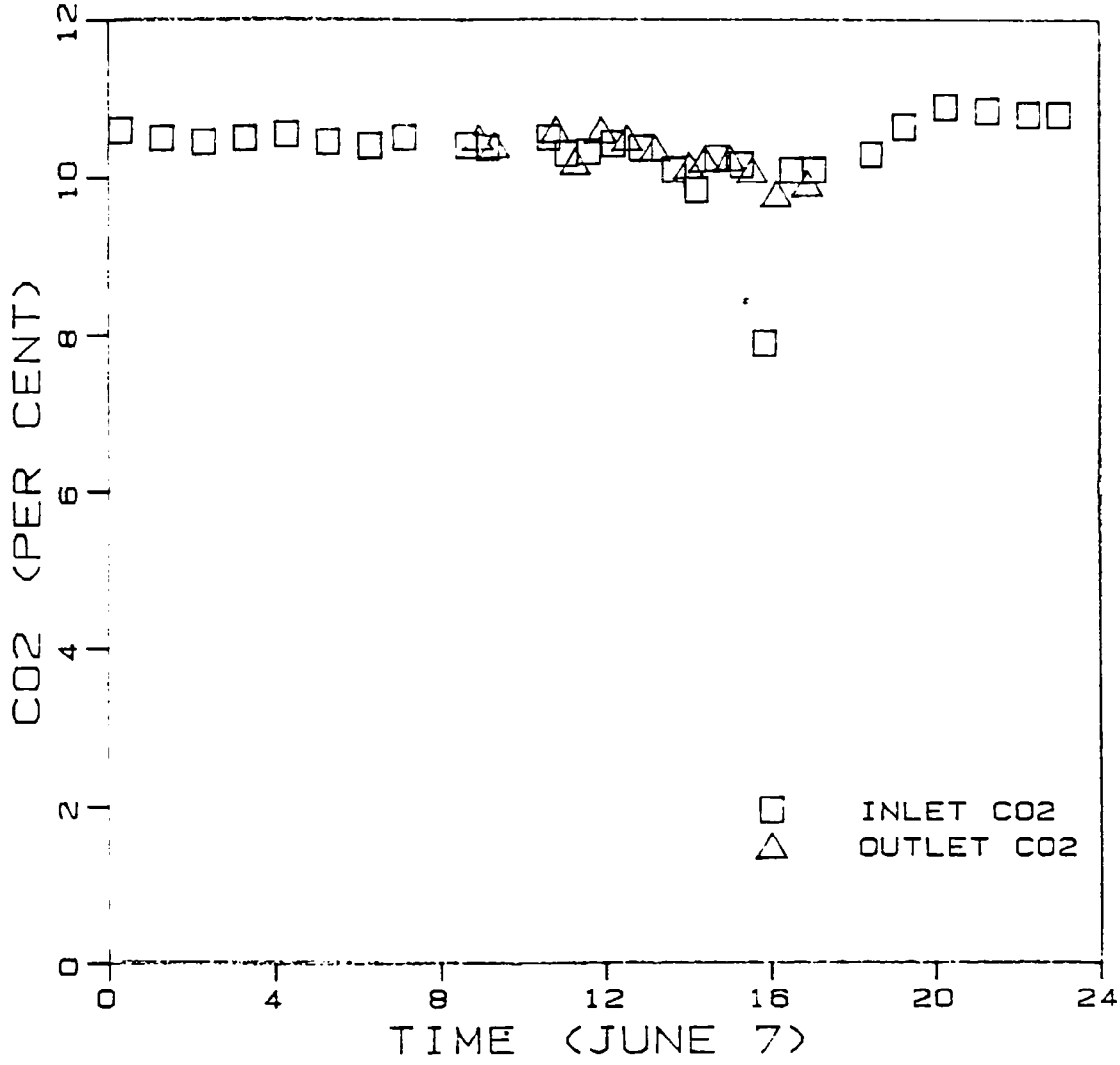


Figure 3-4. Exhaust gas CO_2 during comprehensive tests.

This condition was maintained until approximately 5:00 p.m. when all emission measurements were concluded.

CO emissions exceeded 3,000 ppm as measured by the low range CO analyzer in the Acurex van (the high range CO analyzer was inoperative on the comprehensive test day). This is above the quantitation limit of the analyzer. However, SoCal instrumentation provided data on CO during the test period. These emissions showed CO in excess of 1 percent at both inlet and outlet concentration. Only a 10 percent CO reduction by the catalyst was recorded by SoCal.

NO_x emissions at the catalyst inlet ranged from about 1,650 to 1,850 ppm as measured (at zero percent O_2) outlet emissions showed a greater variation, from 300 to 800 ppm. Figure 3-5 shows the variation in NO_x emissions over the test period. Inlet NO_x emissions corrected to 15 percent O_2 were about 800 ppm prior to the start of the comprehensive tests. Following engine adjustment for richer burning condition, inlet concentration decreased to about 530 ppm at the start of the tests with an apparent further decrease to 470 ppm at the end of the tests. At the conclusion of the tests, the engine load and A/F changed, resulting in an increase in NO_x back to about 800 ppm (15 percent O_2). Catalyst outlet NO_x emissions were monitored during the 8-hr comprehensive test period. These data show an initial concentration of about 90 ppm (at 15 percent O_2) followed by a gradual increase to 230 ppm at the end of the tests.

The resulting NO_x reduction efficiency of the catalyst during this time period is illustrated in Figure 3-6. Catalyst performance ranged from a maximum of 81 percent NO_x reduction at the start of the tests to 54 percent at the end of the tests. This reduced efficiency may have been caused by a

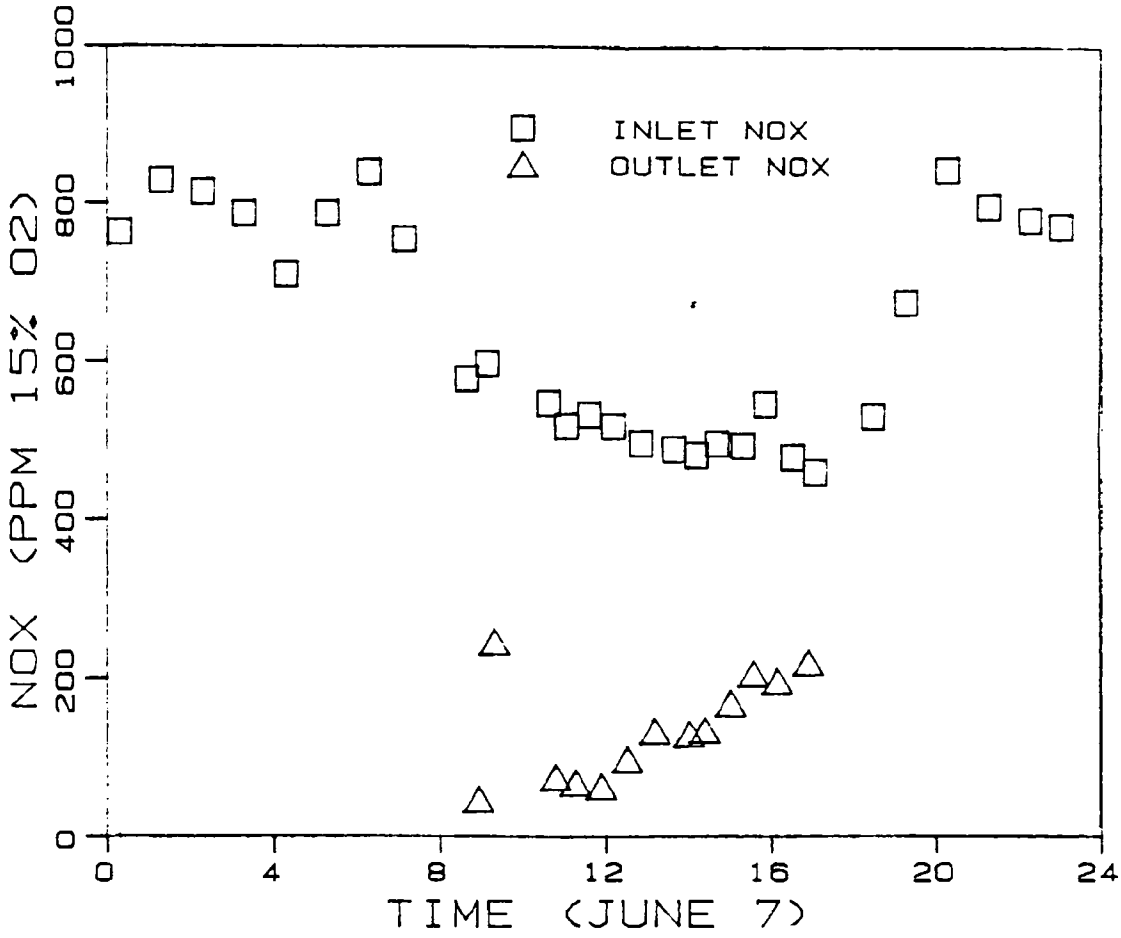


Figure 3-5. Exhaust gas NO_x emissions during comprehensive tests.

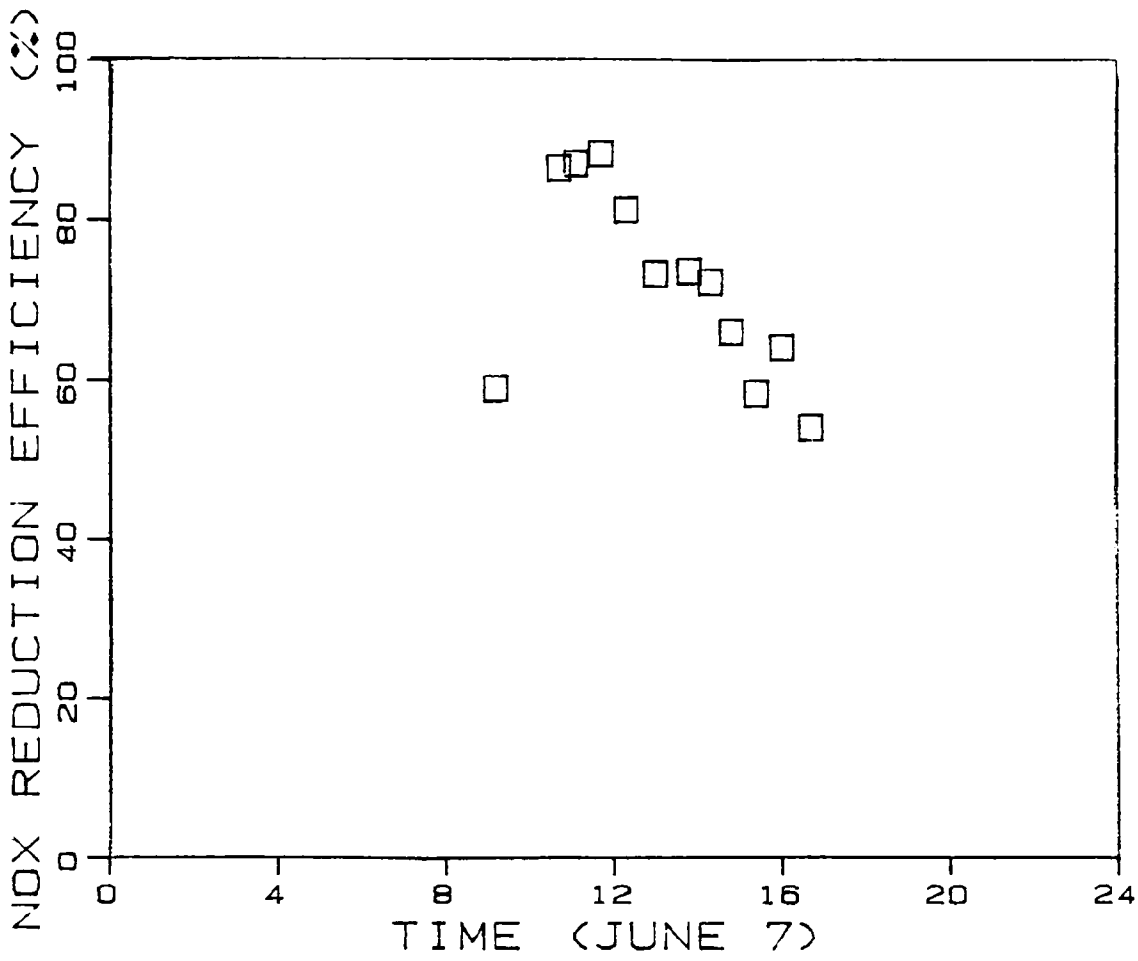


Figure 3-6. Catalyst NO_x reduction efficiency during comprehensive tests.

small perturbations in A/F. As indicated earlier, the exhaust O_2 of near zero percent indicates combustion at or below stoichiometric conditions. Small perturbations in A/F in this range would not be detected from monitoring O_2 levels which were already near zero. Neither the NO_x reduction efficiency nor the outlet NO_x concentrations measured during this test would meet the SCAQMD rule 1110 efficiency of 90 percent or an emission rate of 0.28 µg/J heat output.

Total unburned hydrocarbon ranged from 140 to 370 ppm as measured (215 ppm average) at the inlet. These emissions were reduced on passage through the catalyst to a range of 80 to 200 ppm (125 ppm average) at the outlet. This corresponds to an average hydrocarbon emission reduction of 42 percent. Figure 3-7 shows the variation in TUHC emissions over the test day. The increase in TUHC at about 8:00 a.m. corresponds to the adjustment in engine A/F toward rich burning condition.

Ammonia emissions were measured with an extractive sampling train, once at the inlet location and twice at the outlet location. The inlet concentration was 31 ppm at stack conditions (0.05g/Bhp-hr). Outlet NH_3 emissions ranged from 440 to 530 ppm (0.66 to 0.80g/Bhp-hr) with an average of 483 ppm (0.82g/Bhp-hr). This corresponds to a 15-fold increase in NH_3 emissions across the catalyst. Total cyanide emissions althougn lower than NH_3 emissions at both locations also showed a significant increase from about 0.02 ppm as measured at the inlet (0.051 mg/Bhp-hr) to 8.2 ppm (22 mg/Bhp-hr) at the outlet, a 400-fold increase.

Solid particulate emissions measured by the SASS train at both locations showed essentially no change from the inlet to outlet location.

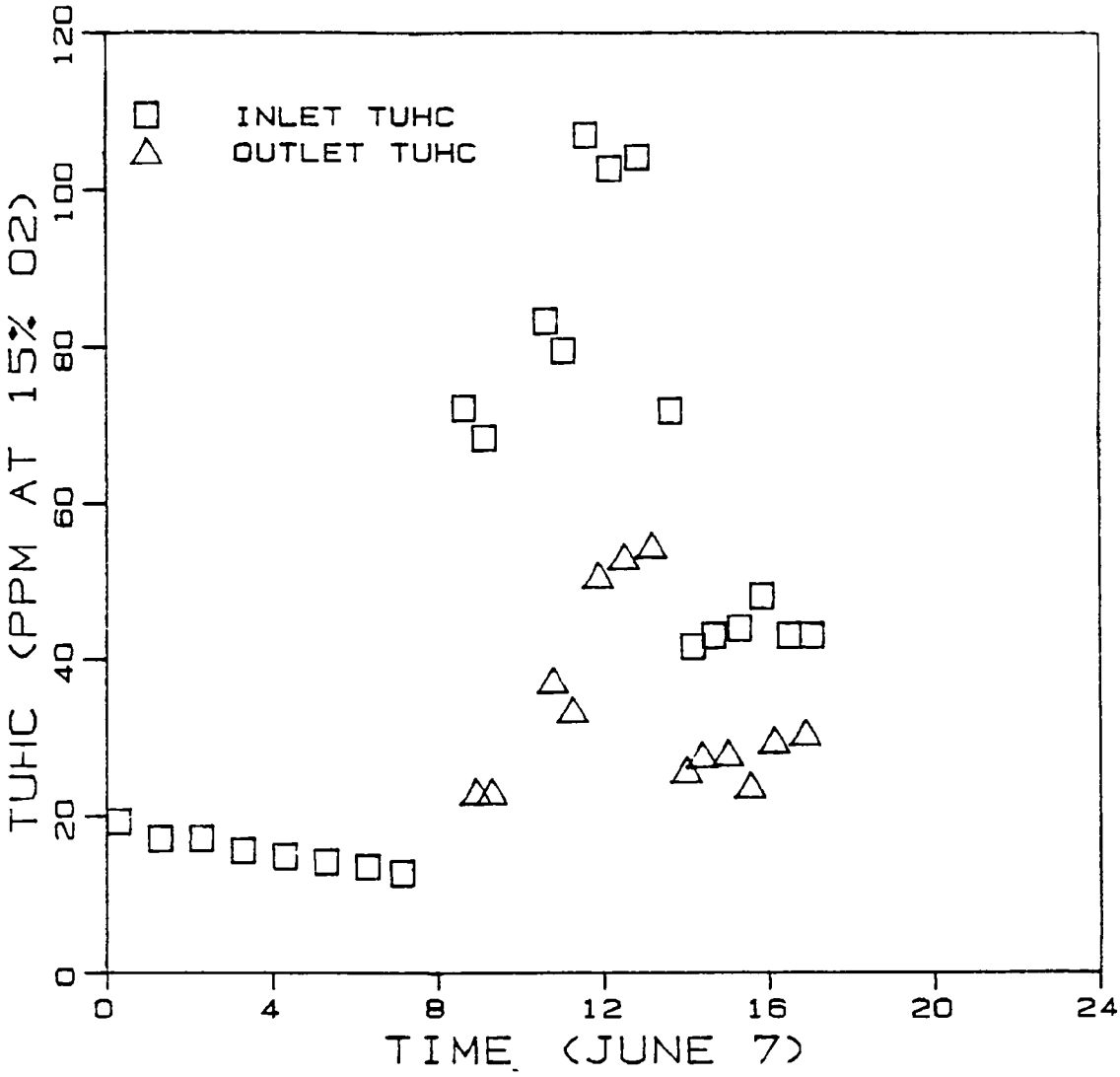


Figure 3-7. Exhaust gas hydrocarbon emissions during comprehensive tests.

N_2O emissions were measured by gas chromatography with electron capture detection of exhaust gas samples taken at the inlet and outlet of the catalyst. Table 3-2 summarizes these results. Information on O_2, NO, NO_x, and NO_2 (by difference) are also indicated. These emissions were recorded by continuous analyzers during the grab sampling of the gas for N_2O analyses. As indicated, no NO_x reduction was taking place during the time the N_2O samples were taken. The concentration of NO_2 varied from about 6 to 8 percent of the total NO_x. N_2O measured in duplicate tests at both inlet and outlet locations ranged from 64 to about 180 ppm at the inlet and 17 to 56 ppm at the outlet. All concentrations are corrected to 3 percent O_2. These N_2O concentrations represent about 2 to 7 percent of the total inlet NO_x and 0.6 to 2 percent of the total outlet NO_x. Previous N_2O data collected in the CMEA program has shown that N_2O from uncontrolled external combustion sources has ranged between 15 to 20 percent of the total NO_x (Reference 3-2). Although the concentration of N_2O varied for these two tests, the percent reduction by the catalyst remained fairly constant at 70 percent N_2O reduction by the catalyst. Conversely apparent NO_2 reduction by the catalyst was 15 to 20 percent.

3.3 TRACE ELEMENT EMISSIONS

Inorganic trace element concentrations were measured in the exhaust gas samples collected at the inlet and outlet of the catalytic reactor. Laboratory analyses included spark source mass spectroscopy (SSMS) for 70 elements and atomic absorption spectroscopy (AAS) for mercury, antimony, and arsenic. AAS was also used to confirm SSMS results on selected organics whose concentration exceeded the upper quantitation limit of the SSMS analyses. Once concentrations in the samples were determined by these analyses, trace element concentrations in both flue gas streams could be

TABLE 3-2. N_2O AND NO_x EMISSIONS[a]

Component	Upstream of catalyst	Downstream of catalyst
O_2, percent dry	2.8	2.0
NO_x, ppm dry	2,700	2,840
ppm dry at 3 percent O_2	2,670	2,690
NO, ppm dry	2,500	2,660
ppm dry at 3 percent O_2	2,470	2,520
NO_2[b], ppm dry	200	180
ppm dry at 3 percent O_2	198	171
N_2O, test 1, ppm dry	181	56
ppm dry at 3 percent O_2	179	53
N_2O -- test 2, ppm dry	65	18
ppm dry at 3 percent O_2	64	17

[a]Emissions are measured the day after the comprehensive tests are completed.
[b]By difference, NO_x to NO.

computed. These concentrations are summarized in Appendix B. Table 3-3 summarizes the emission rate of inorganic elements at the catalyst inlet and outlet locations. Only those elements detected at greater than blank levels in at least one sample are noted in the table. The emissions are reported in micrograms per second (µg/s). The mass balance is expressed by the ratio of emission rate to input rate from the lube oil. The consumption of lube oil was assumed to be 0.093 ml/s (1.37 gal/Bhp-hr) based on the engine manufacturer specifications.

Sulfur emissions were the highest of all elements ranging from 89 to 280 mg/s (240 to 740 mg/dscm). These emissions translate to a sulfur concentration in the natural gas fuel of about 0.01 to 0.04 percent, corresponding to a typical H_2S concentration. The sulfur concentration in the lube oil accounted for an insignificant fraction of these emissions. Sodium emissions were second highest after sulfur. Again, the lube oil did not contribute to these emissions. It is possible that sodium salts may have been present in the gas fuel along with sulfur. It is also likely that suspended salts (NaCl and other sodium compounds) may have been present in the intake air.

Other trace elements whose emission rate exceeded 10 µg/s (26 µg/dscm) at either inlet or outlet location were barium, calcium, chromium, copper, fluorine, iron, magnesium, manganese, nickel, potassium, silicon, silver, tungsten, and zinc. In nearly all cases, the catalyst outlet emissions were higher than the inlet emissions, often by as much as one order of magnitude. This was especially the case for metals such as copper, iron, magnesium, manganese, nickel, and zinc. In general, the lube oil trace element input rates were insufficient to account for either catalyst inlet or outlet

TABLE 3-3. INORGANIC TRACE ELEMENT EMISSION RATES

Element	Emissions (μg/s)		Mass balance (exhaust gas/lube oil)	
	Inlet	Outlet	Catalyst inlet/lube	Catalyst Outlet/lube
Aluminum	6.5	2.4	15	5.6
Antimony	0.0025	0.11	NA[a]	NA
Arsenic	0.064	0.25	NA	NA
Barium	19	23	0.23	0.28
Beryllium	<0.0000064	<0.041	NA	NA
Bismuth	0.0010	0.043	0.061	0.25
Bromine	0.015	0.88	NA	NA
Cadmium	0.00047	--	NA	NA
Calcium	180	58	6.2	2.0
Cerium	3.1	0.20	NA	NA
Cesium	0.00015	1.6	NA	NA
Chlorine	>1.5	>1.4	>1.7	1.7
Chromium	0.26	290	15	>17,000
Cobalt	5.7	2.3	340	>140
Copper	5.9	>420	70	5,000
Fluorine	>0.83	>120	>1.9	>290
Gallium	0.20	1.9	NA	NA
Germanium	0.00060	0.00086	NA	NA
Hafnium	0.0030	0.0043	NA	NA
Iodine	0.32	0.024	19	1.4
Iron	15	150	36	350
Lanthanum	31	<0.20	NA	NA
Lead	0.056	0.15	3.3	9.1
Lithium	0.29	0.19	11	7.3
Magnesium	10	57	30	170
Manganese	0.4	12	4.7	140
Mercury	0.070	0.037	13	6.9
Molybdenum	3.1	0.99	37	12
Neodymium	0.00049	0.0047	NA	NA
Nickel	0.31	250	1.8	1,500

[a]NA -- Not applicable -- lube oil concentration was zero.

TABLE 3-3. (concluded)

Element	Emissions (µg/s)		Mass balance (exhaust gas/lube oil)	
	Inlet	Outlet	Catalyst inlet/lube	Catalyst Outlet/lube
Niobium	1.5	0.17	NA	NA
Palladium	0.0010	0.0057	NA	NA
Phosphorus	2.0	11	0.038	0.21
Potassium	68	130	40	77
Praseodymium	0.00013	0.000094	NA	NA
Rhodium	0.012	0.0043	NA	NA
Rubidium	--	0.41	NA	NA
Ruthenium	<0.00015	<0.00043	NA	NA
Scandium	--	0.21	0	>25
Selenium	0.0090	0.55	0.053	3.2
Silicon	220	500	88	200
Silver	0.59	79	NA	NA
Sodium	59,000	60,000	23,000	23,000
Strontium	1.0	2.0	12	24
Sulfur	89,000	280,000	250	780
Tantalum	--	4.1	NA	NA
Tellurium	0.00016	0.12	NA	NA
Thorium	0.0045	0.0072	NA	NA
Tin	0.031	0.013	NA	NA
Titanium	--	4.1	0	>240
Tungsten	51	2.6	NA	NA
Uranium	0.0032	0.0016	NA	NA
Vanadium	0.030	0.40	1.8	24
Yttrium	0.0016	0.044	NA	NA
Zinc	9.5	170	0.43	7.7
Zirconium	--	1.1	0	26

[a]NA -- Not applicable -- lube oil concentration was zero

emission rates. This suggests that metallic element emissions originated from internal parts of the engine, the muffler and/or the catalytic reactor. However, some contamination of the samples by means of sampling trains may also have been possible. This is probable in the case of silver results because silver nitrate is used in one of the SASS impingers as an absorbing solution.

Overall, it is quite evident that the exhaust gas trace element content increased across the catalyst. Platinum and rhodium, the two noble metals of the catalyst, generally were present at low levels. In fact, platinum was not detected in the exhaust gas at either location. This result was in part due to blank concentration exceeding sample concentration. Rhodium emissions were in the range of 4.3 to 12 ng/s. However, there was no detected increase across the catalyst.

3.4 ORGANIC SPECIES EMISSIONS

Organic analyses were performed on the exhaust gas samples collected at the catalyst inlet and outlet locations. SASS samples were analyzed for semivolatile and nonvolatile organics according to the EPA Level 1 protocol (Reference 3-1) as outlined in Appendix A. Semivolatile organic compounds with boiling points in the nominal C_7 to C_{16} range of 100° to 300°C (210° to 570°F) were determined in the laboratory by total chromatographable organic (TCO) analysis of the combined organic module sorbent (XAD-2) and condensate extracts. Nonvolatile organic species having boiling points in the nominal C_{16+} range of >300°C (570°F) were measured by gravimetric (GRAV) analysis of SASS sample extracts.

Infrared spectrometry (IR) was performed on the GRAV residue of SASS train extracts to identify organic functional groups possibly present. Gas

chromatography/mass spectrometry (GC/MS) analyses of the XAD-2 extracts were also performed to identify specific polynuclear aromatic hydrocarbons (PAH) and other organic components (the semivolatile organic priority pollutants). The components sought in the GC/MS analysis and their respective detection limits are listed in Table 3-4. In addition, liquid chromatography (LC) separation of selected sample extracts, with TCO and GRAV, and the analyses of the fractions eluted from the column, were performed.

3.4.1 TCO, GRAV, GC/MS and IR Analyses of Total Sample Extracts

Table 3-5 summarizes organic emission results based on TCO, GRAV and GC/MS analyses. The concentration of organics at the catalyst inlet location is significantly higher than that at the outlet location. This is evidenced by both TCO and GRAV results as well as by the concentration of the priority pollutants noted. The high levels of organics at the catalyst inlet reflect the near stoichiometric A/F setting prevalent during these tests. The reduction in organic emissions across the catalyst parallels the decrease in CO and hydrocarbon emissions noted in the preceding section.

Total organics in the range of $>C_6$ (boiling points greater than 100°C) were about 15 mg/dscm at the catalyst inlet location. The corresponding concentration at the catalyst outlet was about 2.0 mg/dscm.

Priority pollutants at the catalyst inlet whose concentration exceeded 10 µg/dscm were acenapthene, acenaphthylene, fluorene, and phenanthrene. All these compounds showed concentrations below or near the method detection limit (0.4 µg/dscm) at the outlet location indicating oxidation by the catalyst.

Interestingly, the PAH compounds most abundant in the catalyst inlet exhaust were those containing three or more fused rings. Naphthalene, the

TABLE 3-4. COMPOUNDS SOUGHT IN THE GC/MS AND THEIR DETECTION LIMITS (ng/μl INJECTED)

Acid Compounds			
2,4,6-trichlorophenol	5	2-nitrophenol	5
p-chloro-m-cresol	5	4-nitrophenol	20
2-chlorophenol	5	2,4-dinitrophenol	20
2,4-dichlorophenol	5	4,6-dinitro-o-cresol	20
2,4-dimethylphenol	5	pentachlorophenol	5
		phenol	1

Base Neutral Compounds			
1,2,4-trichlorobenzene	1	benzo(c)phenanthrene	40
1,2-dichlorobenzene	1	bis(2-chloroethoxy)methane	1
1,2-diphenylhydrazine (as azobenzene)	1	bis(2-chloroethyl)ether	1
		bis(2-chloroisopropyl)ether	1
1,3-dichlorobenzene	1	bis(2-ethylhexyl)phthalate	1
1,4-dichlorobenzene	1	butyl benzyl phthalate	1
2,4-dinitrotoluene	1	chrysene	1
2,6-dinitrotoluene	1	di-n-butyl phthalate	1
2-chloronaphthalene	1	di-n-octyl phthalate	1
3,3'-dichlorobenzidine	5	dibenzo(a,h)anthracene	5
3-methyl cholanthrene	40	dibenzo(c,g)carbazoleloteher	40
4-bromophenyl phenyl ether	1	diethyl phthalate	1
4-chlorophenyl phenyl ether	1	dimethyl phthalate	1
7,12-dimethyl benz(a)anthracene	40	fluoranthene	1
N-nitrosodi-n-propylamine	5	fluorene	1
N-nitrosodimethylamine	NA	hexachlorobenzene	1
N-nitrosodiphenylamine	1	hexachlorobutadiene	1
acenaphthene	1	hexachlorocyclopentadiene	1
acenaththylene	1	hexachloroethane	1
anthracene	1	indeno(1,2,3-cd)pyrene	5
benzo(ghi)perylene	5	isophorone	1
benzidine	20	naphthalene	1
benzo(b)fluoranthene	1	nitrobenzene	1
benzo(k)fluoranthene	1	perylene	40
benzo(a)anthracene	1	phenanthrene	1
benzo(a)pyrene	1	pyrene	1

TABLE 3-5. TOTAL ORGANIC AND SEMIVOLATILE ORGANIC PRIORITY POLLUTANT EMISSIONS, µg/dscm

	Catalyst inlet	Catalyst outlet	
• Organic Category:			
C_7 to C_{16} (TCO)	8,000[a]	1,800	
C_{16}^+ (GRAV)	7,400	300	
Total, $\geq C_7$	15,400	2,100	
• Semivolatile Priority Pollutants		Run 1	Run 2	Average
Acenapthene	16.5	<0.4	<0.4	<0.4
Acenaphthylene	62.3	1.2	1.2	1.2
Benz(a)anthracene	5.1	<0.4	<0.4	<0.4
Benzofluoranthenes	1.9	<0.4	<0.4	<0.4
Bis(2-chloroethyl)ether	2.1	<0.4	<0.4	<0.4
Bis(2-ethylhexyl)phthalate[b]	54.9	1.0	1.3	1.2
Butyl benzyl phthalate[b]	0.7	<0.4	<0.4	<0.4
Chrysene	1.9	<0.4	<0.4	<0.4
Fluoranthene	0.5	<0.4	<0.4	<0.4
Fluorene	17.9	<0.4	<0.4	<0.4
Naphthalene	<0.4	26.8	30.2	28.5
Phenanthrene	40.3	1.2	1.5	1.4
Phenol	<0.4	1.6	2.1	1.8
Pyrene	2.2	<0.4	<0.4	<0.4

[a]This number is based on the average of results of duplicate analyses which showed 270 mg and 170 mg TCO, respectively.
[b]Level corresponds to that commonly found in laboratory blanks.

two-fused-ring PAH very commonly found in combustion system exhaust gas, was absent in the catalyst inlet gas, as was phenol. At the catalyst outlet, however, levels of the higher order PAH's were much lower, but naphthalene and phenol levels were increased. Evidently, the higher order PAH's were being oxidized, though not completely, with naphthalene and phenol as incomplete oxidation products.

Table 3-6 summarizes results of the IR spectroscopy analyses of the XAD-2 plus organic module condensate extracts. As noted in the table, the catalyst outlet sorbent module extract and the sorbent blank extract had weak IR spectra (no peaks). The spectrum for the catalyst inlet sorbent extract (which had higher total organic content) suggests the presence of aliphatic hydrocarbons and oxygenates such as alcohols, carboxylic acids, aldehydes, and ketones.

3.4.2 Column Chromatography Separation and IR Spectra of LC Fractions

The XAD-2 and organic module sample extracts for the catalyst inlet sample were separated by polar character via LC fractionation on silica gel. GRAV and TCO content were then obtained for each LC fraction. Results of these analyses are summarized in Table 3-7. The data show a relatively even distribution of organics in each fraction, although the concentration in fraction 2 was the lowest at 0.16 mg/dscm. The highest was in LC6 with 1.9 mg/dscm. Fraction 6 normally contains oxygenated organics such as alcohols, phenols, esters, ketones, and amines. Fraction 3, the second highest in concentration generally contains aromatic hydrocarbons. Fractions 1 and 4, both at about 1 mg/dscm, generally contain aliphatic hydrocarbons and less polar oxygenated hydrocarbons such as ethers, respectively.

TABLE 3-6. IR SPECTRA SUMMARY

Sample	Number (cm^{-1})	Intensity[a]	Assignment
XAD-2 + OMC extract, catalyst inlet	3571-2944	M	O-H stretch
	2907	S	CH alkyl
	1673	S	C=O stretch
	1538	M	Unassigned
	1439	M	CH_2 alkyl
	1266	M	C-O stretch
XAD-2 + OMC extract, catalyst outlet	No peaks		
XAD-2 blank extract	No peaks		

[a]S = Strong
M = Moderate

TABLE 3-7. TCO AND GRAV RESULTS FOR THE LC FRACTIONS OF THE CATALYST INLET XAD-2 EXTRACT[a]

Fraction	TCO mg/dscm	GRAV mg/dscm	Total mg/dscm	Total ng/J heat input	Total mg/Bhp-hr
LC1	<0.033	0.99	0.99	0.23	2.3
LC2	0.033	0.13	0.16	0.037	0.37
LC3	0.51	1.2	1.7	0.39	3.9
LC4	0.073	0.92	0.99	0.23	2.3
LC5	<0.018	0.55	0.55	0.13	1.3
LC6	<0.018	1.9	1.9	0.44	4.3
LC7	<0.018	0.51	0.51	0.12	1.2
Total	0.62	6.2	6.8	1.6	15.7

[a]Results are based on the total organics recovered in each fraction corrected to total organics in the original sample.

IR spectra were obtained on the GRAV residue of each LC fraction. Table 3-8 summarizes these IR spectra results. Absorbances consistent with the presence only of aliphatic hydrocarbons were in the LC1 spectrum. The spectra of LC3 and 4 suggest the possible presence of aldehydes. Other oxygenated hydrocarbons such as carboxylic acids, alcohols, and ketones are suggested by the spectra of LC6 and 7. Comparing Table 3-5 to Table 3-7 shows that all absorbances in the spectrum of the total sample extract are accounted for in the fraction spectra. In fact the LC fraction spectra are more defined.

3.5 EXTENDED CONTINUOUS EMISSIONS MONITORING

Continuous monitoring for exhaust gas O_2, CO_2, CO, NO_x and TUHC was performed for a 15-day period from June 6 to June 21, 1983. With the exception of June 7, the engine was operated under normal conditions with no restrictions imposed on load or A/F; recall that the engine had no automatic A/F controller. Figures 3-8 through 3-12 illustrate emission data over this period. The emission data in these figures represent hourly averages of data taken on 5- to 15-minute intervals.

Although this method of presenting the test data represents a more manageable task, it also tends to "smooth out" some of the peaks in emissions that occurred during abrupt changes in engine operation. Nevertheless, the data do highlight some important characteristics of NSCR performance during unconstrained engine operation.

Exhaust O_2 data, summarized in Figure 3-8, show the near stoichiometric A/F of the comprehensive tests performed during June 7. Following these tests, the A/F was increased resulting in exhaust O_2 of about 2 percent at the catalyst inlet for most of the 15-day test period. Occasionally, the O_2

TABLE 3-8. SUMMARY OF IR SPECTRA FOR LC FRACTIONS OF THE CATALYST INLET XAD-2 EXTRACT[a]

Fraction	Frequency (cm^{-1})	Intensity[b]	Possible assignment	Possible compound categories present[c]
LC1	2945	S	C-H Alkyl	Aliphatic Hydrocarbons
LC2	No Peaks	--	--	--
LC3	2940	S	C-H Alkyl	Hydrocarbons, aldehydes
	1715	S	C=O	
LC4	2930	M	C-H Alkyl	Hydrocarbons, aldehydes
	1700	S	C=O	
	1555	M	Not assigned	
LC5	2930	S	C-H Alkyl	Hydrocarbons
LC6	3360	M	O-H Stretch	
	3065	W	C-H Alkyl	
	2935	S	C-H Alkyl	Hydrocarbons (Alkyl and
	1710	S	C=O Stretch	alkenyl), carboxylic acids,
	1605	W	C-C Alkenyl	alcohols, ketones
	1555	M	Not assigned	
	1540	W	CH_2	
	1380	W	CH_3	
	1278	W	C-O	
	740	W	C-H Alkyl	
LC7	3540	S	O-H Stretch	
	2940	W	C-H Alkyl	Hydrocarbons, carboxylic
	1710	W	C=O Stretch	acids, alcohols

[a]Spectra for the XAD-2 blank LC fractions had no peak.
[b]S = Strong, M Moderate, W Weak
[c]Possible compound categories present consistent with spectra and LC fraction.

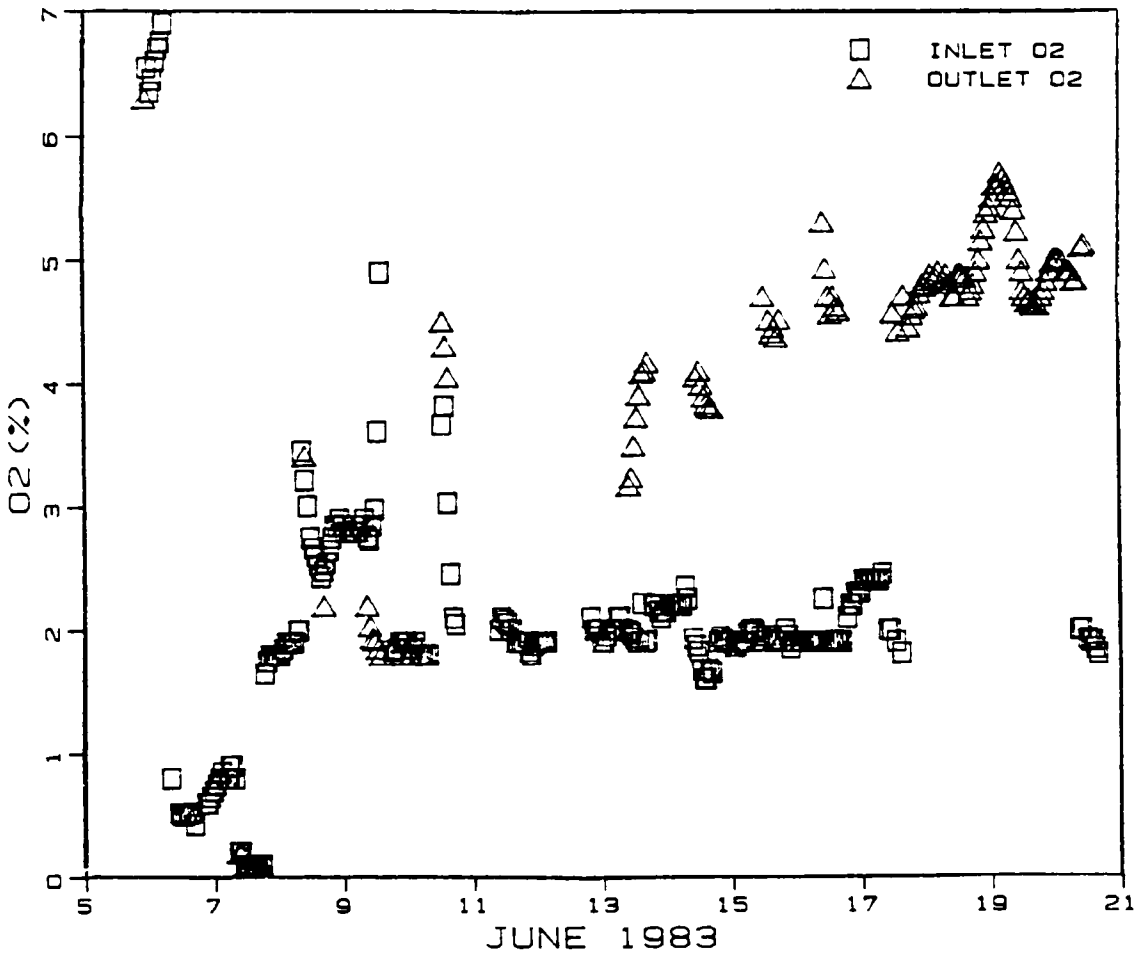


Figure 3-8. Exhaust O_2 for the 15-day continuous monitoring period.

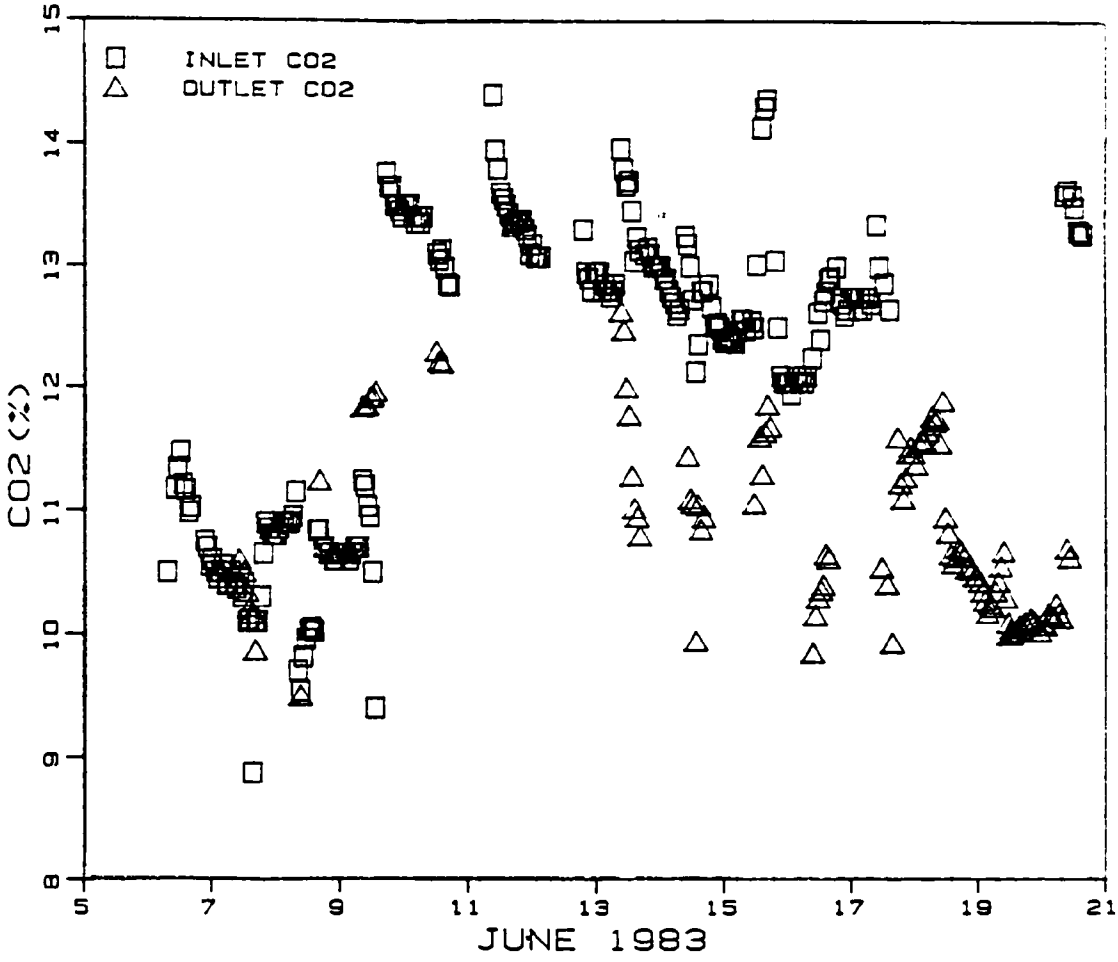


Figure 3-9. Exhaust CO_2 for the 15-day continuous monitoring period.

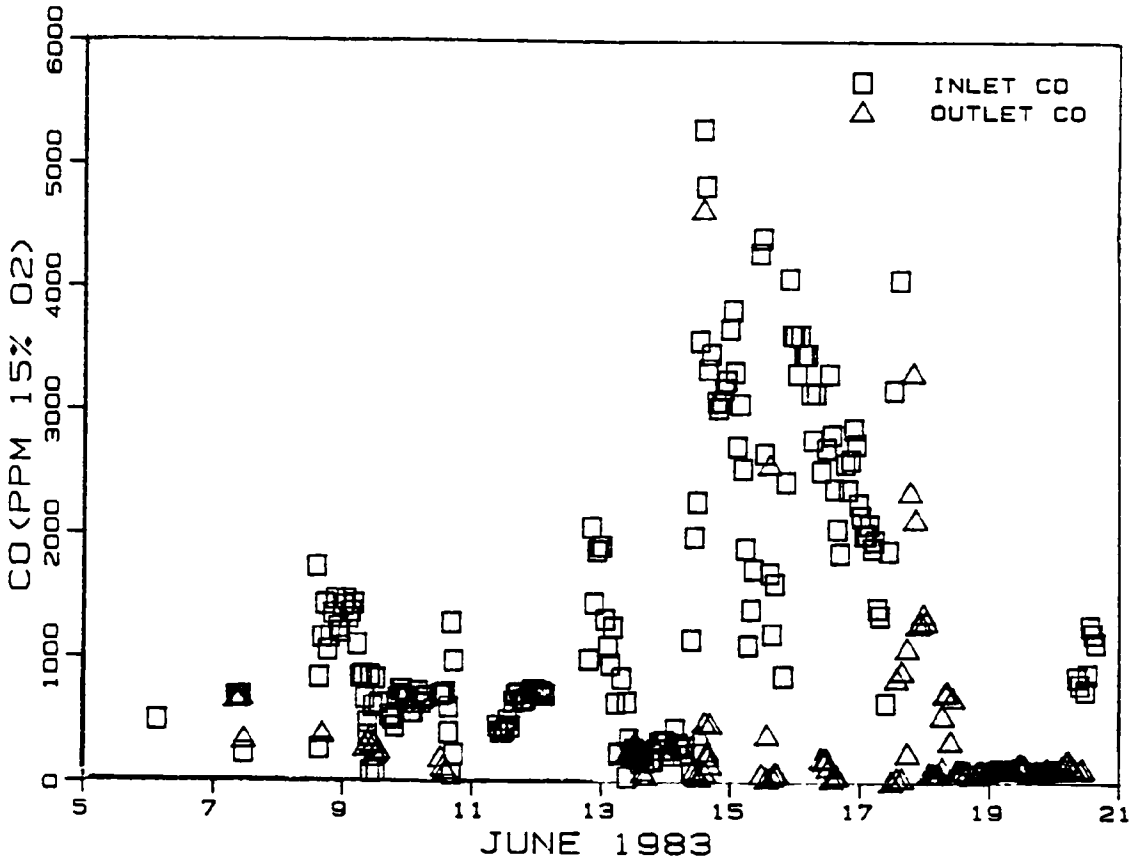


Figure 3-10. CO emissions for the 15-day continuous monitoring period.

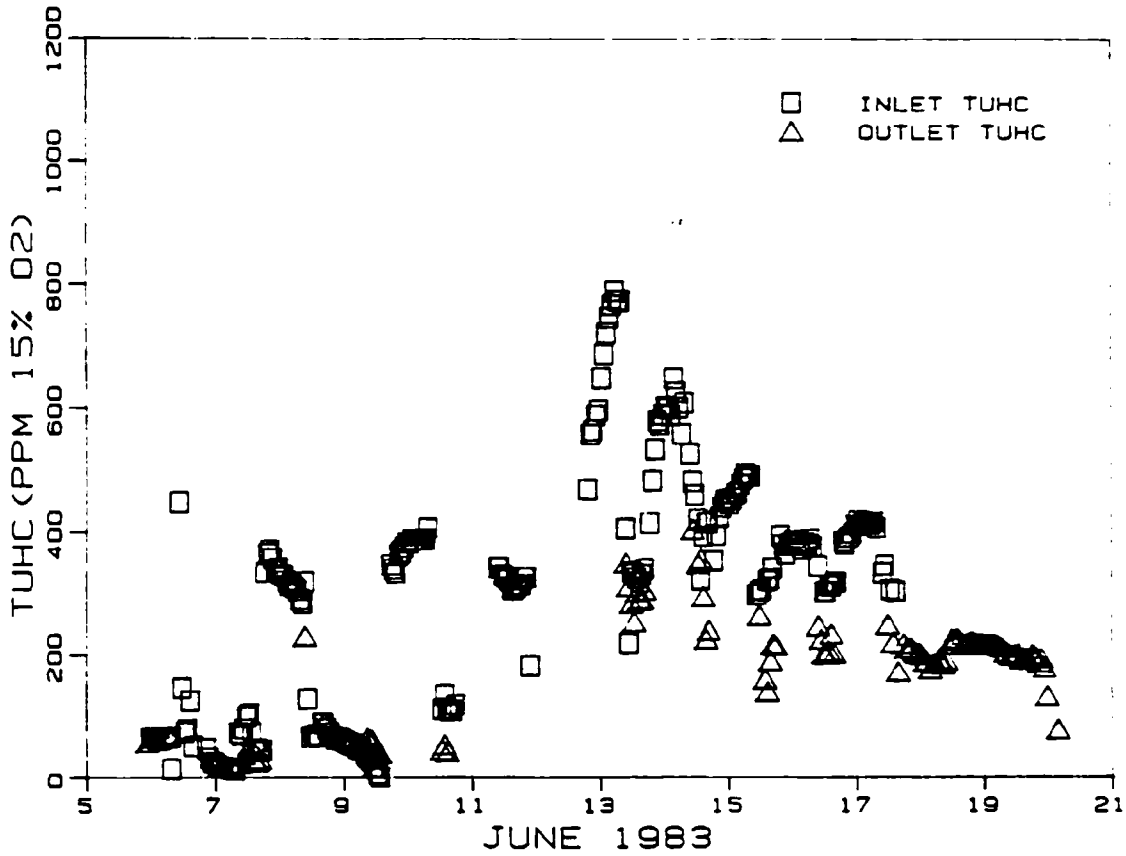


Figure 3-11. TUHC emissions for the 15-day continuous monitoring period.

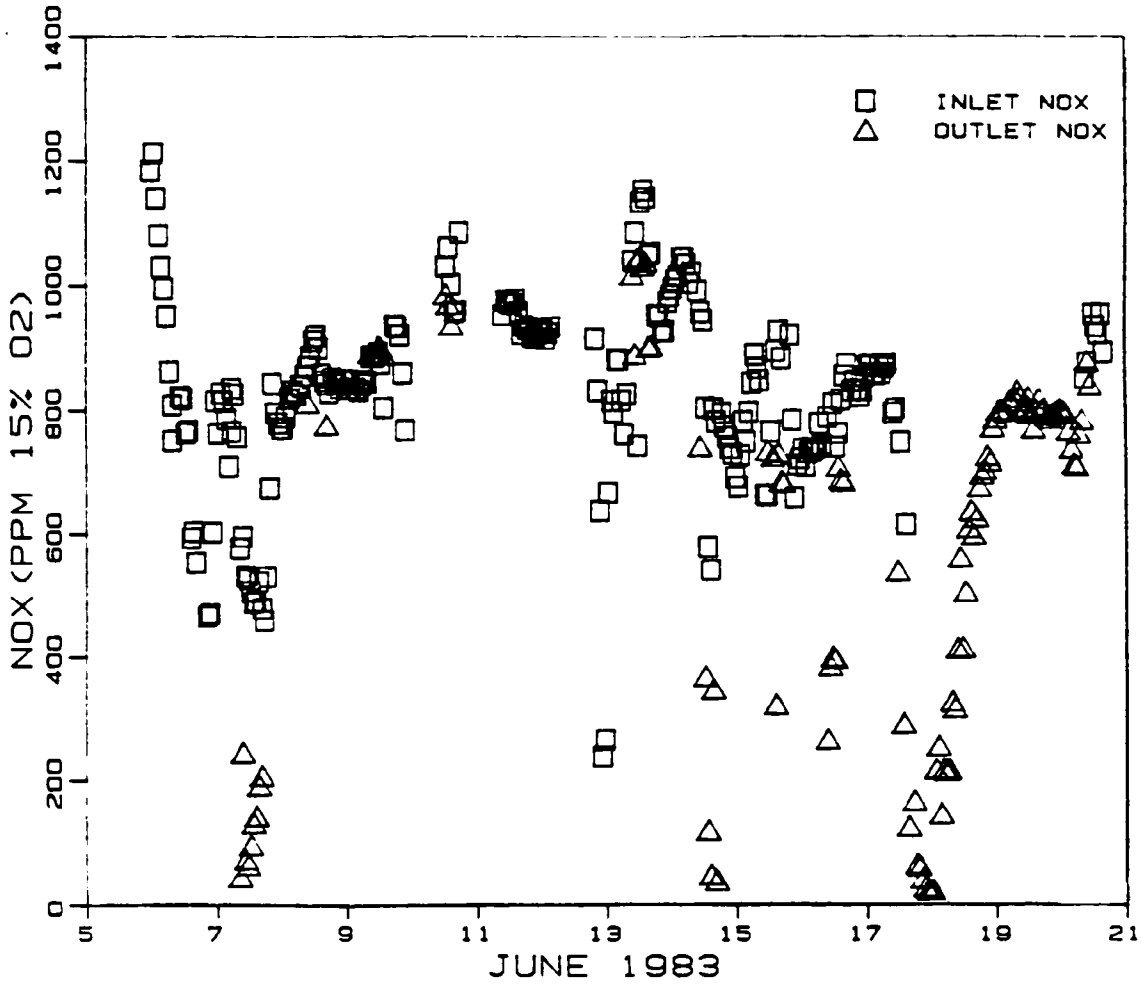


Figure 3-12. NO_x emissions for the 15-day continuous monitoring period.

the catalyst inlet for most of the 15-day test period. Occasionally, the O_2 climbed as high as 3 and 4 percent but remained at this level for less than a day. The difference between outlet O_2 and inlet O_2 shown in the data for the period following June 13 is considered suspect since it is unlikely that the O_2 would increase across the catalytic reactor.

Figure 3-9 illustrates the CO_2 emission trends. During the comprehensive tests and periods immediately preceding and following these tests exhaust CO_2 ranged from about 10 to 11 percent on a dry basis. Since stoichiometric CO_2 for the natural gas burned during these tests is 12 percent the CO emissions were probably in the range of 1 to 2 percent. The increase in inlet CO_2 to 13 and 14 percent after June 10 is considered suspect. In contrast, outlet CO_2 concentration was usually in the range of 10 to 12 percent. This may be more indicative of actual combustion conditions. This range of 10 to 12 percent CO_2 corresponds to 3.5 and zero percent O_2, respectively, with complete combustion.

Figure 3-10 illustrates the CO emission trends. Generally CO emissions were 700 ppm, corrected to 15 percent O_2, or lower for most of the test period. Although simultaneous inlet/outlet data were often not available. CO at the catalyst outlet was always lower than at the catalyst inlet.

Spikes of CO up to 5,000 ppm (corrected to 15 percent O_2) at either the inlet or outlet location can be seen. These are indicative of richer burning conditions. These spikes were often accompanied by improved NO_x reduction performance by the catalyst. A trend toward lower CO emissions in the latter part of the 15-day test period is also apparent. This is in agreement with the increased O_2 levels measured.

TUHC emissions, illustrated in Figure 3-11, show a substantial increase following the comprehensive tests on June 7. The highest emissions, up to 800 ppm at 15 percent O_2) were registered just prior to June 13. CO emissions were also highest during this period. Following this peak, TUHC emission decreased, in parallel with CO emissions as noted above. Outlet TUHC generally was 100 ppm lower than inlet TUHC.

Figure 3-12 illustrates catalytic inlet and outlet NO_x emissions over the monitoring period. The effective catalyst NO_x reduction during the comprehensive tests of June 7 is clearly evident. Also evident is the reduced catalyst performance throughout most of the remaining test period. One clear exception is the test data taken late in the day of June 17 and into the following morning. During this period outlet NO_x was reduced to below 50 ppm (15 percent O_2). This increased catalyst NO_x reduction performance occurred during richer engine operation, as suggested by the high measured CO emissions.

REFERENCES FOR SECTION 3

3-1. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition," EPA-600/7-78-201, NTIS PB293795, October 1978.

3-2. Waterland, L. R., et al., "Environmental Assessment of Industrial Boilers Firing Coal-Liquid Mixtures and Wood," in Proceedings of the 1982 Joint Symposium of Stationary Combustion NO_x Control, Volume 2. EPRI CS-3182, July 1983.

SECTION 4

ENVIRONMENTAL ASSESSMENT

This section discusses the potential environmental significance of the engine tested, including results of the bioassay testing of samples collected during the tests. As a means of ranking species discharged for possible further consideration, exhaust gas discharge stream species concentrations are compared to occupational exposure guidelines. Bioassay analyses were conducted as a more direct measure of the potential health and ecological effects of the emission stream. Both these analyses are aimed at identifying problem areas and providing the basis for ranking of pollutant species and discharge streams for further consideration.

4.1 EMISSIONS ASSESSMENT

To obtain a measure of the potential significance of the pollutant levels in the exhaust gas analyzed in this test program, exhaust concentrations were compared to an available set of health-effects-related indices. The indices used for comparison were occupational exposure guidelines. Two sources of such guidelines were used: the time-weighted-average Threshold Limit Values (TLV's) defined by the American Conference of Governmental Industrial Hygienists (ACGIH) (Reference 4-1) and 8-hr time-weighted-average exposure limits established by the Occupational Safety and Health Administration (OSHA) (Reference 4-2).

The comparisons of discharge stream species concentrations to these indices should be used only for ranking species emission levels for further testing and analyses. Table 4-1 lists those pollutant species emitted in the catalyst inlet and outlet exhaust gas streams at levels greater than 10 percent of their occupational exposure guideline.

4.2 BIOASSAY RESULTS

Health effects bioassay tests were performed on the organic sorbent (XAD-2) extract collected by the SASS train at the catalyst inlet and outlet locations. A detailed description of the biological analyses performed is presented in Volume II (Data Supplement) of this report. The bioassay tests performed (Reference 4-3) were:

- Ames assay, based on the property of Salmonella typhimurium mutants to revert due to exposure to various classes of mutagens
- Cytotoxicity assay (CHO) with mammalian cells in culture to measure cellular metabolic impairment and death resulting from exposure to soluble toxicants

The results of these assays are summarized in Table 4-2. The data suggest that the XAD-2 extracts from both locations were of high mutagenicity and high to moderate toxicity. These are typical bioassay responses for combustion source XAD-2 extract.

TABLE 4-1. EXHAUST GAS COMPONENTS EMITTED AT LEVELS EXCEEDING 10 PERCENT OF THEIR OCCUPATIONAL EXPOSURE GUIDELINE

Pollutant	Emission concentration, mg/dscm		Occupational exposure guideline (mg/m^3)
	Catalyst inlet	Catalyst outlet	
Carbon monoxide, CO	5,350	4,840	55
Nitrogen oxide, NO_x	3,410	1,180	6.0
Ammonia, NH_3	23	320	18
Nitrous oxides, N_2O[b]	270	170	--[c]
Cyanide, HCN	0.022	10	5.0
Sodium, Na	150	160	2.0[d]
Barium, Ba	0.049	0.064	0.5
Calcium, Ca	0.45	0.16	2.0
Chromium, Cr	0.0007	>0.78	0.05
Copper, Cu	0.015	>1.2	0.10[e]
Iron, Fe	0.039	0.41	1.0
Nickel, Ni	0.0008	0.69	0.10
Phosphorus, P	0.005	0.030	0.10
Potassium, K	0.17	0.36	2.0[d]
Silicon, Si	0.57	1.4	10
Silver, Ag	0.0015	0.22	0.010
Zinc, Zn	0.024	0.46	1.0

[a]TLV unless noted (Reference 4-1).
[b]N_2O emissions measured low catalyst NO_x reduction efficiency following completion of comprehensive tests.
[c]-- denotes no occupational exposure guideline applicable.
[d]Ceiling value.
[e]8-hr time-weighted-average OSHA exposure limit (Reference 4-2).

TABLE 4-2. BIOASSAY RESULTS

Sample	Assay	
	Ames[a]	CHO[b]
Catalyst inlet XAD-2 extract	H	H/M
Catalyst outlet XAD-2 extract	H	M

[a]Mutagenicity assay.
[b]Toxicity assay.
H = high; M = moderate; H/M = high to moderate.

REFERENCES FOR SECTION 4

4-1. "Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with Intended Changes for 1983-84," American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1983.

4-2. OSHA Safety and Health Standards, 29 CFR 1910, Subpart Z.

4-3. Brusick, D. J., and R. R. Young, "IERL-RTP Procedures Manual: Level 1 Environmental Assessment, Biological Tests," EPA 600/8-81-024, NTIS PB81-228766, October 1981.

SECTION 5

TEST QUALITY ASSURANCE AND QUALITY CONTROL

Quality assurance (QA) activities implemented for this test included:

- Certification of the NO_x continuous monitoring analyzer using standard EPA Method 7 protocol for accuracy determination of NO_x readings.
- Duplicate SSMS, TCO and GC/MS analyses of SASS samples for determination of analytical precision.

The following paragraphs discuss the results of these QA activities.

5.1 NO_x CERTIFICATION RESULTS

EPA Method 7 test protocols were used twice during the 15-day continuous monitoring period to certify the accuracy of the NO_x analyzers. Table 5-1 shows that, for the first certification test conducted on June 8, the NO_x monitor readings were consistently 550 to 650 ppm higher than corresponding Method 7 results. The associated relative accuracy of the instrument as determined by this test was 29 percent. This compares to an allowable relative accuracy of 20 percent in performance specification 2 (40 CFR, Part 60, Appendix B). However, the Method 7 results for this first test may be suspect. Insufficient O_2 may have been present in the engine exhaust tested to completely oxidize all the NO to NO_2 as required by the method. Method 7 procedures caution that if the gas being sampled contains insufficient O_2 for the conversion of NO to NO_2, then O_2 should be introduced

TABLE 5-1. METHOD 7 CERTIFICATION RESULTS: JUNE 8

Test No.	NO_x Reference Method Samples (ppm)				Average Analyzer Reading Catalyst Inlet (ppm)	Difference (ppm)
	Sample 1	Sample 2	Sample 3	Sample Average		
1	1,760	1,960	2,580	2,100	2,650	550
2	2,770	1,880	2,170	2,270	2,660	390
3	2,040	2,110	2,130	2,090	2,750	660
4	2,110	2,450	2,400	2,320	2,790	470
5	2,500	2,330	2,020	2,280	2,820	540
6	2,470	1,940	2,380	2,260	2,800	540
7	2,070	2,100	2,090	2,090	2,770	680
8	2,250	1,870	2,190	2,100	2,750	650
9	2,260	2,210	2,000	2,160	2,800	640
Mean reference method test value						2,190
Mean of differences						570

95 percent confidence interval = 70 ppm

$$\text{Relative accuracy} = \frac{\text{Mean of differences} + \text{95 percent confidence interval}}{\text{Mean reference method value}} \times 100$$

$$= 29 \text{ percent}^a$$

[a]Poor relative accuracy (≤20 percent allowed) due to insufficient O_2 in gas sample to efficiently oxidize NO to NO_2

into the sampling flasks. However, the method procedures offer no guide as to what constitutes insufficient O_2. For this first certification test, exhaust O_2 was about 2.7 percent; NO_x analyzer readings were 2,700 to 2,800 ppm. During the test it was decided that sufficient O_2 was available. However the discrepancy between the Method 7 results and the analyzer readings suggest this may not have been the case. For the second certification test performed on June 20, O_2 (air) was added to the Method 7 sampling flasks. Exhaust O_2 for this test was about 1.9 percent; NO_x analyzer readings were 2,900 to 3,000 ppm. Table 5-2 shows that, for this second certification test, Method 7 results and analyzer readings were in much closer agreement. The calculated relative accuracy of the analyzer during this test was 9.2 percent, well within the performance specification.

5.2 DUPLICATE ANALYSES

Blind duplicates were submitted for analysis of trace elements by SSMS. Precision of the analysis was then determined based on the relative standard deviation of the replicate samples. Table 5-3 summarizes the results of these SSMS duplicate analyses.

The average relative standard deviation for all the trace elements was 53 percent within the acceptable range of -50 to 100 percent or a factor of 2 in analytical precision.

Results of duplicate analyses for organic samples are summarized in Table 5-4. The average relative standard deviation for these duplicate analyses was 21 percent, well within the project precision goal for these measurements.

TABLE 5-2. METHOD 7 CERTIFICATION RESULTS: JUNE 20

Test No.	NO_x Reference Method Samples (ppm)				Average Analyzer Reading Catalyst Inlet (ppm)	Difference (ppm)
	Sample 1	Sample 2	Sample 3	Sample Average		
1	2,770	2,670	2,940	2,790	2,970	180
2	2,680	2,610	2,860	2,720	3,020	300
3	2,830	2,780	2,860	2,820	2,900	80
4	2,870	2,820	2,800	2,830	3,070	240
5	2,590	2,740	3,000	2,780	2,960	180
6	2,460	2,660	2,830	2,650	2,950	300
7	2,750	2,890	2,990	2,880	2,870	(10)
8	2,990	2,880	3,000	2,960	2,840	(120)
9	2,710	2,760	2,770	2,750	2,880	130
Mean reference method test value						2,800
Mean of differences						140

95 percent confidence interval = 110 ppm

$$\text{Relative accuracy} = \frac{\text{Mean of differences} + \text{95 percent confidence interval}}{\text{Mean reference method value}} \times 100$$

$$= 8.9 \text{ percent}^a$$

[a]Air was cycled to the flasks to ensure sufficient oxidant for NO to NO_2 conversion resulting in relative accuracy within Method 7 performance specification

TABLE 5-3. DUPLICATE SSMS ANALYSES OF CATALYST OUTLET SASS IMPINGER 1 SAMPLE, mg/l

Element	Sample 819379	Sample 819394	Relative standard deviation (percent)
Silver	1.75	2.12	13.5
Chlorine	<3	<3	0
Fluorine	4.18	4.44	1.6
Sodium	1,440	1,480	1.9
Sulfur	9,000	4,800	43
Selenium	<0.002	0.003	28
Mercury	0.0003	0.0004	20
Lead	0.02	0.02	0
Tungsten	0.01	0.007	25
Lanthanum	0.005	0.006	13
Barium	0.09	0.06	28
Tellerium	0.003	<0.001	71
Molybdenum	0.02	0.1	94
Niobium	0.002	0.007	79
Zirconium	0.003	0.009	71
Yttrium	0.002	0.001	47
Strontium	0.009	0.05	98
Bromine	0.04	0.05	16
Arsenic	0.001	0.001	0
Gallium	0.08	0.03	64
Zinc	10	5	47
Copper	>10	>10	0
Nickel	0.3	0.2	28
Cobalt	0.01	0.01	0
Iron	0.5	0.3	35
Manganese	0.1	0.07	25
Chromium	0.2	0.07	68
Vanadium	0.004	0.005	9
Titanium	0.4	0.2	47
Scandium	0.01	0.002	94
Calcium	2	2	0
Potassium	6	0.8	108
Phosphorus	0.3	0.2	28
Silicon	1	2	47
Aluminum	0.2	0.07	68
Magnesium	2	0.1	128
Boron	0.002	0.001	47
Beryllium	0.001	0.001	0
Lithium	0.007	0.002	79
Average standard deviation			53

TABLE 5-4. RESULTS OF DUPLICATE ORGANIC ANALYSES OF SASS SAMPLES

Analyses	Sample No. 369 Total mg	Sample No. 370 Total µg	Relative standard deviation (percent)
TCO	270,170		38
GC/MS:			
Phenol		42, 55	19
Naphthalene		710, 800	8.4
Acenaphthylene		31, 32	2.2
Phenanthrene		31, 41	20
Bis(2-ethyl hexyl)-phthalate		26, 35	21
Average standard deviation			21

APPENDIX A

SAMPLING AND ANALYSIS METHODS

Emissions test equipment was provided by Acurex Corporation. Onsite equipment included a continuous monitoring system for emissions measurements of gaseous criteria pollutants; the SASS train for particulate mass, selected inorganics, and semivolatile and nonvolatile organics; two separate sampling trains for NH_3 and HCN measurement; gas grab sampling equipment for determining N_2O emissions by laboratory gas chromatography, and for validation of NO_x measurements with EPA Method 7. The following sections summarize the sampling and analysis equipment and methods used in the field and laboratory.

A.1 CONTINUOUS MONITORING SYSTEM

Acurex provided a continuous monitoring system modified to allow online simultaneous NO_x sampling capability at inlet and outlet of the catalytic reactor. Figure A-1 illustrates a simplified schematic of the gas conditioning and monitoring system. The monitoring capability included O_2, CO_2, CO (high and low concentrations), NO, NO_x, NO_x + NH_3, and TUHC. A refrigeration gas conditioning system was used primarily at the inlet location and provided NO emissions. The heated sample line system was used primarily at the outlet location and provided data on NO and total NO_x. Table A-1 lists the instrumentation constituting the continuous monitoring and flue gas extractive sampling system. A datalogger was used in addition to strip charts to record data continuously.

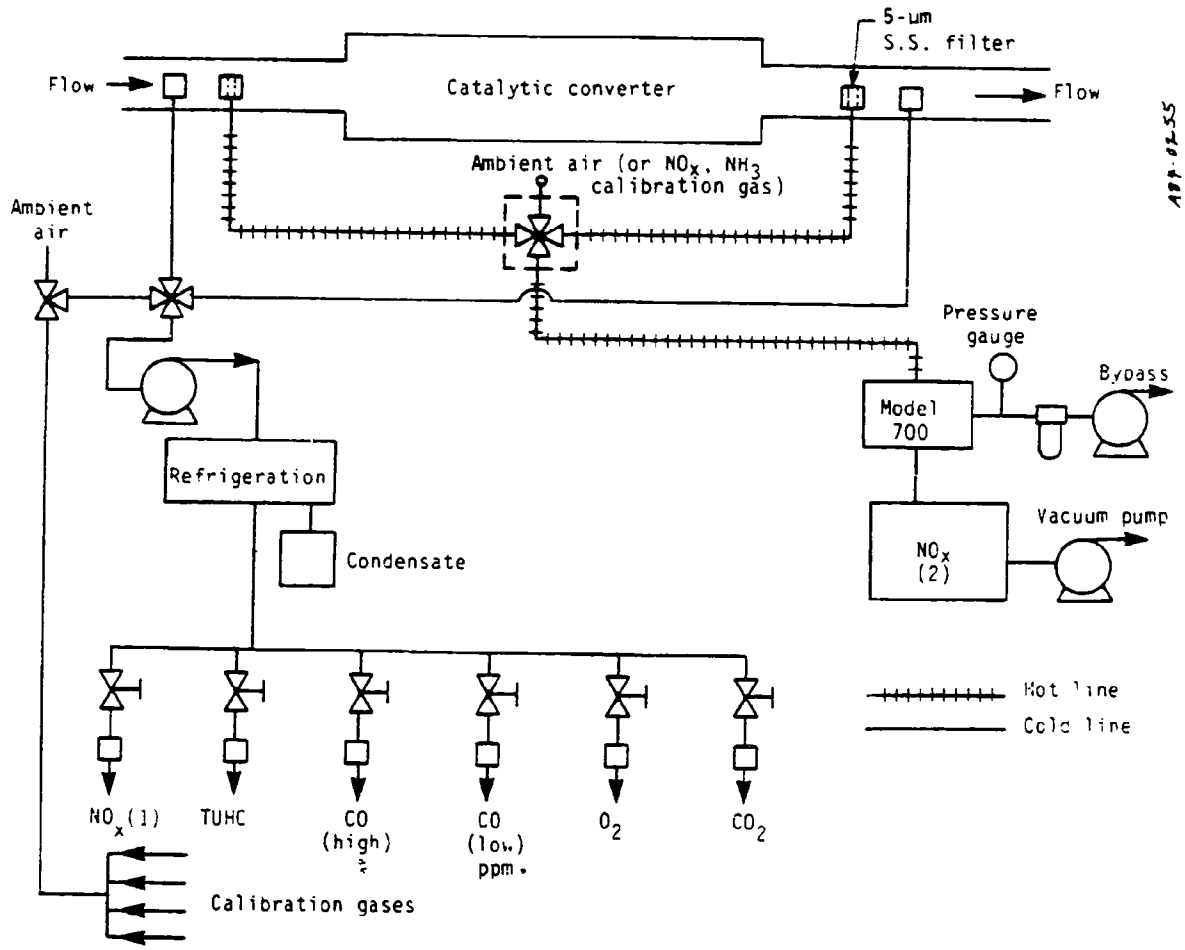


Figure A-1. Schematic of gas conditioning and continuous monitoring system.

Table A-1. CONTINUOUS MONITORING EQUIPMENT IN THE MOBILE LABORATORY

Instrument	Principle of operation	Manufacturer	Instrument model	Range
NO[a] NO_x	Chemiluminescence	Thermo Electron	10 AR	0-100 ppm 0-500 ppm 0-1,000 ppm 0-5,000 ppm
TUHC	Flame ionization detection	Beckman	400	0-10 ppm 0-100 ppm 0- 1,000 ppm
CO	Nondispersive infrared (NDIR)	ANARAD	500R	0-1,000 ppm
CO_2	Nondispersive infrared (NDIR)	ANARAD	AR500	0-20 percent
O_2	Fuel cell	Teledyne		0-5 precent 0-25 percent
Sample gas conditioner	Refrigerant dry-condenser	Hankinson	E-4G-SS	10 scfm
Data Logger	Electronic	Acurex	Audodata 9	99 channels
Strip chart recorder	Dual pen analog	Linear	400	1-10 mV 1-100 mV 0-1 V 0-10 V

[a]Two analyzers used for simultaneous inlet and outlet sampling

A.2 TRACE ELEMENTS AND ORGANIC EMISSIONS

Emissions of inorganic trace elements and organic compounds were sampled using the source assessment sampling system (SASS). Designed for Level 1 environmental assessment (Reference A-1), the SASS collects large quantities of gas and solid samples required for subsequent analyses of inorganic and organic emissions.

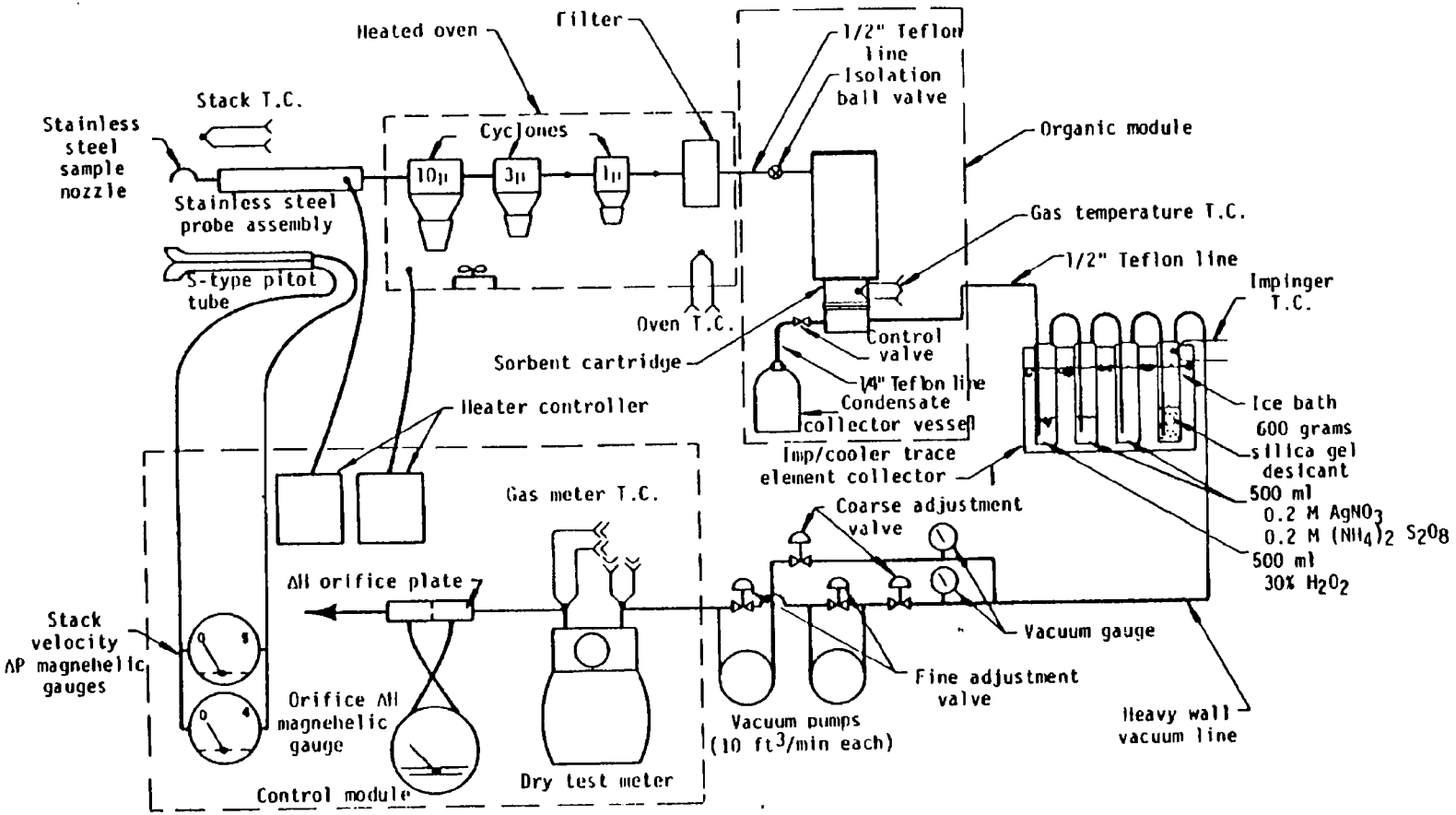
The SASS, illustrated in Figure A-2, is generally similar to the system utilized for total particulate mass emission tests (a high volume Method 5 train) with the exception of:

- The addition of a gas cooler and organic sampling module
- The addition of necessary vacuum pumps to allow a sampling rate of 2 l/s (4 cfm)

Particulate cyclones shown in Figure A-2 were not used for these tests because of low particulate loading in the flue gas.

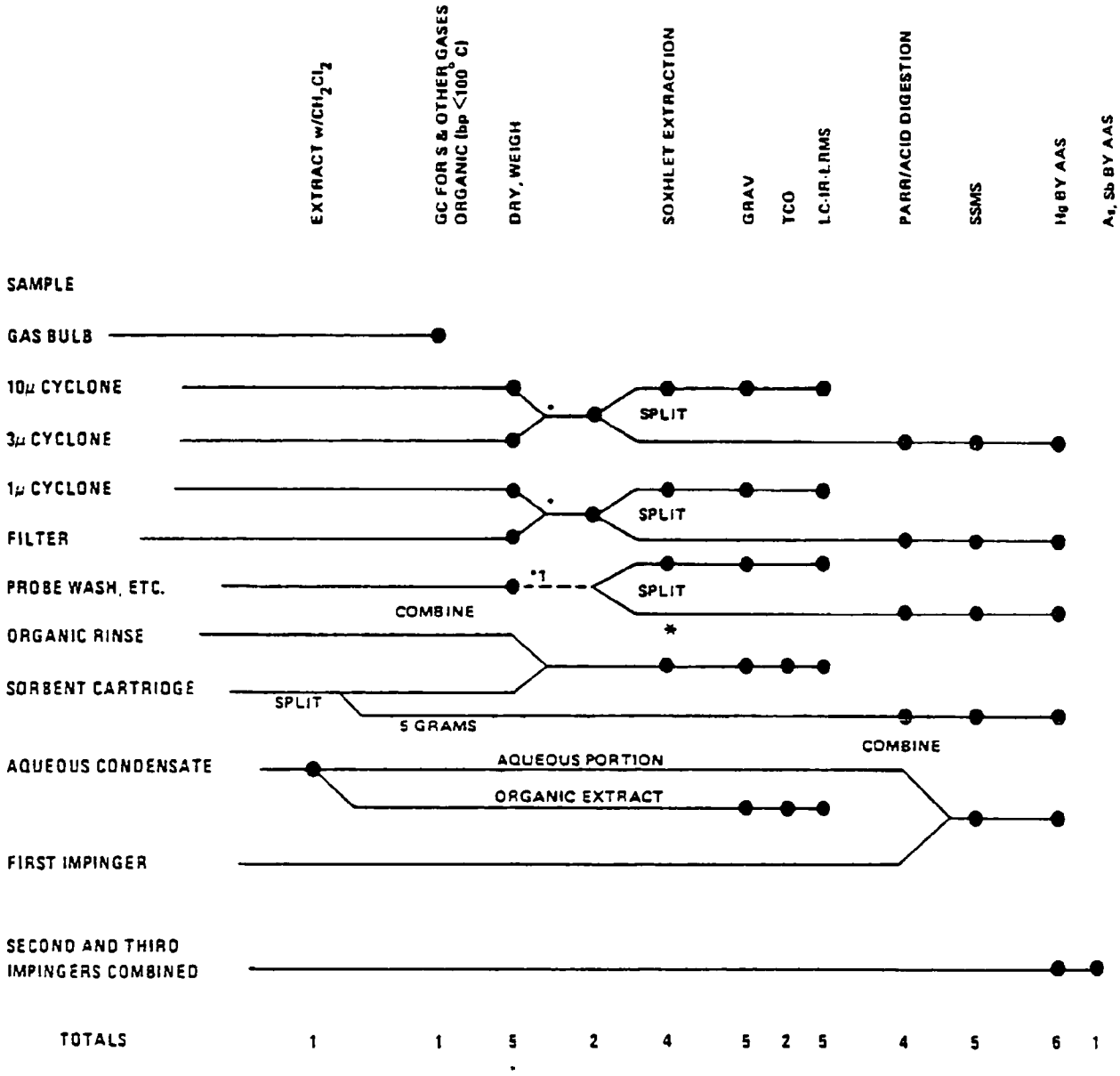
Schematics outlining the standard sampling and analytical procedures using the SASS equipment are presented in Figures A-3 and A-4. The following paragraphs briefly describe analytical procedures used in measuring trace elements and organic emissions.

Inorganic analyses of samples from the SASS train were performed by spark source mass spectroscopy (SSMS) for most of the trace elements. Atomic absorption spectrometry (AAS) was used for analyses of volatile mercury (Hg), antimony (Sb), and arsenic (As). Confirmatory analyses for selected metals were performed using flame atomic absorption spectrophotometry. Phosphorus was determined colorimetrically and sulfur was determined turbidimetrically in samples needing confirmatory analyses.



Note: T.C. = Thermocouple

Figure A-2. Source assessment sampling train schematic.



* If required, sample should be set aside for biological analysis at this point.

[1] This step is required to define the total mass of particulate catch. If the sample exceeds 10% of the total cyclone and filter sample weight proceed to analysis. If the sample is less than 10% of the catch, hold in reserve.

Figure A-3. Flue gas analysis protocol for SASS samples.

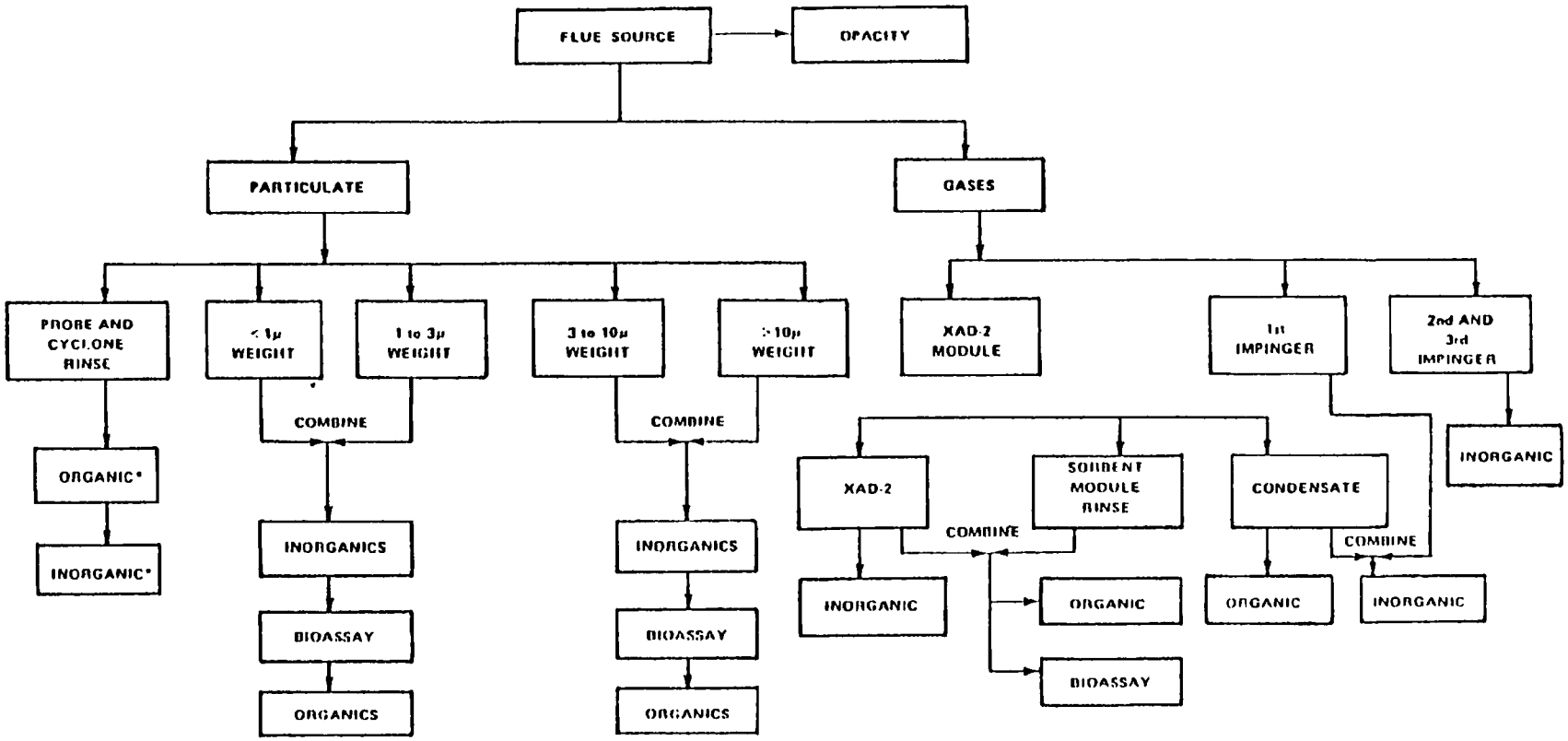


Figure A-4. Flue gas sample analysis protocol.

Quantitative information on total organic emissions was obtained by gas chromatography/flame ionization detector for total chromatographable organics (TCO) and by gravimetry (GRAV) of sample extracts. Infrared spectroscopy (IR) and gas chromatography/mass spectroscopy (GC/MS) were used for identification of organic functional groups and for determining polycyclic organic matter (POM) and other organic species concentrations (the semivolatile organic priority pollutants) in extract samples. Figure A-5 illustrates the organic analysis methodology used.

Passivation of the SASS train with 15 percent by volume HNO_3 solution was performed prior to equipment preparation and sampling to produce biologically inert surfaces. Detailed descriptions of equipment preparation, sampling procedures, and sample recovery are discussed in Reference A-1 and will not be repeated here.

A.3 NH_3 AND HCN SAMPLING AND ANALYSES

NH_3 and HCN were measured at the inlet and outlet locations of the catalytic converter utilizing two separate sampling trains. Both trains were similar to an EPA Method 6 train except that impinger solutions for NH_3 absorption were acid based (HCl) and for HCN were caustic based (NaOH). Concentrations of NH_3 and HCN in solutions were determined in the laboratory using approved wet chemical methods (Reference A-2).

A.4 N_2O SAMPLING AND ANALYSES

The stack gas grab samples were extracted into stainless steel cylinders for laboratory analysis for N_2O using a sampling train illustrated in Figure A-6. For analysis each sample cylinder was externally heated to 120°C (250°F), then a 1-ml sample was withdrawn with a gas-tight syringe for injection into the gas chromatograph (GC) equipped with an electron capture

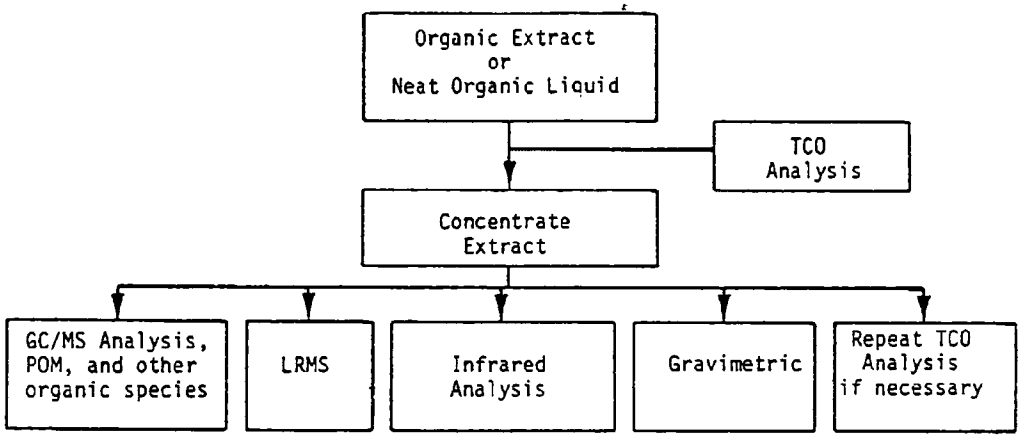


Figure A-5. Organic analysis methodology.

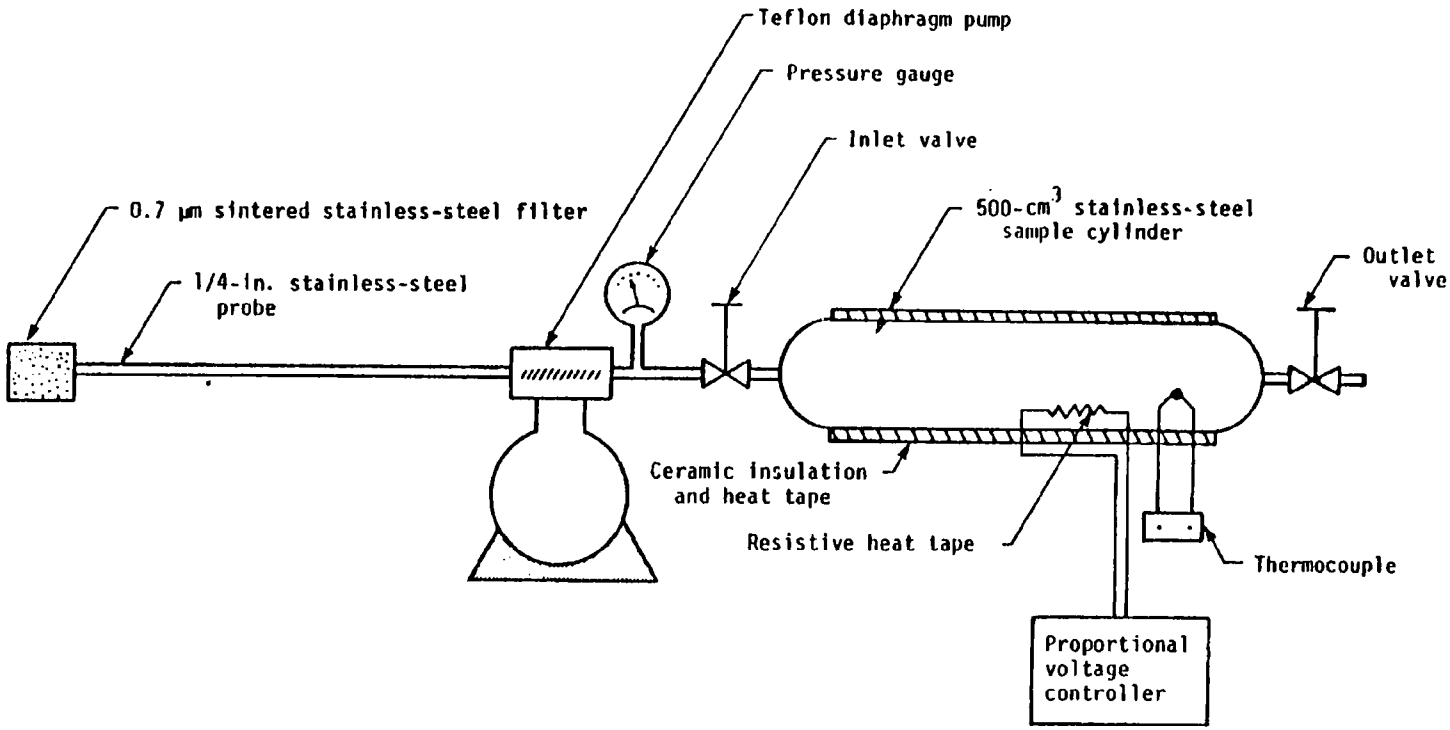


Figure A-6. N_2O sampling system.

detector (ECD). The GC column used was a 10 ft x 1/8 in. stainless steel column packed with 80/100 mesh chromosorb 101. The flow of nitrogen was 20 ml/min with the column kept at 45°C. Elution time for N_2O was approximately 5 min.

A.5 NO_x SAMPLING AND ANALYSES

Certification of the continuous NO_x monitor was performed using the standard EPA Method 7 equipment and protocols.

REFERENCES FOR APPENDIX A

A-1. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

A-2. "Methods for Chemical Analysis of Water and Wastes," EPA-600/4-79-020, NTIS PB 297 686, March 1979.

APPENDIX B

TRACE ELEMENT CONCENTRATIONS

The following tables present sample trace element analysis results and trace element discharge stream concentrations. The tables labeled "ppm" represent element analysis results (µg/g or µg/ml) for each sample analyzed. The composition of lube oil and all catalyst inlet and outlet SASS train samples (filter, XAD-2, first impinger, and second and third impinger) are noted.

The tables labeled "concentration" give the calculated flue gas concentration (µg/dscm) of each element corresponding to each SASS train catalyst sample, and the SASS train sum (labeled "catalyst inlet" and "stack outlet," respectively).

Symbols appearing in the tables are:

- dscm Dry standard cubic meter at 1 atm and 20°C
- MCG Microgram
- ppm parts per million by weight
- < Less than
- > Greater than
- N Element not analyzed

Trace element concentrations less than the detectable limit or having a blank value greater than the sample value were given an arbitrary concentration of zero.

Detectability limits for the various SASS and liquid samples were the following:

- Filter -- <0.1 µg/g
- XAD-2 -- <0.1 µg/g
- Impinger and organic module concentrate -- <0.1 µg/ml
- Lube oil -- <0.1 µg/ml

The data inputs to a computer code for calculation of trace element flowrates were the following:

- Inlet Location
  - -- Gas volume sampled by SASS = 27.3 dscm
  - -- Calculated exhaust gas flowrate = 0.362 dscm/s
  - -- Weight of final filter = 1.0264g
  - -- Filter tare weight 0.9897g
  - -- Weight of XAD-2 = 130g
  - -- SASS impinger 1 final volume 1,725 ml
  - -- Organic condensate final volume = 1,900 ml
  - -- SASS impinger 2 and 3 final volume 1,735 ml
- Outlet Location
  - -- Gas volume sampled by SASS = 26.5 dscm
  - -- Calculated exhaust gas flowrate 0.366 dscm/s
  - -- Weight of final filter = 1.0326g
  - -- Filter tare weight i= 0.9950g
  - -- Weight of XAD-2 130g
  - -- SASS impinger 1 final volume = 1,425 ml
  - -- Organic condensate final volume = 1,515 ml
  - -- SASS impinger 2 and 3 final volume 2,600 ml

- Engine Parameters
  - -- Total heat input rate = 1.73 MW
  - -- Lube oil consumption rate - 0.093 ml/s

HONOR RANCHO ENGINE
NAT. GAS BASELINE

PPM LUBE OIL

ELEMENT	PPM LUBE OIL	ELEMENT	PPM LUBE OIL
ALUMINUM	.500E+01	STRONTIUM	.100E+02
ANTIMONY	.000E+00	SULFUR	.420E+04
ARSENIC	.000E+00	TANTALUM	.000E+00
BARIUM	.970E+03	TELLURIUM	.000E+00
BERYLLIUM	.000E+00	THORIUM	.000E+00
BISMUTH	.200E+00	TIN	.000E+00
BORON	.100E+00	TITANIUM	<.200E+00
BROMINE	.000E+00	TUNGSTEN	.000E+00
CADMIUM	.000E+00	URANIUM	.000E+00
CALCIUM	.334E+03	VANADIUM	.200E+00
CERIUM	.000E+00	YTTRIUM	.000E+00
CESIUM	.000E+00	ZINC	.260E+03
CHLORINE	.100E+02	ZIRCONIUM	.500E+00
CHROMIUM	<.200E+00		
COBALT	<.200E+00		
COPPER	.100E+01		
FLUORINE	.500E+01		
GALLIUM	.000E+00		
GERMANIUM	.000E+00		
HAFNIUM	.000E+00		
IODINE	.200E+00		
IRON	.500E+01		
LANTHANUM	.000E+00		
LEAD	.200E+00		
LITHIUM	.300E+00		
MAGNESIUM	.400E+01		
MANGANESE	.100E+01		
MERCURY	.620E-01		
MOLYBDENUM	.100E+01		
NEODYMIUM	.000E+00		
NICKEL	.200E+01		
NIOBIUM	.000E+00		
PALLADIUM	.000E+00		
PHOSPHORUS	.620E+03		
POTASSIUM	.200E+02		
PRASEODYMIUM	.000E+00		
RHODIUM	.000E+00		
RUBIDIUM	.000E+00		
RUTHENIUM	.000E+00		
SAMARIUM	.000E+00		
SCANDIUM	<.100E+00		
SELENIUM	.200E+01		
SILICON	.300E+02		
SILVER	.000E+00		
SODIUM	.300E+02		

HONOR RANCHO ENGINE
NAT. GAS BASELINE
PPM

PPM INLET ELEMENT	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.438E+03	.000E+00	.000E+00	.000E+00
ANTIMONY	.171E+00	.000E+00	.000E+00	.000E+00
ARSENIC	.433E+01	.000E+00	.000E+00	.000E+00
BARIUM	.130E+04	.000E+00	.000E+00	.000E+00
BERYLLIUM	<.434E-03	.000E+00	.000E+00	.000E+00
BISMUTH	.700E-01	.000E+00	.000E+00	.000E+00
BORON	U.000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.104E+01	.000E+00	.000E+00	.000E+00
CADMIUM	.317E-01	.000E+00	.000E+00	.000E+00
CALCIUM	.177E+04	.800E+02	.000E+00	.000E+00
CERIUM	.235E+00	.160E+01	.200E-02	.000E+00
CESIUM	.100E-01	.000E+00	.000E+00	.000E+00
CHLORINE	>.100E+03	000E+00	.000E+00	.000E+00
CHROMIUM	.176E+02	.000E+00	.000E+00	.000E+00
COBALT	.213E+02	.290E+01	.000E+00	.000E+00
COPPER	.562E+01	.200E+01	.400E-01	.000E+00
FLUORINE	>.560E+02	.000E+00	.000E+00	.000E+00
GALLIUM	.617E+00	.100E+00	.000E+00	.000E+00
GERMANIUM	.404E-01	.000E+00	.000E+00	.000E+00
HAFNIUM	.200E+00	.000E+00	.000E+00	.000E+00
IODINE	.113E+00	.000E+00	.600E-02	.000E+00
IRON	.104E+04	.000E+00	.000E+00	.000E+00
LANTHANUM	.426E+00	.250E+01	.600E-02	.100E+01
LEAD	.381E+01	.000E+00	.000E+00	.000E+00
LITHIUM	.000E+00	.100E+00	.200E-02	.000E+00
MAGNESIUM	.264E+03	.000E+00	.120E+00	.000E+00
MANGANESE	.233E+01	.000E+00	.700E-02	.000E+00
MERCURY	.982E-01	.180E-01	.000E+00	.140E-02
MOLYBDENUM	.207E+02	.150E+01	.000E+00	.000E+00
NEODYMIUM	.330E-01	.000E+00	.000E+00	.000E+00
NICKEL	.210E+02	.000E+00	.000E+00	.000E+00
NIOBIUM	.330E+00	.000E+00	.300E-01	.000E+00
PALLADIUM	.700E-01	000E+00	.000E+00	.000E+00
PHOSPHORUS	.134E+03	000E+00	.000E+00	.000E+00
POTASSIUM	.000E+00	.310E+02	.200E+00	.000E+00
PRASEODYMIUM	.868E-02	.000E+00	.000E+00	.000E+00
RHODIUM	.800E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.322E-01	.000E+00	.000E+00	.000E+00
RUTHENIUM	<.100E-01	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00
SCANDIUM	.000E+00	.000E+00	.000E+00	.000E+00
SELENIUM	.613E+00	.000E+00	.000E+00	.000E+00
SILICON	.323E+04	.100E+02	.300E+01	.000E+00
SILVER	.394E+01	.000E+00	.100E-01	.000E+00
SODIUM	.281E+01	.100E+02	.113E+04	.000E+00
STRONTIUM	.542E+02	.100E+00	.100E-02	.000E+00
SULFUR	.126E+03	.100E+02	.170E+04	.000E+00
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00
TELLURIUM	.109E-01	.000E+00	.000E+00	.000E+00
THORIUM	.304E+00	.000E+00	.000E+00	.000E+00
TIN	.304E+00	.000E+00	<.100E-02	.000E+00
TITANIUM	U.000E+00	.000E+00	.000E+00	.000E+00
TUNGSTEN	.900E+01	.000E+00	.980E+00	.000E+00
URANIUM	.214E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.204E+01	.000E+00	.000E+00	.000E+00
YTTRIUM	.109E+00	.000E+00	.000E+00	.000E+00
ZINC	.290E+03	.000E+00	.100E+00	.000E+00
ZIRCONIUM	.000E+00	.000E+00	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE

PPM OUTLET

ELEMENT	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.508E+02	.000E+00	.400E-01	.000E+00
ANTIMONY	.371E+00	.000E+00	<.500E-02	.000E+00
ARSENIC	.173E+02	.000E+00	.000E+00	.000E+00
BARIUM	.159E+04	.000E+00	.200E-01	.000E+00
BERYLLIUM	<.331E-03	.000E+00	<.100E-02	.000E+00
BISMUTH	.300E+00	.000E+00	.000E+00	.000E+00
BORON	U.000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.403E+01	.000E+00	.200E-01	.000E+00
CADMIUM	.000E+00	.000E+00	.000E+00	.000E+00
CALCIUM	.116E+04	.000E+00	.100E+01	.000E+00
CERIUM	.123E+01	.100E+00	.000E+00	.000E+00
CESIUM	<.100E-01	.000E+00	.400E-01	.000E+00
CHLORINE	>.100E+03	.000E+00	<.270E+01	.000E+00
CHROMIUM	.301E+02	.157E+03	.100E+00	.000E+00
COBALT	.290E+02	.900E+00	.700E-02	.000E+00
COPPER	.396E+02	.800E+01	>.998E+01	.000E+00
FLUORINE	>.555E+02	.150E+02	.231E+01	.000E+00
GALLIUM	.613E+00	.000E+00	.460E-01	.000E+00
GERMANIUM	.603E-01	.000E+00	.000E+00	.000E+00
HAFNIUM	.300E+00	.000E+00	.000E+00	.000E+00
IODINE	.171E+01	.000E+00	.000E+00	.000E+00
IRON	.221E+03	.750E+02	.300E+00	.000E+00
LANTHANUM	.000E+00	.000E+00	<.500E-02	.000E+00
LEAD	.108E+02	.000E+00	.000E+00	.000E+00
LITHIUM	.426E+00	.100E+00	.000E+00	.000E+00
MAGNESIUM	.116E+03	.100E+02	.920E+00	.000E+00
MANGANESE	.632E+01	.480E+01	.770E-01	.000E+00
MERCURY	.113E+00	.160E-01	.150E-03	.000E+00
MOLYBDENUM	.671E+01	.500E+00	.000E+00	.000E+00
NEODYMIUM	.332E+00	.000E+00	.000E+00	.000E+00
NICKEL	.240E+02	.135E+03	.193E+00	.000E+00
NIOBIUM	.323E+00	.000E+00	400E-02	.000E+00
PALLADIUM	400E+00	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.143E+03	.500E+01	.000E+00	.000E+00
POTASSIUM	.000E+00	.110E+02	.270E+01	.000E+00
PRASEODYMIUM	.662E-02	.000E+00	.000E+00	.000E+00
RHODIUM	.300E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.517E-01	.000E+00	.100E-01	.000E+00
RUTHENIUM	<.300E-01	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00
SCANDIUM	.510E+00	.000E+00	.500E-02	.000E+00
SELENIUM	.710E+00	.300E+00	.000E+00	.000E+00
SILICON	.126E+04	.270E+03	.000E+00	.000E+00
SILVER	.194E+01	.900E+00	.194E+01	.000E+00
SODIUM	.000E+00	.100E+02	.146E+04	.000E+00
STRONTIUM	.482E+02	.100E+00	.280E-01	.000E+00
SULFUR	.214E+03	.000E+00	.680E+04	.000E+00
TANTALUM	.100E+00	.000E+00	.100E+00	.000E+00
TELLURIUM	.662E-03	.000E+00	.300E-02	.000E+00
THORIUM	.503E+00	.000E+00	.000E+00	.000E+00
TIN	.903E+00	.000E+00	.000E+00	.000E+00
TITANIUM	U.000E+00	.000E+00	.100E+00	.000E+00
TUNGSTEN	.700E+01	.000E+00	.600E-01	.000E+00
URANIUM	.113E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.303E+01	.200E+00	.000E+00	.000E+00
YTTRIUM	.207E+00	.000E+00	.100E-02	.000E+00
ZINC	.327E+03	.300E+01	.390E+01	.000E+00
ZIRCONIUM	.298E+00	.600E+00	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE

CONCENTRATION MCG/DSCM ELEMENT	CATALYST INLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.165E+02	.165E+02	.000E+00	.000E+00	.000E+00
ANTIMONY	.644E-02	.644E-02	.000E+00	.000E+00	.000E+00
ARSENIC	.163E+00	.163E+00	.000E+00	.000E+00	.000E+00
BARIUM	.490E+02	490E+02	.000E+00	.000E+00	.000E+00
BERYLLIUM	< .163E-04	< .163E-04	.000E+00	.000E+00	.000E+00
BISMUTH	.263E-02	.263E-02	.000E+00	.000E+00	.000E+00
BORON	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.392E-01	.392E-01	.000E+00	.000E+00	.000E+00
CADMIUM	.119E-02	.119E-02	.000E+00	.000E+00	.000E+00
CALCIUM	448E+03	.666E+02	.381E+03	.000E+00	.000E+00
CERIUM	.789E+01	.882E-02	.762E+01	.266E+00	.000E+00
CESIUM	.376E-03	.376E-03	.000E+00	.000E+00	.000E+00
CHLORINE	> .000E+00	> .376E+01	.000E+00	.000E+00	.000E+00
CHROMIUM	.661E+00	.661E+00	.000E+00	.000E+00	.000E+00
COBALT	.146E+02	.801E+00	.138E+02	.000E+00	.000E+00
COPPER	.151E+02	.211E+00	.952E+01	.532E+01	.000E+00
FLUORINE	> .000E+00	> .211E+01	.000E+00	.000E+00	.000E+00
GALLIUM	.499E+00	.232E-01	.476E+00	.000E+00	.000E+00
GERMANIUM	.152E-02	.152E-02	.000E+00	.000E+00	.000E+00
HAFNIUM	.752E-02	.752E-02	.000E+00	.000E+00	.000E+00
IODINE	.803E+00	.425E-02	.000E+00	.798E+00	.000E+00
IRON	.392E+02	.392E+02	.000E+00	.000E+00	.000E+00
LANTHANUM	.763E+02	.160E-01	.119E+02	.798E+00	.636E+02
LEAD	.143E+00	.143E+00	.000E+00	.000E+00	.000E+00
LITHIUM	.742E+00	.000E+00	.476E+00	.266E+00	.000E+00
MAGNESIUM	.259E+02	.994E+01	.000E+00	.160E+02	.000E+00
MANGANESE	.102E+01	.876E-01	.000E+00	.932E+00	.000E+00
MERCURY	.178E+00	.369E-02	.857E-01	.000E+00	.890E-01
MOLYBDENUM	.792E+01	.779E+00	.714E+01	.000E+00	.000E+00
NEODYMIUM	.124E-02	.124E-02	.000E+00	.000E+00	.000E+00
NICKEL	.788E+00	.788E+00	.000E+00	.000E+00	.000E+00
NIOBIUM	400E+01	.124E-01	.000E+00	.399E+01	.000E+00
PALLADIUM	.263E-02	.263E-02	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.504E+01	.504E+01	.000E+00	.000E+00	.000E+00
POTASSIUM	.174E+03	.000E+00	.148E+03	.266E+02	.000E+00
PRASEODYMIUM	.326E-03	.326E-03	.000E+00	.000E+00	.000E+00
RHODIUM	.301E-01	.301E-01	.000E+00	.000E+00	.000E+00
RUBIDIUM	.121E-02	.121E-02	.000E+00	.000E+00	.000E+00
RUTHENIUM	< .376E-03	< .376E-03	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

(continued)

HONOR RANCHO ENGINE
NAT. GAS BASELINE
MCG/DSCM

CONCENTRATION ELEMENT	CATALYST INLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
SCANDIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
SELENIUM	.230E-01	.230E-01	.000E+00	.000E+00	.000E+00
SILICON	.568E+03	.122E+03	.476E+02	.399E+03	.000E+00
SILVER	.148E+01	.148E+00	.000E+00	.133E+01	.000E+00
SODIUM	.150E+06	.106E+00	476E+02	.150E+06	.000E+00
STRONTIUM	.265E+01	.204E+01	.476E+00	.133E+00	.000E+00
SULFUR	.226E+06	.473E+01	.476E+02	.226E+06	.000E+00
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
TELLURIUM	.409E-03	.409E-03	.000E+00	.000E+00	.000E+00
THORIUM	.114E-01	.114E-01	.000E+00	.000E+00	.000E+00
TIN	<X<.145E+00	.114E-01	.000E+00	< .133E+00	.000E+00
TITANIUM	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
TUNGSTEN	.131E+03	.338E+00	.000E+00	.130E+03	.000E+00
URANIUM	.804E-02	.804E-02	.000E+00	.000E+00	.000E+00
VANADIUM	.768E-01	.768E-01	.000E+00	.000E+00	.000E+00
YTTRIUM	.409E-02	.409E-02	.000E+00	.000E+00	.000E+00
ZINC	.242E+02	.109E+02	.000E+00	.133E+02	.000E+00
ZIRCONIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE
MCG/DSCM

CONCENTRATION ELEMENT	CATALYST OUTLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.645E+01	.198E+01	.000E+00	.447E+01	.000E+00
ANTIMONY	<X<.573E+00	.145E-01	.000E+00	< .558E+00	.000E+00
ARSENIC	.675E+00	.675E+00	.000E+00	.000E+00	.000E+00
BARIUM	.640E+02	.618E+02	.000E+00	.223E+01	.000E+00
BERYLLIUM	< .112E+00	< .129E-04	.000E+00	< .112E+00	.000E+00
BISMUTH	.117E-01	.117E-01	.000E+00	.000E+00	.000E+00
BORON	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.239E+01	.157E+00	.000E+00	.223E+01	.000E+00
CADMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
CALCIUM	.157E+03	.453E+02	.000E+00	.112E+03	.000E+00
CERIUM	.538E+00	.478E-01	.491E+00	.000E+00	.000E+00
CESIUM	.447E+01	< .390E-03	.000E+00	.447E+01	.000E+00
CHLORINE	> .000E+00	> .390E+01	.000E+00	< .302E+03	.000E+00
CHROMIUM	.783E+03	.117E+01	.770E+03	.112E+02	.000E+00
COBALT	.633E+01	.113E+01	.442E+01	.782E+00	.000E+00
COPPER	> .000E+00	.154E+01	.392E+02	> .111E+04	.000E+00
FLUORINE	> .000E+00	> .216E+01	.736E+02	.258E+03	.000E+00
GALLIUM	.516E+01	.239E-01	.000E+00	.514E+01	.000E+00
GERMANIUM	.235E-02	.235E-02	.000E+00	.000E+00	.000E+00
HAFNIUM	.117E-01	.117E-01	.000E+00	.000E+00	.000E+00
IODINE	.666E-01	.666E-01	.000E+00	.000E+00	.000E+00
IRON	.410E+03	.861E+01	.368E+03	.335E+02	.000E+00
LANTHANUM	< .558E+00	.000E+00	.000E+00	< .558E+00	.000E+00
LEAD	.421E+00	.421E+00	.000E+00	.000E+00	.000E+00
LITHIUM	.507E+00	.166E-01	.491E+00	.000E+00	.000E+00
MAGNESIUM	.156E+03	.453E+01	.491E+02	.103E+03	.000E+00
MANGANESE	.324E+02	.246E+00	.235E+02	.860E+01	.000E+00
MERCURY	.996E-01	.440E-02	.785E-01	.168E-01	.000E+00
MOLYBDENUM	.271E+01	.261E+00	.245E+01	.000E+00	.000E+00
NEODYMIUM	.129E-01	.129E-01	.000E+00	.000E+00	.000E+00
NICKEL	.685E+03	.933E+00	.662E+03	.216E+02	.000E+00
NIOBIUM	459E+00	.126E-01	.000E+00	.447E+00	.000E+00
PALLADIUM	.156E-01	.156E-01	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.301E+02	.556E+01	.245E+02	.000E+00	.000E+00
POTASSIUM	.356E+03	.000E+00	.540E+02	.302E+03	.000E+00
PRASEODYMIUM	.258E-03	.258E-03	.000E+00	.000E+00	.000E+00
RHODIUM	.117E-01	.117E-01	.000E+00	.000E+00	.000E+00
RUBIDIUM	.112E+01	.201E-02	.000E+00	.112E+01	.000E+00
RUTHENIUM	< .117E-02	< .117E-02	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

(continued)

HONOR RANCHO ENGINE
NAT. GAS BASELINE

CONCENTRATION MCG/DSCM

ELEMENT	CATALYST OUTLET		FILTER	XAD	IMPINGER 1	IMPINGER 2+3
SCANDIUM	.578E+00		.199E-01	.000E+00	.558E+00	.000E+00
SELENIUM	.150E+01		.277E-01	.147E+01	.000E+00	.000E+00
SILICON	.137E+04		.491E+02	.132E+04	.000E+00	.000E+00
SILVER	.217E+03		.757E-01	.000E+00	.217E+03	.000E+00
SODIUM	.163E+06		.000E+00	.491E+02	.163E+06	.000E+00
STRONTIUM	.549E+01		.188E+01	.491E+00	.313E+01	.000E+00
SULFUR	.760E+06		.832E+01	.000E+00	.760E+06	.000E+00
TANTALUM	.112E+02		.390E-02	.000E+00	.112E+02	.000E+00
TELLURIUM	.335E+00		.258E-04	.000E+00	.335E+00	.000E+00
THORIUM	.196E-01		.196E-01	.000E+00	.000E+00	.000E+00
TIN	.352E-01		.352E-01	.000E+00	.000E+00	.000E+00
TITANIUM	.112E+02	U	.000E+00	.000E+00	.112E+02	.000E+00
TUNGSTEN	.697E+01		.273E+00	.000E+00	.670E+01	.000E+00
URANIUM	.440E-02		.440E-02	.000E+00	.000E+00	.000E+00
VANADIUM	.110E+01		.118E+00	.981E+00	.000E+00	.000E+00
YTTRIUM	.120E+00		.805E-02	.000E+00	.112E+00	.000E+00
ZINC	.463E+03		.127E+02	.147E+02	.436E+03	.000E+00
ZIRCONIUM	.295E+01		.116E-01	.294E+01	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	CATALYST INLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.377E-02	.377E-02	.000E+00	.000E+00	.000E+00
ANTIMONY	.147E-05	.147E-05	.000E+00	.000E+00	.000E+00
ARSENIC	.373E-04	.373E-04	.000E+00	.000E+00	.000E+00
BARIUM	.112E-01	.112E-01	.000E+00	.000E+00	.000E+00
BERYLLIUM	< .374E-08	< .374E-08	.000E+00	.000E+00	.000E+00
BISMUTH	.603E-06	.603E-06	.000E+00	.000E+00	.000E+00
BORON	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.898E-05	.898E-05	.000E+00	.000E+00	.000E+00
CADMIUM	.273E-06	.273E-06	.000E+00	.000E+00	.000E+00
CALCIUM	.102E+00	.152E-01	.872E-01	.000E+00	.000E+00
CERIUM	.181E-02	.202E-05	.174E-02	.609E-04	.000E+00
CESIUM	.861E-07	.861E-07	.000E+00	.000E+00	.000E+00
CHLORINE	> .000E+00	> .861E-03	.000E+00	.000E+00	.000E+00
CHROMIUM	.151E-03	.151E-03	.000E+00	.000E+00	.000E+00
COBALT	.334E-02	.183E-03	.316E-02	.000E+00	.000E+00
COPPER	.345E-02	.484E-04	.218E-02	.122E-02	.000E+00
FLUORINE	> .000E+00	> .482E-03	.000E+00	.000E+00	.000E+00
GALLIUM	.114E-03	.531E-05	.109E-03	.000E+00	.000E+00
GERMANIUM	.348E-06	.348E-06	.000E+00	.000E+00	.000E+00
HAFNIUM	.172E-05	.172E-05	.000E+00	.000E+00	.000E+00
IODINE	.184E-03	.973E-06	.000E+00	.183E-03	.000E+00
IRON	.896E-02	.896E-02	.000E+00	.000E+00	.000E+00
LANTHANUM	.175E-01	.367E-05	.273E-02	.183E-03	.145E-01
LEAD	.328E-04	.328E-04	.000E+00	.000E+00	.000E+00
LITHIUM	.170E-03	.000E+00	.109E-03	.609E-04	.000E+00
MAGNESIUM	.593E-02	.228E-02	.000E+00	.366E-02	.000E+00
MANGANESE	.233E-03	.201E-04	.000E+00	.213E-03	.000E+00
MERCURY	.408E-04	.845E-06	.196E-04	.000E+00	.204E-04
MOLYBDENUM	.181E-02	.178E-03	.164E-02	.000E+00	.000E+00
NEODYMIUM	.284E-06	.284E-06	.000E+00	.000E+00	.000E+00
NICKEL	.180E-03	.180E-03	.000E+00	.000E+00	.000E+00
NIOBIUM	.917E-03	.284E-05	.000E+00	.914E-03	.000E+00
PALLADIUM	.603E-06	.603E-06	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.115E-02	.115E-02	.000E+00	.000E+00	.000E+00
POTASSIUM	.399E-01	.000E+00	.338E-01	.609E-02	.000E+00
PRASEODYMIUM	.747E-07	.747E-07	.000E+00	.000E+00	.000E+00
RHODIUM	.689E-05	.689E-05	.000E+00	.000E+00	.000E+00
RUBIDIUM	.277E-06	.277E-06	.000E+00	.000E+00	.000E+00
RUTHENIUM	< .861E-07	< .861E-07	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

(continued)

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	CATALYST INLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
SCANDIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
SELENIUM	.528E-05	.528E-05	.000E+00	.000E+00	.000E+00
SILICON	.130E+00	.278E-01	.109E-01	.914E-01	.000E+00
SILVER	.339E-03	.339E-04	.000E+00	.305E-03	.000E+00
SODIUM	.344E+02	.242E-04	.109E-01	.344E+02	.000E+00
STRONTIUM	.606E-03	.467E-03	.109E-03	.305E-04	.000E+00
SULFUR	.518E+02	.108E-02	.109E-01	.518E+02	.000E+00
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
TELLURIUM	.935E-07	.935E-07	.000E+00	.000E+00	.000E+00
THORIUM	.262E-05	.262E-05	.000E+00	.000E+00	.000E+00
TIN	<X<.331E-04	.262E-05	.000E+00	< .305E-04	.000E+00
TITANIUM	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
TUNGSTEN	.299E-01	.775E-04	.000E+00	.299E-01	.000E+00
URANIUM	.184E-05	.184E-05	.000E+00	.000E+00	.000E+00
VANADIUM	.176E-04	.176E-04	.000E+00	.000E+00	.000E+00
YTTRIUM	.935E-06	.935E-06	.000E+00	.000E+00	.000E+00
ZINC	.554E-02	.250E-02	.000E+00	.305E-02	.000E+00
ZIRCONIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	CATALYST OUTLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.138E-02	.423E-03	.000E+00	.955E-03	.000E+00
ANTIMONY	<X<.122E-03	.309E-05	.000E+00	< .119E-03	.000E+00
ARSENIC	.144E-03	.144E-03	.000E+00	.000E+00	.000E+00
BARIUM	.137E-01	.132E-01	.000E+00	.478E-03	.000E+00
BERYLLIUM	< .239E-04	< .276E-08	.000E+00	< .239E-04	.000E+00
BISMUTH	.250E-05	.250E-05	.000E+00	.000E+00	.000E+00
BORON	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.511E-03	.336E-04	.000E+00	.478E-03	.000E+00
CADMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
CALCIUM	.336E-01	.969E-02	.000E+00	.239E-01	.000E+00
CERIUM	.115E-03	.102E-04	.105E-03	.000E+00	.000E+00
CESIUM	.955E-03	< .833E-07	.000E+00	.955E-03	.000E+00
CHLORINE	> .000E+00	> .833E-03	.000E+00	< .645E-01	.000E+00
CHROMIUM	.167E+00	.250E-03	.165E+00	.239E-02	.000E+00
COBALT	.135E-02	.242E-03	.944E-03	.167E-03	.000E+00
COPPER	> .000E+00	.330E-03	.839E-02	> .238E+00	.000E+00
FLUORINE	> .000E+00	> .462E-03	.157E-01	.552E-01	.000E+00
GALLIUM	.110E-02	.511E-05	.000E+00	.110E-02	.000E+00
GERMANIUM	.502E-06	.502E-06	.000E+00	.000E+00	.000E+00
HAFNIUM	.250E-05	.250E-05	.000E+00	.000E+00	.000E+00
IODINE	.142E-04	.142E-04	.000E+00	.000E+00	.000E+00
IRON	.876E-01	.184E-02	.786E-01	.716E-02	.000E+00
LANTHANUM	< .119E-03	.000E+00	.000E+00	< .119E-03	.000E+00
LEAD	.900E-04	.900E-04	.000E+00	.000E+00	.000E+00
LITHIUM	.108E-03	.355E-05	.105E-03	.000E+00	.000E+00
MAGNESIUM	.334E-01	.969E-03	.105E-01	.220E-01	.000E+00
MANGANESE	.692E-02	.527E-04	.503E-02	.184E-02	.000E+00
MERCURY	.213E-04	.941E-06	.168E-04	.358E-05	.000E+00
MOLYBDENUM	.580E-03	.559E-04	.524E-03	.000E+00	.000E+00
NEODYMIUM	.277E-05	.277E-05	.000E+00	.000E+00	.000E+00
NICKEL	.146E+00	.199E-03	.142E+00	.461E-02	.000E+00
NIOBIUM	.982E-04	.269E-05	.000E+00	.955E-04	.000E+00
PALLADIUM	.333E-05	.333E-05	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.643E-02	.119E-02	.524E-02	.000E+00	.000E+00
POTASSIUM	.760E-01	.000E+00	.115E-01	.645E-01	.000E+00
PRASEODYMIUM	.551E-07	.551E-07	.000E+00	.000E+00	.000E+00
RHODIUM	.250E-05	.250E-05	.000E+00	.000E+00	.000E+00
RUBIDIUM	.239E-03	.430E-06	.000E+00	.239E-03	.000E+00
RUTHENIUM	< .250E-06	< .250E-06	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

(continued)

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	CATALYST OUTLET		FILTER	XAD	IMPINGER 1	IMPINGER 2+3
SCANDIUM	.124E-03		.425E-05	.000E+00	.119E-03	.000E+00
SELENIUM	.320E-03		.591E-05	.315E-03	.000E+00	.000E+00
SILICON	.294E+00		.105E-01	.283E+00	.000E+00	.000E+00
SILVER	.463E-01		.162E-04	.000E+00	.463E-01	.000E+00
SODIUM	.348E+02		.000E+00	.105E-01	.348E+02	.000E+00
STRONTIUM	.117E-02		.401E-03	.105E-03	.669E-03	.000E+00
SULFUR	.162E+03		.178E-02	.000E+00	.162E+03	.000E+00
TANTALUM	.239E-02		.833E-06	.000E+00	.239E-02	.000E+00
TELLURIUM	.716E-04		.551E-08	.000E+00	.716E-04	.000E+00
THORIUM	.419E-05		.419E-05	.000E+00	.000E+00	.000E+00
TIN	.752E-05		.752E-05	.000E+00	.000E+00	.000E+00
TITANIUM	.239E-02	U	.000E+00	.000E+00	.239E-02	.000E+00
TUNGSTEN	.149E-02		.583E-04	.000E+00	.143E-02	.000E+00
URANIUM	.941E-06		.941E-06	.000E+00	.000E+00	.000E+00
VANADIUM	.235E-03		.253E-04	.210E-03	.000E+00	.000E+00
YTTRIUM	.256E-04		.172E-05	.000E+00	.239E-04	.000E+00
ZINC	.990E-01		.272E-02	.315E-02	.931E-01	.000E+00
ZIRCONIUM	.632E-03		.248E-05	.629E-03	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE
MCG/SEC

MASS FLOW ELEMENT	LUBE OIL	CATALYST INLET	CATALYST OUTLET
ALUMINUM	.424E+00	.645E+01	.236E+01
ANTIMONY	.000E+00	.252E-02	.529E-02<X<.210E+00
ARSENIC	.000E+00	.638E-01	.247E+00
BARIUM	.824E+02	.192E+02	.234E+02
BERYLLIUM	.000E+00	< .640E-05	< 409E-01
BISMUTH	.170E-01	.103E-02	428E-02
BORON	.849E-02	.000E+00	.000E+00
BROMINE	.000E+00	.154E-01	.875E+00
CADMIUM	.000E+00	.468E-03	.000E+00
CALCIUM	.284E+02	.175E+03	.575E+02
CERIUM	.000E+00	.309E+01	.197E+00
CESIUM	.000E+00	.147E-03	.164E+01
CHLORINE	.849E+00	> .147E+01	> .143E+01
CHROMIUM	< .170E-01	.259E+00	.286E+03
COBALT	< .170E-01	.573E+01	.232E+01
COPPER	.849E-01	.590E+01	> .423E+03
FLUORINE	.424E+00	> .825E+00	> .122E+03
GALLIUM	.000E+00	.196E+00	.189E+01
GERMANIUM	.000E+00	.596E-03	.860E-03
HAFNIUM	.000E+00	.295E-02	.428E-02
IODINE	.170E-01	.315E+00	.244E-01
IRON	424E+00	.153E+02	.150E+03
LANTHANUM	.000E+00	.299E+02	< .204E+00
LEAD	.170E-01	.561E-01	.154E+00
LITHIUM	.255E-01	.291E+00	.186E+00
MAGNESIUM	.340E+00	.102E+02	.572E+02
MANGANESE	.849E-01	.400E+00	.119E+02
MERCURY	.526E-02	.699E-01	.365E-01
MOLYBDENUM	.849E-01	.311E+01	.993E+00
NEODYMIUM	.000E+00	.487E-03	.474E-02
NICKEL	.170E+00	.309E+00	.251E+03
NIOBIUM	.000E+00	.157E+01	.168E+00
PALLADIUM	.000E+00	.103E-02	.570E-02
PHOSPHORUS	.526E+02	.197E+01	.110E+02
POTASSIUM	.170E+01	.683E+02	.130E+03
PRASEODYMIUM	.000E+00	.128E-03	.944E-04
RHODIUM	.000E+00	.118E-01	.428E-02
RUBIDIUM	.000E+00	.474E-03	.410E+00
RUTHENIUM	.000E+00	< .147E-03	< .428E-03
SAMARIUM	.000E+00	.000E+00	.000E+00
SCANDIUM	< .849E-02	.000E+00	.212E+00
SELENIUM	.170E+00	.903E-02	.549E+00
SILICON	.255E+01	.223E+03	.503E+03
SILVER	.000E+00	.580E+00	.793E+02
SODIUM	.255E+01	.589E+05	.597E+05
STRONTIUM	.849E+00	.104E+01	.201E+01
SULFUR	.357E+03	.887E+05	.278E+06
TANTALUM	.000E+00	.000E+00	.409E+01
TELLURIUM	.000E+00	.160E-03	.123E+00
THORIUM	.000E+00	.449E-02	.718E-02
TIN	.000E+00	.449E-02<X<.567E-01	.129E-01
TITANIUM	< .170E-01	.000E+00	.409E+01
TUNGSTEN	.000E+00	.513E+02	.255E+01
URANIUM	.000E+00	.315E-02	.161E-02
VANADIUM	.170E-01	.301E-01	.402E+00
YTTRIUM	.000E+00	.160E-02	.438E-01
ZINC	.221E+02	.949E+01	.169E+03
ZIRCONIUM	.424E-01	.000E+00	.108E+01

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS FLOW MCG/SEC

ELEMENT	CATALYST INLET	XAD	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.645E+01	.000E+00	.000E+00	.000E+00	.000E+00
ANTIMONY	.252E-02	.000E+00	.000E+00	.000E+00	.000E+00
ARSENIC	.638E-01	.000E+00	.000E+00	.000E+00	.000E+00
BARIUM	.192E+02	.000E+00	.000E+00	.000E+00	.000E+00
BERYLLIUM	< .640E-05	.000E+00	.000E+00	.000E+00	.000E+00
BISMUTH	.103E-02	.000E+00	.000E+00	.000E+00	.000E+00
BORON	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.154E-01	.000E+00	.000E+00	.000E+00	.000E+00
CADMIUM	.468E-03	.000E+00	.000E+00	.000E+00	.000E+00
CALCIUM	.175E+03	.149E+03	.149E+03	.000E+00	.000E+00
CERIUM	.309E+01	.299E+01	.299E+01	.104E+00	.000E+00
CESIUM	.147E-03	.000E+00	.000E+00	.000E+00	.000E+00
CHLORINE	> .000E+00	.000E+00	.000E+00	.000E+00	.000E+00
CHROMIUM	.259E+00	.000E+00	.000E+00	.000E+00	.000E+00
COBALT	.573E+01	.541E+01	.541E+01	.000E+00	.000E+00
COPPER	.590E+01	.373E+01	.373E+01	.209E+01	.000E+00
FLUORINE	> .000E+00	.000E+00	.000E+00	.000E+00	.000E+00
GALLIUM	.196E+00	.187E+00	.187E+00	.000E+00	.000E+00
GERMANIUM	.596E-03	.000E+00	.000E+00	.000E+00	.000E+00
HAFNIUM	.295E-02	.000E+00	.000E+00	.000E+00	.000E+00
IODINE	.315E+00	.000E+00	.000E+00	.313E+00	.000E+00
IRON	.153E+02	.000E+00	.000E+00	.000E+00	.000E+00
LANTHANUM	.299E+02	.467E+01	.467E+01	.313E+00	.249E+02
LEAD	.561E-01	.000E+00	.000E+00	.000E+00	.000E+00
LITHIUM	.291E+00	.187E+00	.187E+00	.104E+00	.000E+00
MAGNESIUM	.102E+02	.000E+00	.000E+00	.626E+01	.000E+00
MANGANESE	.400E+00	.000E+00	.000E+00	.365E+00	.000E+00
MERCURY	.699E-01	.336E-01	.336E-01	.000E+00	.349E-01
MOLYBDENUM	.311E+01	.280E+01	.280E+01	.000E+00	.000E+00
NEODYMIUM	.487E-03	.000E+00	.000E+00	.000E+00	.000E+00
NICKEL	.309E+00	.000E+00	.000E+00	.000E+00	.000E+00
NIOBIUM	.157E+01	.000E+00	.000E+00	.156E+01	.000E+00
PALLADIUM	.103E-02	.000E+00	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.197E+01	.000E+00	.000E+00	.000E+00	.000E+00
POTASSIUM	.683E+02	.579E+02	.579E+02	.104E+02	.000E+00
PRASEODYMIUM	.128E-03	.000E+00	.000E+00	.000E+00	.000E+00
RHODIUM	.118E-01	.000E+00	.000E+00	.000E+00	.000E+00
RUBIDIUM	.474E-03	.000E+00	.000E+00	.000E+00	.000E+00
RUTHENIUM	< .147E-03	.000E+00	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

(continued)

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS FLOW MCG/SEC

ELEMENT	CATALYST INLET	XAD	XAD	IMPINGER 1	IMPINGER 2+3
SCANDIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
SELENIUM	.903E-02	.000E+00	.000E+00	.000E+00	.000E+00
SILICON	.223E+03	.187E+02	.187E+02	.156E+03	.000E+00
SILVER	.580E+00	.000E+00	.000E+00	.522E+00	.000E+00
SODIUM	.589E+05	.187E+02	.187E+02	.589E+05	.000E+00
STRONTIUM	.104E+01	.187E+00	.187E+00	.522E-01	.000E+00
SULFUR	.887E+05	.187E+02	.187E+02	.887E+05	.000E+00
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
TELLURIUM	.160E-03	.000E+00	.000E+00	.000E+00	.000E+00
THORIUM	.449E-02	.000E+00	.000E+00	.000E+00	.000E+00
TIN	<X<.567E-01	.000E+00	.000E+00	< .522E-01	.000E+00
TITANIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
TUNGSTEN	.513E+02	.000E+00	.000E+00	.511E+02	.000E+00
URANIUM	.315E-02	.000E+00	.000E+00	.000E+00	.000E+00
VANADIUM	.301E-01	.000E+00	.000E+00	.000E+00	.000E+00
YTTRIUM	.160E-02	.000E+00	.000E+00	.000E+00	.000E+00
ZINC	.949E+01	.000E+00	.000E+00	.522E+01	.000E+00
ZIRCONIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE
MASS FLOW MCG/SEC

ELEMENT	CATALYST OUTLET	FILTER	XAD	IMPINGER 1	IMPINGER 2+3
ALUMINUM	.236E+01	.725E+00	.000E+00	.164E+01	.000E+00
ANTIMONY	<X< .210E+00	.529E-02	.000E+00	< .204E+00	.000E+00
ARSENIC	.247E+00	.247E+00	.000E+00	.000E+00	.000E+00
BARIUM	.234E+02	.226E+02	.000E+00	.818E+00	.000E+00
BERYLLIUM	< .409E-01	< .472E-05	.000E+00	< .409E-01	.000E+00
BISMUTH	.428E-02	.428E-02	.000E+00	.000E+00	.000E+00
BORON	.000E+00	U .000E+00	.000E+00	.000E+00	.000E+00
BROMINE	.875E+00	.575E-01	.000E+00	.818E+00	.000E+00
CADMIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
CALCIUM	.575E+02	166E+02	.000E+00	.409E+02	.000E+00
CERIUM	.197E+00	.175E-01	.180E+00	.000E+00	.000E+00
CESIUM	.164E+01	< .143E-03	.000E+00	.164E+01	.000E+00
CHLORINE	> .000E+00	> .143E+01	.000E+00	< .110E+03	.000E+00
CHROMIUM	.286E+03	.429E+00	.282E+03	.409E+01	.000E+00
COBALT	.232E+01	.414E+00	.162E+01	.286E+00	.000E+00
COPPER	> .000E+00	.565E+00	.144E+02	> .408E+03	.000E+00
FLUORINE	> .000E+00	> .792E+00	.269E+02	.944E+02	.000E+00
GALLIUM	.189E+01	.875E-02	.000E+00	.188E+01	.000E+00
GERMANIUM	.860E-03	.860E-03	.000E+00	.000E+00	.000E+00
HAFNIUM	428E-02	.428E-02	.000E+00	.000E+00	.000E+00
IODINE	.244E-01	.244E-01	.000E+00	.000E+00	.000E+00
IRON	.150E+03	.315E+01	.135E+03	.123E+02	.000E+00
LANTHANUM	< .204E+00	.000E+00	.000E+00	< .204E+00	.000E+00
LEAD	.154E+00	.154E+00	.000E+00	.000E+00	.000E+00
LITHIUM	.186E+00	.608E-02	.180E+00	.000E+00	.000E+00
MAGNESIUM	.572E+02	.166E+01	.180E+02	.376E+02	.000E+00
MANGANESE	.119E+02	.902E-01	.862E+01	.315E+01	.000E+00
MERCURY	.365E-01	.161E-02	.287E-01	.613E-02	.000E+00
MOLYBDENUM	.993E+00	.957E-01	.898E+00	.000E+00	.000E+00
NEODYMIUM	.474E-02	.474E-02	.000E+00	.000E+00	.000E+00
NICKEL	.251E+03	.342E+00	.242E+03	.789E+01	.000E+00
NIOBIUM	.168E+00	.461E-02	.000E+00	.164E+00	.000E+00
PALLADIUM	.570E-02	.570E-02	.000E+00	.000E+00	.000E+00
PHOSPHORUS	.110E+02	.204E+01	.898E+01	.000E+00	.000E+00
POTASSIUM	.130E+03	.000E+00	.198E+02	.110E+03	.000E+00
PRASEODYMIUM	.944E-04	.944E-04	.000E+00	.000E+00	.000E+00
RHODIUM	.428E-02	.428E-02	.000E+00	.000E+00	.000E+00
RUBIDIUM	.410E+00	.737E-03	.000E+00	.409E+00	.000E+00
RUTHENIUM	< .428E-03	< .428E-03	.000E+00	.000E+00	.000E+00
SAMARIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00

(continued)

HONOR RANCHO ENGINE
NAT. GAS BASELINE

MASS FLOW MCG/SEC

ELEMENT	CATALYST OUTLET		FILTER	XAD	IMPINGER 1	IMPINGER 2+3
SCANDIUM	.212E+00		.727E-02	.000E+00	.204E+00	.000E+00
SELENIUM	.549E+00		.101E-01	.539E+00	.000E+00	.000E+00
SILICON	.503E+03		.180E+02	.485E+03	.000E+00	.000E+00
SILVER	.793E+02		.277E-01	.000E+00	.793E+02	.000E+00
SODIUM	.597E+05		.000E+00	.180E+02	.596E+05	.000E+00
STRONTIUM	.201E+01		.687E+00	.180E+00	.114E+01	.000E+00
SULFUR	.278E+06		.305E+01	.000E+00	.278E+06	.000E+00
TANTALUM	.409E+01		.143E-02	.000E+00	.409E+01	.000E+00
TELLURIUM	.123E+00		.944E-05	.000E+00	.123E+00	.000E+00
THORIUM	.718E-02		.718E-02	.000E+00	.000E+00	.000E+00
TIN	.129E-01		.129E-01	.000E+00	.000E+00	.000E+00
TITANIUM	.409E+01	U	.000E+00	.000E+00	.409E+01	.000E+00
TUNGSTEN	.255E+01		.998E-01	.000E+00	.245E+01	.000E+00
URANIUM	.161E-02		.161E-02	.000E+00	.000E+00	.000E+00
VANADIUM	402E+00		433E-01	.359E+00	.000E+00	.000E+00
YTTRIUM	.438E-01		.295E-02	.000E+00	.409E-01	.000E+00
ZINC	.169E+03		.466E+01	.539E+01	.159E+03	.000E+00
ZIRCONIUM	.108E+01		.425E-02	.108E+01	.000E+00	.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE

OUTPUT=CATALYST INLET

ENGINE MASS BALANCE
INPUT = LUBE OIL (MAIN FUEL = NATURAL GAS, NOT ANALYZED FOR TRACE ELEMENTS)

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
ALUMINUM	.424E+00	.645E+01	.152E+02
ANTIMONY		.252E-02	•
ARSENIC		.638E-01	•
BARIUM	.824E+02	.192E+02	.233E+00
BERYLLIUM		X<.640E-05	•
BISMUTH	.170E-01	.103E-02	.608E-01
BORON	.849E-02		.000E+00
BROMINE		.154E-01	•
CADMIUM		.468E-03	•
CALCIUM	.284E+02	.175E+03	.619E+01
CERIUM		.309E+01	•
CESIUM		.147E-03	•
CHLORINE	.849E+00	.147E+01 <X	.174E+01 <X
CHROMIUM	X<.170E-01	.259E+00	.153E+02 <X
COBALT	X<.170E-01	.573E+01	.337E+03 <X
COPPER	.849E-01	.590E+01	.695E+02
FLUORINE	.424E+00	.825E+00 <X	.194E+01 <X
GALLIUM		.196E+00	•
GERMANIUM		.596E-03	•
HAFNIUM		.295E-02	•
IODINE	.170E-01	.315E+00	.185E+02
IRON	.424E+00	.153E+02	.362E+02
LANTHANUM		.299E+02	•
LEAD	.170E-01	.561E-01	.331E+01
LITHIUM	.255E-01	.291E+00	.114E+02
MAGNESIUM	.340E+00	.102E+02	.299E+02
MANGANESE	.849E-01	.400E+00	.471E+01
MERCURY	.526E-02	.699E-01	.133E+02
MOLYBDENUM	.849E-01	.311E+01	.366E+02
NEODYMIUM		.487E-03	•
NICKEL	.170E+00	.309E+00	.182E+01
NIOBIUM		.157E+01	•
PALLADIUM		.103E-02	•
PHOSPHORUS	.526E+02	.197E+01	.375E-01
POTASSIUM	.170E+01	.683E+02	.402E+02
PRASEODYMIUM		128E-03	•
RHODIUM		.118E-01	•
RUBIDIUM		.474E-03	•
RUTHENIUM		X<.147E-03	•
SAMARIUM			•
SCANDIUM	X<.849E-02		.000E+00
SELENIUM	.170E+00	.903E-02	.532E-01
SILICON	.255E+01	.223E+03	.875E+02
SILVER		.580E+00	•
SODIUM	.255E+01	.589E+05	.231E+05
STRONTIUM	.849E+00	.104E+01	.122E+01
SULFUR	.357E+03	.887E+05	.249E+03
TANTALUM			•
TELLURIUM		.160E-03	•
THORIUM		449E-02	•
TIN		.449E-02<X<.567E-01	•
TITANIUM	X<.170E-01		.000E+00
TUNGSTEN		.513E+02	•
URANIUM		.315E-02	•
VANADIUM	.170E-01	.301E-01	.177E+01
YTTRIUM		.160E-02	•
ZINC	.221E+02	.949E+01	.430E+00
ZIRCONIUM	.424E-01		.000E+00

HONOR RANCHO ENGINE
NAT. GAS BASELINE

OUTPUT=CATALYST OUTLET

ENGINE + CATALYST
INPUT = LUBE OIL (MAIN FUEL = NATURAL GAS, NOT ANALYZED FOR TRACE ELEMENTS)

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
ALUMINUM	.424E+00	.236E+01	.556E+01
ANTIMONY		.529E-02<X<.210E+00	•
ARSENIC		.247E+00	•
BARIUM	.824E+02	.234E+02	.284E+00
BERYLLIUM		X<.409E-01	•
BISMUTH	.170E-01	.428E-02	.252E+00
BORON	.849E-02		.000E+00
BROMINE		.875E+00	•
CADMIUM			•
CALCIUM	.284E+02	.575E+02	.203E+01
CERIUM		.197E+00	•
CESIUM		.164E+01	•
CHLORINE	.849E+00	.143E+01 <X,	.168E+01 <X
CHROMIUM	X<.170E-01	.286E+03	.169E+05 <X
COBALT	X<.170E-01	.232E+01	.136E+03 <X
COPPER	.849E-01	.423E+03 <X	.498E+04 <X
FLUORINE	424E+00	.122E+03 <X	.288E+03 <X
GALLIUM		.189E+01	•
GERMANIUM		.860E-03	•
HAFNIUM		428E-02	•
IODINE	.170E-01	.244E-01	.144E+01
IRON	.424E+00	.150E+03	.354E+03
LANTHANUM		X<.204E+00	•
LEAD	.170E-01	.154E+00	.908E+01
LITHIUM	.255E-01	.186E+00	.729E+01
MAGNESIUM	.340E+00	.572E+02	.169E+03
MANGANESE	.849E-01	.119E+02	.140E+03
MERCURY	.526E-02	.365E-01	.693E+01
MOLYBDENUM	.849E-01	.993E+00	.117E+02
NEODYMIUM		.474E-02	•
NICKEL	.170E+00	.251E+03	.148E+04
NIOBIUM		.168E+00	•
PALLADIUM		.570E-02	•
PHOSPHORUS	.526E+02	.110E+02	.209E+00
POTASSIUM	.170E+01	.130E+03	.766E+02
PRASEODYMIUM		.944E-04	•
RHODIUM		.428E-02	•
RUBIDIUM		.410E+00	•
RUTHENIUM		X<.428E-03	•
SAMARIUM			•
SCANDIUM	X<.849E-02	.212E+00	.249E+02 <X
SELENIUM	.170E+00	.549E+00	.323E+01
SILICON	.255E+01	.503E+03	.197E+03
SILVER		.793E+02	•
SODIUM	.255E+01	.597E+05	.234E+05
STRONTIUM	.849E+00	.201E+01	.237E+01
SULFUR	.357E+03	.278E+06	.780E+03
TANTALUM		.409E+01	•
TELLURIUM		.123E+00	•
THORIUM		.718E-02	•
TIN		.129E-01	•
TITANIUM	X<.170E-01	.409E+01	.241E+03 <X
TUNGSTEN		.255E+01	•
URANIUM		.161E-02	•
VANADIUM	.170E-01	402E+00	.237E+02
YTTRIUM		.438E-01	•
ZINC	.221E+02	.169E+03	.768E+01
ZIRCONIUM	.424E-01	.108E+01	.255E+02

HONOR RANCHO ENGINE
NAT. GAS BASELINE

CATALYST
INPUT = CATALYST INLET OUTPUT = CATALYST OUTLET

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
ALUMINUM	.645E+01	.236E+01	.366E+00
ANTIMONY	.252E-02	.529E-02<X<.210E+00	.210E+01<X<.831E+02
ARSENIC	.638E-01	.247E+00	.387E+01
BARIUM	.192E+02	.234E+02	.122E+01
BERYLLIUM	X<.640E-05	X<.409E-01	*
BISMUTH	.103E-02	.428E-02	.415E+01
BORON			*
BROMINE	.154E-01	.875E+00	.569E+02
CADMIUM	.468E-03		.000E+00
CALCIUM	.175E+03	.575E+02	.328E+00
CERIUM	.309E+01	.197E+00	.637E-01
CESIUM	.147E-03	.164E+01	.111E+05
CHLORINE	.147E+01 <X	.143E+01 <X	*
CHROMIUM	.259E+00	.286E+03	.110E+04
COBALT	.573E+01	.232E+01	.404E+00
COPPER	.590E+01	.423E+03 <X	.716E+02 <X
FLUORINE	.825E+00 <X	.122E+03 <X	*
GALLIUM	.196E+00	.189E+01	.965E+01
GERMANIUM	.596E-03	.860E-03	.144E+01
HAFNIUM	.295E-02	.428E-02	.145E+01
IODINE	.315E+00	.244E-01	.775E-01
IRON	.153E+02	.150E+03	.978E+01
LANTHANUM	.299E+02	X<.204E+00	.000E+00<X<.684E-02
LEAD	.561E-01	.154E+00	.275E+01
LITHIUM	.291E+00	.186E+00	.638E+00
MAGNESIUM	.102E+02	.572E+02	.563E+01
MANGANESE	.400E+00	.119E+02	.297E+02
MERCURY	.699E-01	.365E-01	.522E+00
MOLYBDENUM	.311E+01	.993E+00	.320E+00
NEODYMIUM	.487E-03	.474E-02	.973E+01
NICKEL	.309E+00	.251E+03	.812E+03
NIOBIUM	.157E+01	.168E+00	.107E+00
PALLADIUM	.103E-02	.570E-02	.553E+01
PHOSPHORUS	.197E+01	.110E+02	.558E+01
POTASSIUM	.683E+02	.130E+03	.191E+01
PRASEODYMIUM	.128E-03	.944E-04	.738E+00
RHODIUM	.118E-01	.428E-02	.363E+00
RUBIDIUM	.474E-03	.410E+00	.864E+03
RUTHENIUM	X<.147E-03	X<.428E-03	*
SAMARIUM			*
SCANDIUM		.212E+00	*
SELENIUM	.903E-02	.549E+00	.607E+02
SILICON	.223E+03	.503E+03	.226E+01
SILVER	.580E+00	.793E+02	.137E+03
SODIUM	.589E+05	.597E+05	.101E+01
STRONTIUM	.104E+01	.201E+01	.194E+01
SULFUR	.887E+05	.278E+06	.313E+01
TANTALUM		.409E+01	*
TELLURIUM	.160E-03	.123E+00	.766E+03
THORIUM	.449E-02	.718E-02	.160E+01
TIN	.449E-02<X<.567E-01	.129E-01	.227E+00<X<.287E+01
TITANIUM		.409E+01	*
TUNGSTEN	.513E+02	.255E+01	.498E-01
URANIUM	.315E-02	.161E-02	.511E+00
VANADIUM	.301E-01	.402E+00	.134E+02
YTTRIUM	.160E-02	.438E-01	.274E+02
ZINC	.949E+01	.169E+03	.179E+02
ZIRCONIUM		.108E+01	*

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA-600/7-84-073a/b	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Environmental Assessment of a Reciprocating Engine Retrofitted with Nonselective Catalytic Reduction; Vol. I. Technical Results; Vol. II. Data Supplement		5. REPORT DATE July 1984 6. PERFORMING ORGANIZATION CODE 7733
7. AUTHOR(S) C. Castaldini and L. R. Waterland		8. PERFORMING ORGANIZATION REPORT NO. TR-84-153/EE
9. PERFORMING ORGANIZATION NAME AND ADDRESS Acurex Corporation Environmental and Energy Division P. O. Box 7555		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. 68-02-3188
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory. Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 6/83 - 5/84 14. SPONSORING AGENCY CODE EPA/600/13
15. SUPPLEMENTARY NOTES IERL-RTP project officer is Robert E. Hall, Mail Drop 65; 919/541-2477.		

16. ABSTRACT The two-volume report describes results from testing a rich-burn reciprocating internal combustion engine retrofitted with a nonselective catalytic reduction system for NOx reduction. A comprehensive test program was performed to characterize catalyst inlet and outlet organic and inorganic emissions at optimum catalyst NOx reduction performance, followed by a 15-day exhaust emission monitoring program to measure the catalyst performance under typical engine operating conditions. Over the 1-day comprehensive test period, the NOx reduction performance of the catalyst ranged between 54 and 81%, averaging 70%. NOx emissions averaged 1700 ppm at the catalyst inlet and 550 ppm at the catalyst outlet. Catalyst inlet CO and total unburned hydrocarbon (TUHC) concentrations averaged 14,600 and 115 ppm, respectively. These inlet combustible concentrations were the result of engine operation at an air/fuel ratio near or slightly below the stoichiometry required for efficient NOx reduction. Catalyst outlet CO and TUHC levels were reduced to 13,200 and 125 ppm, respectively. Total organic emissions were also reduced by the catalyst from 15.5 to 2.1 mg/dscm. Ammonia and cyanide levels increased by factors of 15 and 450, respectively, across the catalyst. Over the 15-day monitoring period, NOx reduction performance was mostly in the 0 to 40% range.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Internal Combustion Engines Reciprocating Engines Catalysis Assessments	Pollution Control Stationary Sources Environmental Assessment Nonselective Catalytic Reduction (NCR)	13B 21K 21G 07D 14B
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified 20. SECURITY CLASS (This page) Unclassified	21. NO. OF PAGES 99 22. PRICE