United States
Environmental Protection
Agency

EPA-600/7-86-013a

April 1986

EPA

Research and Development

ENVIRONMENTAL ASSESSMENT OF AN ENHANCED OIL RECOVERY STEAM GENERATOR EQUIPPED WITH AN EPA HEAVY OIL LOW-NO_X BURNER

Volume I. Technical Results

Prepared for

Office of Air Quality Planning and Standards

Prepared by

Air and Energy Engineering Research
Laboratory
Research Triangle Park NC 27711

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Volume I
Technical Results

by

C. Castaldini, L. R. Waterland, and R. DeRosier
Acurex Corporation
Energy & Environmental Division
485 Clyde Avenue
P.O. Box 7044
Mountain View, California 94039

EPA Contract 68-02-3188

EPA Project Officer: J. A. McSorley
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ABSTRACT

Comprehensive emission measurements and 30-day flue gas monitoring were performed on a 16-MW (55 million Btu/hr) enhanced oil recovery steam generator equipped with the EPA low-NO_x burner firing high-nitrogen crude. The 1-day comprehensive measurements included quantification of semivolatile organics and 73 trace elements; volatile organic sampling train (VOST) quantitation of volatile organic priority pollutants; EPA Method 5/8 for particulate and SO_x; controlled condensation for SO_x; Andersen impactors for particle size distribution; grab samples for N_2O; and continuous flue gas monitoring. NO_x emissions during the comprehensive tests averaged 70 ppm at 3 percent O_2, well below the target level of 85 ppm. CO emissions were below 30 ppm, and SO_2 averaged about 550 ppm. Solid particulates were emitted at about 27 ng/J (96 mg/dscm); condensible particulates were about half that level. Volatile organics (benzene, toluene, and ethylbenzene) were measured in the 0.4 to 20 ppb range. Semivolatile organics (naphthalene and phenol) were detected in the 0.3 ppb range. Subsequent continuous monitoring of flue gas criteria emissions showed NO_x below 80 ppm at 3 percent O_2 with an average of 70 ppm. CO emissions were generally less than 30 ppm.

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ACKNOWLEDGEMENTS

This test was performed in cooperation with Chevron U.S.A., Inc. and the Energy and Environmental Research Corporation (EERC). Appreciation is greatly extended to Rich Podgers of Chevron U.S.A., and Glenn England and Yul Kwan of EERC. Special recognition and thanks are extended to the Acurex field test crew of Curtis Beeman, Regan Best, Bruce DaRos, Pete Kaufmann, Cary Milburn, and Martha Murray.

SECTION 1

INTRODUCTION

This report describes and presents results for a set of environmental assessment tests performed for the Environmental Protection Agency's Air and Energy Engineering Research Laboratory/Research Triangle Park (EPA-AEERL/RTP) 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 for the environmental assessment were compiled and methodologies were developed. Furthermore, priorities for the schedule and level of effort to be devoted to evaluating 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.

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 spearate reports. These new tests, using standardized Level 1 sampling and analytical procedures (Reference 1-9) are aimed at filling the 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 operation

Within these priority needs, enhanced oil recovery (EOR) steamers were

accorded high ranking because of their emerging importance as an emission source in California.

The petroleum reserves which can be recovered through primary production methods have been essentially exhausted in the oil fields in Kern County, California. These fields still contain significant reserves, although the remaining crude is too heavy (viscous) to be produced by normal means. This crude is currently being produced using what has been termed enhanced oil recovery (EOR). In this process, near saturated (80 to 90 percent quality) crude is currently being produced using what has been termed enhanced oil recovery (EOR). In this process, near saturated (80 to 90 percent quality) steam is injected into a field. This steam heats the oil, thereby decreasing its viscosity and allowing it to be pumped.

The steam for injection is raised by crude-oil-fired steam generators (often termed steamers) which have uncontrolled NO_x emissions of 300 ppm and greater. Since Kern County is only in borderline attainment of the NO_2 ambient air quality standard, EOR steamers have received close regulatory attention with respect to reducing NO_x emissions.

One approach to reducing NO_x emissions from these steamers incorporates a low-NO_x emission burner design. One such burner was developed by the Energy and Environmental Research Corporation (EERC) under EPA sponsorship. The EERC development program, which spanned a period of 6 years, called for the field demonstration of the low-NO_x burner having the capability of meeting the program goal of 85 ppm NO_x, 45 ppm CO (at 3 percent O_2), and acceptable smoke and particulate emissions while burning high nitrogen fuel oil.

The EOR steamer equipped with the EPA low-NO_x burner was tested in the current CMEA program. These tests. described in this report, were conducted to augment the emissions measurements by EERC required under their field demonstration program.

In addition to the tests described in this report, another EOR steamer, this one equipped with a Mitsubishi Heavy Industries (MHI) low-NO_x burner marketed by CE-Natco (a steamer manufacturer), was also tested. Results from these tests are documented in Reference 1-10.

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

TABLE 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 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
Spark-ignited, natural-gas-fueled reciprocating internal combustion engine -- nonselective NO_x reduction catalyst	610-kW (818-hp) Waukesha rich-burn engine equipped with DuPont NSCR system	-- Low-NO_x (with catalyst) -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, NO_x TUHC Lube oil	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 -- Method 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

(continued)

TABLE 1-1. (continued)

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 test with CWS -- 30-day emissions monitoring	Boiler outlet -- SASS -- VOST -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- 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 burner -- 30-day emissions monitoring	Steamer outlet -- SASS -- VOST -- Method 5 -- Method 8 -- Controlled condensation -- Andersen impactors -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, SO_2 Fuel	Chevron U.S.A., EERC
Spark-ignited, natural-gas-fueled reciprocating internal combustion engine -- selective NO_x reduction catalyst	1,500-kW (2,000-hp) Ingersoll-Rand engine equipped with Engelhard SCR system	-- Low-NO_x (with catalyst) -- 15-Day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, NO_x, TUHC Lube oil	Southern California Gas Company

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SECTION 2

SOURCE DESCRIPTION AND OPERATION

The tests were performed on an enhanced oil recovery steam generator (EOR steamer) owned and operated by Chevron U.S.A. The steamer, located in the Kern Front oil field near Bakersfield, California, was retrofitted in 1984 with the EPA low-NO_x burner. The retrofit was part of the field verification of the commercial prototype 16 MW (55 million Btu/hr) low-NO_x burner developed and fabricated by the Energy and Environmental Research Corporation (EERC) under EPA-sponsored programs (References 2-1 and 2-2). The goal of the field demonstration was to validate the low-NO_x capability and thermal performance of the burner firing high nitrogen ($\geq$0.7 percent) Kern County crude.

Figure 2-1 illustrates the low-NO_x burner design. The burner utilizes the staged air combustion concept in which a primary fuel-rich zone is separated from a fuel-lean zone where secondary combustion air is injected. The fuel-rich zone is established in a large refractory lined combustor. Primary combustion air is preheated using a regenerative combustor shell design. Secondary (unpreheated) combustion air is injected radially and axially in the transition zone connecting the combustor to the steamer.

Table 2-1 summarizes the design and operating characteristics of the EPA commercial prototype burner. The important operating parameters for the advanced low-NO_x burner are a low first-stage stoichiometric ratio (SR) in

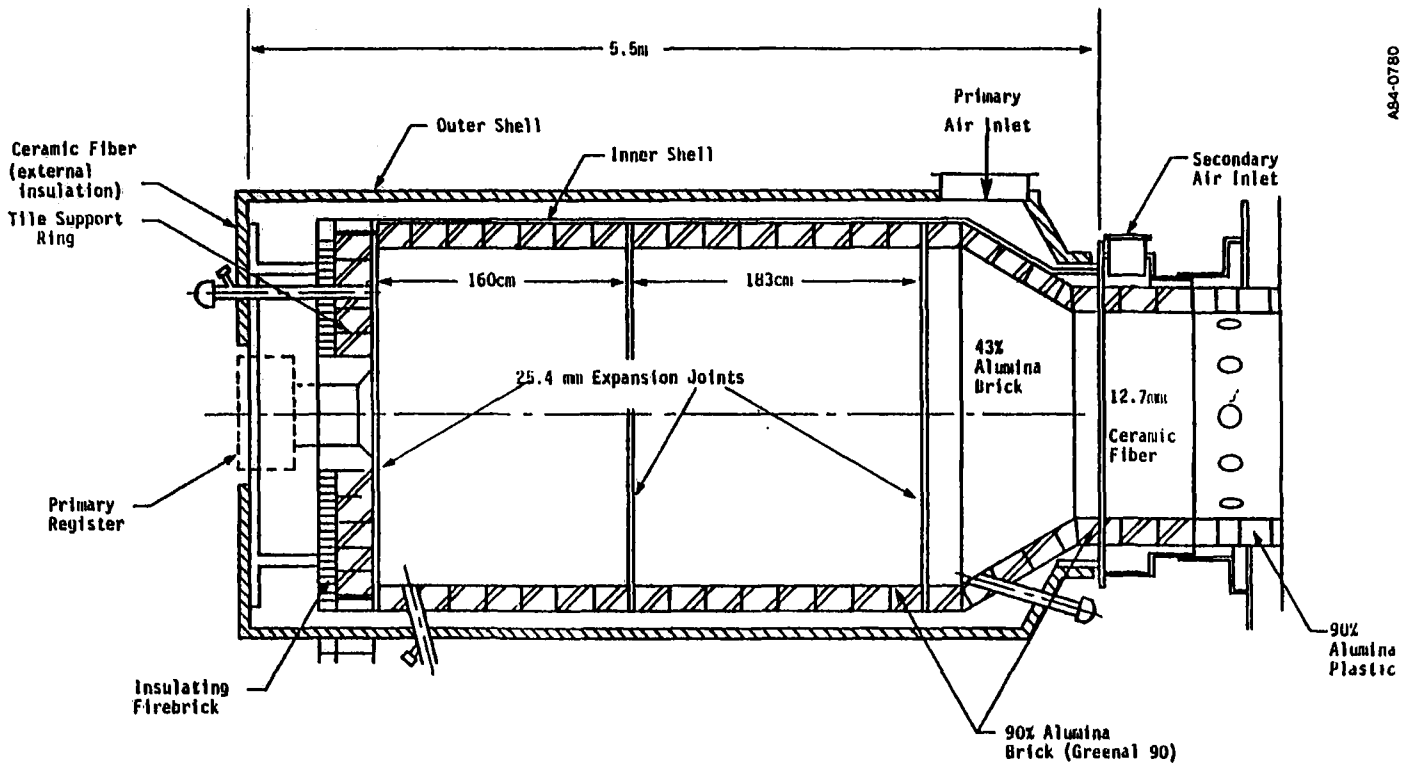


Figure 2-1. EPA low-NO_x burner.

TABLE 2-1. EPA LOW-NO_x BURNER DESIGN CHARACTERISTICS

• Capacity	--	16 MW (55 MBtu/hr) heat input
• Overall combustor length	--	5.5m (18 ft)
• Combustor L/D	--	2.6
• Combustor volume	--	$13m^3$ ($460\ ft^3$)
• Combustor lining	--	alumina refractory
• Temperature in the combustor at full load	--	about 1,430°C (2,600°F)
• Gas residence time in the combustor at full load	--	about 0.6 sec
• Design burner stoichiometry	--	0.60 to 0.65
• Primary air temperature	--	preheated up to 250°C (480°F)
• Secondary air injection	--	combination of radial and axial injection ports
• Performance goals:		
-- Fuel/oil nitrogen content	--	$\geq$0.7 percent
-- NO_x at 3 percent O_2	--	85 ppm maximum
-- CO at 3 percent O_2	--	45 ppm maximum
-- Smoke	--	Bacharach number 4 maximum
-- Sound mechanical and thermal performance		

the range of 0.60 to 0.65, high combustor temperature of $\geq$1,430°C (2,600°F), near the adiabatic flame temperature, and a long first-stage residence time of about 0.6 sec. This combination of long gas residence time and high gas temperature promotes the decay of total fixed nitrogen (TFN) species (HCN and NH_3) to N_2 formed early in the ignition zone from fuel nitrogen under very fuel-rich conditions. Low TFN concentrations at the first-stage exit result in low-fuel NO_x conversion. In the second stage, temperature and fuel/air mixing are important to minimize thermal NO_x while keeping CO, smoke, and particulate in check. Efficient fuel/oil atomization and fuel/air mixing in the ignition zone of the combustor are also beneficial to the decay of TFN in the combustor.

The goals of the low-NO_x burner development were to achieve NO_x levels at or below 85 ppm at 3 percent O_2, with low CO, smoke, and particulate when burning Kern County crude with a typical nitrogen content of 0.7 percent or greater. Subscale burner prototypes tested by EERC had shown that NO_x levels as low as 45 ppm could be achieved using this design approach almost independently of the nitrogen content of the fuel oil. Figure 2-2 illustrates the overall layout of the low-NO_x burner retrofit. Preliminary tests by EERC of the full-scale retrofit had demonstrated that the burner was capable of meeting the EPA program goals.

The objective of the CMEA tests were to augment emission tests performed by EERC as part of the field verification program. The CMEA tests consisted of 30-day continuous monitoring of steamer flue gas emissions (O_2 CO_2, CO, NO_x, and SO_2) during typical unattended steamer operation. In addition, a comprehensive emission test program was performed over a 1-day period, during which burner operation was adjusted to achieve emission goals set by the EPA

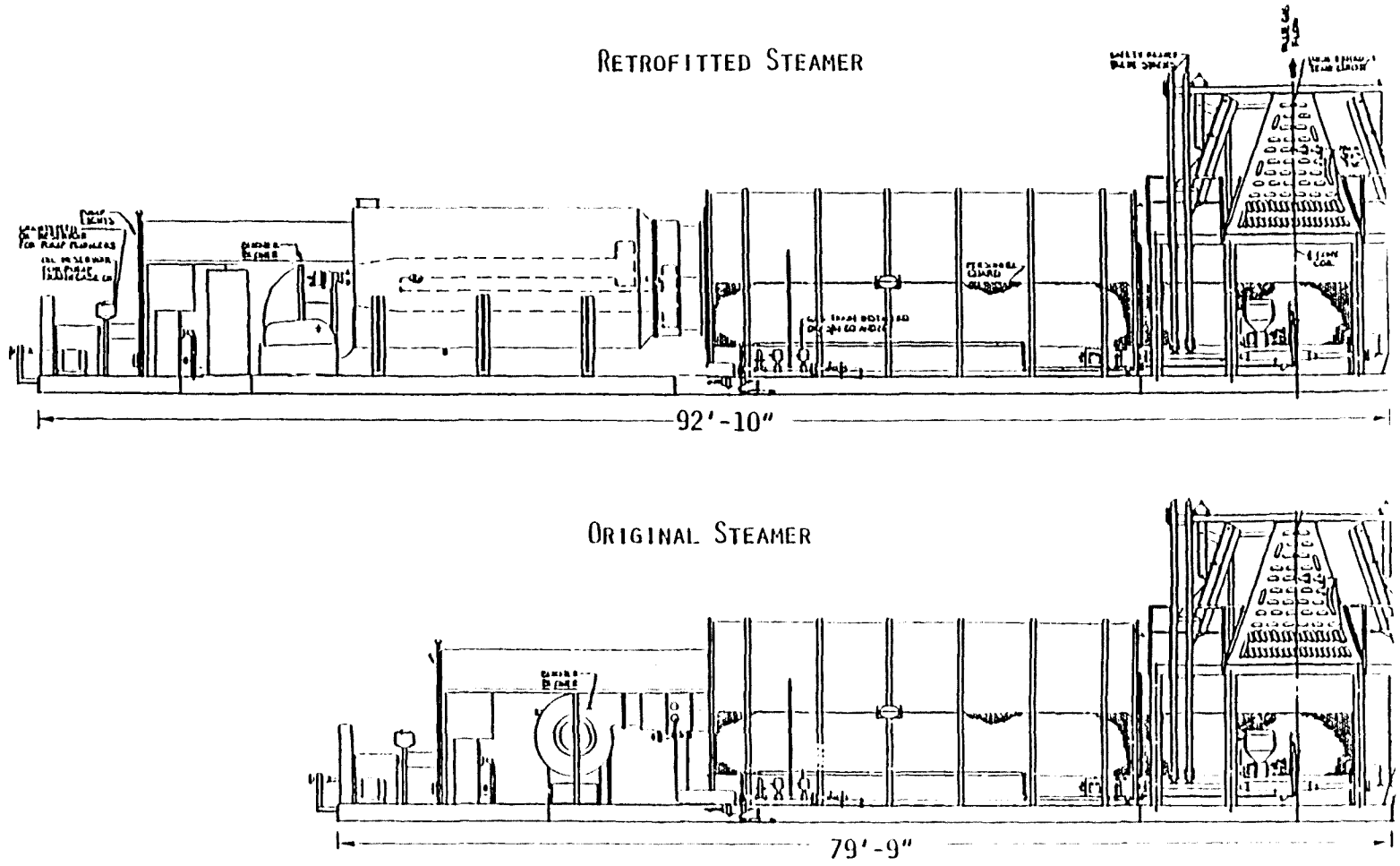


Figure 2-2. Low-NO_x burner retrofit arrangement.

for the field verification program. Table 2-2 summarizes the burner/steamer operation during this 1-day comprehensive testing period. The burner fired Kern County crude with a nitrogen and sulfur content of 1.04 and 1.06 percent, respectively. Total firing rate during this test period averaged approximately 24 l/min (215 bbl/day), corresponding to a heat input rate of nearly 17 MW (57×10^6 Btu/hr). Measurement of primary and secondary airflow indicated a first-stage combustor stoichiometry in the range of 0.61 to 0.65, with an estimated gas residence time of 0.65 sec.

TABLE 2-2. STEAMER/BURNER OPERATION

	Range		Average	
Fuel flow, l/min (bbl/day)	23.4 to 24.1	(212 to 218)	23.8	(215)
Heat input, MW (10^6 Btu/hr)	16.4 to 16.8	(55.8 to 57.4)	16.6	(56.6)
Fuel temperature, °C (°F)	129 to 132	(264 to 269)	130	(267)
Feedwater flow, l/min (10^3 bbl/day)	380 to 400	(3.4 to 3.6)	390	(3.5)
Steam pressure, MPa (psig)	7.03 to 9.10	(1,020 to 1,320)	8.41	(1,220)
Steam temperature, °C (°F)	279 to >300	(535 to >570)	--	--
Stack temperature, °C (°F)	232 to 254	(450 to 490)	242	(468)
Burner primary airflow, m^3/s (scfm)	2.71 to 2.87	(5,740 to 6,080)	2.80	(5,940)
Secondary airflow, m^3/s (scfm)	2.38 to 2.95	(5,040 to 6,260)	2.65	(5,630)
First stage stoichiometry	0.61 to 0.65		0.64	
First stage residence time,[b] sec		--	0.65	
Fuel oil analysis, percent weight (dry basis, unless noted)				
Carbon		--	86.2	
Hydrogen		--	11.3	
Sulfur[c]	1.00 to 1.10		1.06	
Nitrogen[c]	1.00 to 1.09		1.04	
Ash		---	0.03	
Moisture[d]		--	0.57	
Oxygen[e]		--	0.4	
Gross heating value, MJ/kg (Btu/lb)		--	42.78	(18,430)
Specific gravity (degrees API) at 60°F		--	12.6	

[a]Spans the entire 1-day period of comprehensive testing
[b]Assumes a combustor temperature of 1,430°C (2,600°F)
[c]Analyses of sulfur and nitrogen were performed in triplicate
[d]As fired
[e]By difference

REFERENCES FOR SECTION 2

2-1. England, G. C., et al., "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators; Test Report: Preliminary Evaluation of Commercial Prototype Burner," EPA-600/7-83-061, NTIS PB84-128727, December 1983.

2-2. England, G. C., et al., "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators -- Design Phase Report," EPA-600/7-84-076, NTIS PB84-224393, July 1984.

SECTION 3

EMISSION RESULTS

The objectives of this test program were: (1) to measure steamer flue gas emissions during a 30-day test period to evaluate the continuous performance of the EPA low-NO_x burner and (2) to perform comprehensive tests over a 1-day period to measure inorganic and organic pollutant emissions. Emission measurements were performed in cooperation with EERC personnel who assisted the test crew in the operation of the low-NO_x burner.

3.1 SAMPLING PROTOCOL

Table 3-1 summarizes the sampling and analytical test matrix employed during the comprehensive test program. Fuel samples of the crude oil were collected for proximate, ultimate, and selected trace element analyses. All flue gas emissions were measured at the stack, downstream of the steamer economizer section. Continuous monitors for O_2, CO_2, CO, NO_x, and SO_2 were operated during the comprehensive tests as well as throughout the 30-day continuous emission testing period. Volatile organic species emissions were measured with the volatile organic sampling train (VOST) according to EPA protocol (Reference 3-1). Trace element and less volatile organic compounds were measured using the source assessment sampling system (SASS) per an extended EPA level 1 protocol (Reference 3-2). Particulate and sulfur oxide compounds were measured using combined EPA Methods 5 and 8 and a controlled condensation system (CCS). The size distribution of emitted particulate

TABLE 3-1. SAMPLING ANALYSIS TEST MATRIX[a]

Sample/ location	Sampling protocol	Analysis protocol
Fuel	Grab sample	Proximate, ultimate, and selected trace elements
Stack	Continuous emission monitors	NO_x, CO, CO_2, O_2, SO_2
	Volatile organic sampling train (VOST)	Volatile organic priority pollutant species by GC/MS (EPA Method 624)
	Source assessment sampling system (SASS)	Selected trace elements, total semi- and nonvolatile organics, semivolatile organic priority pollutant species by GC/MS (EPA Method 625)
	EPA Method 5/8 train	Particulate emissions by EPA Method 5, SO_2, and SO_3 emissions by EPA Method 8
	Controlled condensation system (CCS)	SO_2 and SO_3 by titration
	Andersen impactor sampling system	Gravimetry of nine-stage impactor for particle size distribution
	Grab sample -- multiple sample bombs	N_2O by laboratory GC/ECD
	Grab sample -- multiple sample flasks	NO_x by EPA Method 7

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

was determined using an Andersen cascade impactor. Flue gas samples were also collected for analyses of nitrous oxide (N_2O), using gas chromatography with electron capture detection. Certification of the NO_x analyzer readings was performed three times during the 30-day test period using the reference EPA Method 7 protocol. Figure 3-1 illustrates the actual test activity schedule.

The following sections summarize the emission test results. Sections 3.2 through 3.4 present the emission results obtained during the comprehensive tests that took place on February 1, 1984. Section 3.5 summarizes results of continuous emission measurements performed over the extended test period from January 21 to February 24, 1984. Section 4 presents results of Quality Assurance (QA) activities performed, including results of the EPA Method 7 certification tests. Details of the sampling and analysis procedures used are discussed in Appendix A.

3.2 CRITERIA POLLUTANT AND OTHER GAS PHASE SPECIES EMISSIONS

Table 3-2 summarizes gaseous and particulate emissions measured during the 1-day comprehensive tests performed on February 1. NO_x emission levels were maintained below 75 ppm as measured, averaging 69 ppm corrected to 3 percent O_2, well below the target of 85 ppm set for the field demonstration program. CO emissions averaged 24 ppm (at 3 percent O_2), again within the 45 ppm program goal. SO_2 emissions measured by continuous monitors were relatively steady at about 565 ppm as measured. Conversion of all fuel sulfur to SO_2 would result in an emission rate of 495 μg/J (643 ppm) compared to the measured level of 435 μg/J (565 ppm).

N_2O levels in the flue gas, at 7 ppm corrected to 3 percent O_2, were about 10 percent of the corresponding NO_x emissions level. This is at the

Test Activity	January 1984											February 1984																							
	21	22	23	24	25	26	27	28	29	30	31	1[a]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Continuous monitoring	△	—	—	—	—	—	—	—	—	—	—	Run continously	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	△
Comprehensive tests																																			
• SASS												△																							
• EPA Methods 5/8												△																							
• VOST												△																							
• Controlled condensation																																		△	
• N_2O												△																							
• Andersen impactor																																	△		
Quality Assurance tests																																			
• EPA Method 7				△															△																△

[a]Comprehensive tests.

Figure 3-1. Test activity schedule.

TABLE 3-2. CRITERIA POLLUTANT AND OTHER GAS SPECIES EMISSIONS -- COMPREHENSIVE TESTS

Pollutant[a]	Range		Average
As measured by continuous gas analyzers			
O_2, percent dry	2.3 to 2.8		2.7
CO_2, percent dry	12.2 to 13.7		13.1
CO, ppm dry	21 to 27		24
NO_x, ppm dry	66 to 75		70
SO_2, ppm dry	560 to 579		565
Corrected average gaseous emissions	ppm[b]	ng/J[c]	lb/MBtu[c]
CO	24	8.2	0.019
NO_x[d]	69	39	0.09
SO_2	556	435	1.01
N_2O[e]	7	0.5	0.001
Particulate mass emissions	mg/dscm		
• SASS solids	26	7.3	0.017
• Method 5/8[e]			
-- Solids	96	26.7	0.062
-- Condensible	50	13.8	0.032
-- Total	146	40.5	0.094

[a]Appendix A discusses continuous monitor analyzers used, the conditioning system, particulate sampling equipment, and other sampling trains
[b]Corrected to 3 percent O_2
[c]On a heat input basis
[d]As NO_2
[e]Average of two test measurements. Condensible particulate measured, since the Kern County Air Pollution Control District continues to regulate this fraction.

low end of the range exhibited in recent data from several fossil-fuel-fired external combustion sources (Reference 3-3). These other data suggest that N_2O emissions are generally about 20 to 25 percent of the corresponding NO_x level.

Particulate emissions were measured using SASS and the combined EPA Methods 5 and 8 sampling trains. Comparison of the solid particulate catch indicates an emission rate of 7.3 ng/J (26 mg/dscm) based on the SASS results, compared to about 27 ng/J (96 mg/dscm) using the EPA Methods 5 and 8 results. This difference may be attributed in part to the higher sampling temperature of the SASS (230°C) versus the Method 5 (120°C). At higher temperatures, condensible matter which might escape the SASS filter could be caught on the Method 5 filter, perhaps causing this disparity. Impinger solutions of the combined EPA Methods 5 and 8 were also analyzed for condensible particulate matter. The Kern County Air Pollution Control District still requires condensible particulate to be included in the total particulate emission result reported. On the average, the condensed matter accounted for about one-third of the total particulate catch of 40.5 ng/J (146 mg/dscm).

Table 3-3 summarizes the particulate emission results of the two EPA Methods 5 and 8 sample runs and the corresponding burner/steamer conditions during each test run. As shown, total particulate emissions for both runs were comparable (149 and 142 mg/dscm). This is in the range typical for uncontrolled EOR steamer emissions. However, the split between solid and condensible particulate between the two runs changed significantly. For run 1, only about 43 percent of the Method 5 catch was solid particulate

TABLE 3-3. FLUE GAS PARTICULATE MEASUREMENT RESULTS

	Run 1		Run 2	
Method 5	(mg/dscm)	(gr/dscf)	(mg/dscm)	(gr/dscf)
Solid (front half)[a]	64	0.028	128	0.056
Condensible (back half)[b]	85	0.037	14	0.006
Total	149	0.065	142	0.062
Burner/steamer operating data:	Range	Average	Range	Average
Fuel flow, l/min (bbl/day)	--	24.1 (219)	--	24.1 (218)
Heat input, MW (10^6 Btu/hr)	--	16.9 (57.7)	--	16.8 (57.4)
Fuel temperature, °C (°F)	129 to 131 (264 to 268)	130 (266)	130 to 131 (266 to 268)	131 (267)
Steam pressure, MPa (psig)	--	7.03 (1,020)	--	9.10 (1,320)
Steam temperature, °C (°F)	--	279 (535)	--	>300 (>570)
Feedwater flow, l/min (10^3 bbl/day)	--	400 (3.6)	--	375 (3.4)
Burner primary air flow, m^3/s (scfm)	167 to 172 (5,900 to 6,080)	170 (6,000)	163 to 172 (5,740 to 6,080)	167 (5,880)
Secondary air flow, m^3/s (scfm)	152 to 158 (5,360 to 5,590	155 (5,460)	153 to 177 (5,390 to 6,260)	170 (6,000)
Combustor stoichiometry[c]	0.62 to 0.64	0.63	0.61 to 0.64	0.62
Stack temperature, °C (°F)	232 to 241 (450 to 466)	236 (456)	244 to 254 (472 to 490)	248 (479)

[a]Solid particulate calculated from the filter and probe catches
[b]Condensible particulate calculated from the impinger solutions; duplicate analyses performed
[c]Assumes combustor temperature of 1,430°C (2,620°F)

(57 percent condensibles); for run 2, 90 percent was solid particulate (10 percent condensibles).

The operating data in Table 3-3 show that two operational changes occurred between the two runs. Steam pressure (thus temperature) was increased in run 2, though fuel flow was held constant. Feedwater flow was, therefore, reduced slightly to maintain steam quality. The net result of this change was slightly higher stack temperature (less heat absorption in the convection section of the steamer) for run 2. In addition, burner primary air flow was slightly lower in run 2, and secondary air flow higher. Combustor stoichiometries, therefore, were slightly lower for run 2, 0.63 versus 0.62 on the average. The slightly lower combustor stoichiometry may have contributed to an increase in emissions of carbonaceous particulate matter and thus an increase in the solid catch of the Method 5 sampling system.

Table 3-4 shows results of the Method 8 analyses for the two combined Methods 5 and 8 runs. For comparison, the average SO_2 continuous monitor reading over each run is also noted. The agreement between the reference method and the SO_2 monitor was within 10 percent for run 1 and 3 percent for run 2. The SO_x (SO_2 + SO_3) levels measured (600 to 632 ppm dry at 3 percent O_2) are as would be expected from total conversion of the fuel sulfur to SO_x (632 ppm at 3 percent O_2, as noted above). Interestingly, the ratio of SO_3 to total SO_x, at between 0.7 percent (run 2) and 2.0 percent (run 1), is much lower than the range typical for oil-fired sources (5 to 10 percent). This ratio is more in the range typical for coal-fired sources (less than 2 percent).

TABLE 3-4. SULFUR SPECIES EMISSIONS BY COMBINED EPA METHODS 5 AND 8[a]

	Run 1	Run 2
Method 8		
SO_2, ppm dry, 3 percent O_2	619	593
SO_3, ppm dry, 3 percent O_2	12.9	4.4
Continuous monitor		
SO_2, ppm dry, 3 percent O_2	557	574
O_2, percent dry	2.7	2.7

[a]Tests performed on February 1, 1984

Table 3-5 shows results of the controlled condensation (CCS) analysis for two separate measurements made on February 23. By this method, SO_2 emissions were about 600 and 610 ppm as measured, in fairly good agreement with the Method 8 results obtained on February 6. Agreement between the CCS SO_2 measurement and the continuous monitor reading was also good, within 7 percent. However, flue gas SO_3 measured with CCS, at 47 and 51 ppm, was much higher than as measured on February 1 using Method 8. The ratio of SO_3 to total SO_x for the CCS measurements was 7.2 to 7.7 percent. This, as noted above, is well within the range typical for oil-fired sources. The authors can not explain this disparity between Method 8 and CCS.

Table 3-6 summarizes particle size distribution data obtained in two separate Andersen impactor measurements. Figure 3-2 indicates a log-normal distribution (as evidenced by the straight curve fits). Mean particle size (D_{50}) was 0.056 μm (run 1) to 0.14 μm (run 2); 90 percent of the total particulate was less than 1.4 μm (run 1) to 11 μm (run 2).

TABLE 3-5. SULFUR SPECIES EMISSIONS BY CONTROLLED CONDENSATION[a]

	Run 1	Run 2
Controlled condensation system		
SO_2, ppm dry, as measured	602	611
(ppm dry, 3 percent O_2)	(653)	--[b]
SO_3, ppm dry, as measured	47	51
(ppm dry, 3 percent O_2)	(51)	--[b]
Continuous monitor		
SO_2, ppm dry, as measured	642	--[c]
O_2, percent dry	4.4	--[c]

[a]Tests performed on February 23, 1984
[b]Cannot be calculated, since flue gas O_2 not known
[c]Monitors inoperative

TABLE 3-6. PARTICLE SIZE DISTRIBUTION RESULTS[a]

	Run 1		Run 2	
Impactor stage	D_{50} (μm)	Cumulative weight percent less than D_{50}	D_{50} (μm)	Cumulative weight percent less than D_{50}
Cyclone	13.04	100	12.52	92.35
1	7.52	100	7.55	89.63
2	7.11	98.45	7.15	85.96
3	4.35	94.03	4.37	83.05
4	3.03	91.94	3.04	79.51
5	1.57	90.23	1.58	74.51
6	0.78	85.65	0.79	68.82
7	0.48	79.60	0.49	64.01
Filter	0.22	72.54	0.22	57.12

[a]Tests performed on February 22, 1984.

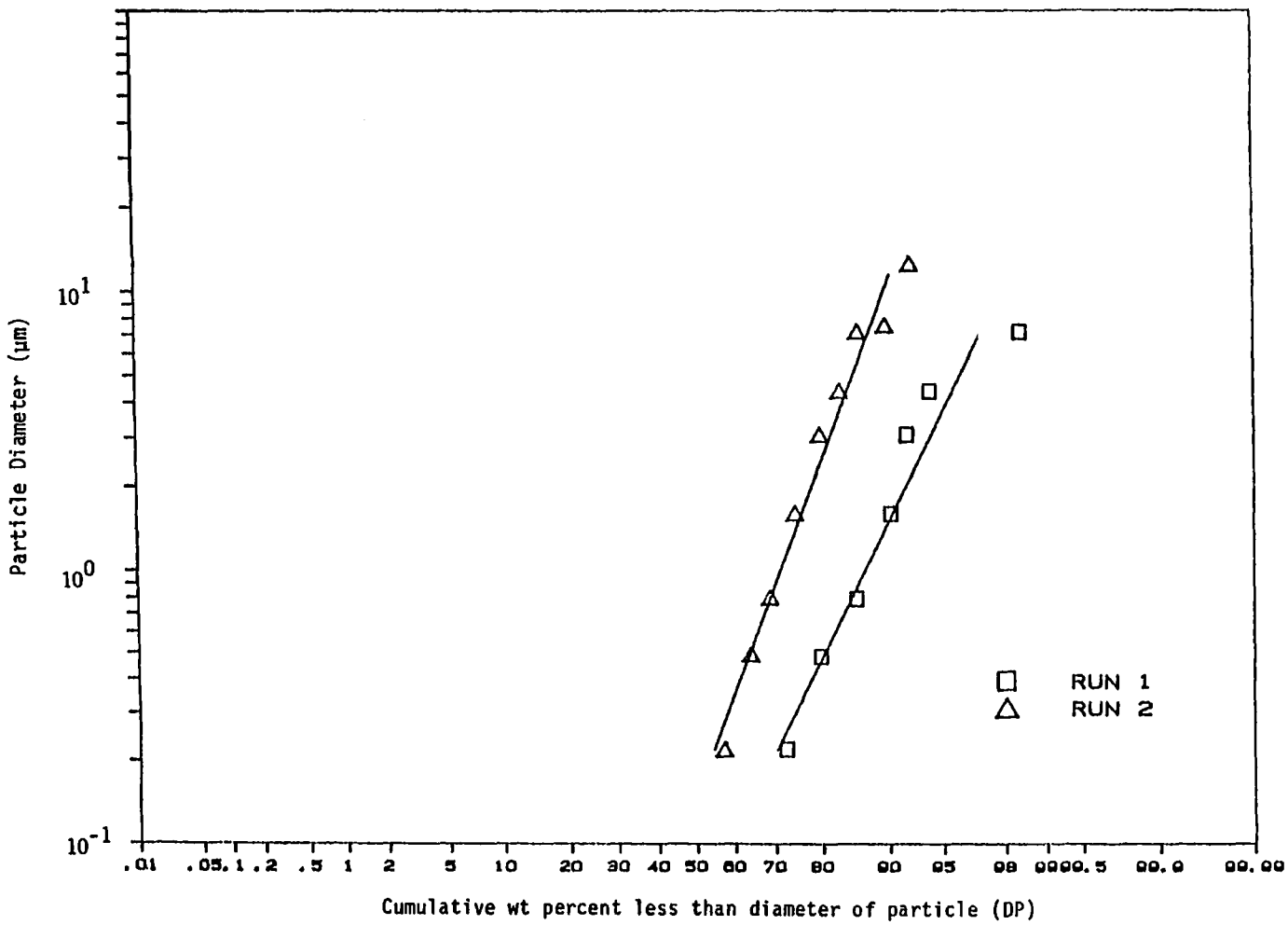


Figure 3-2. Particle size distribution.

Table 3-7 summarizes the particulate loadings obtained using the Andersen impactors, the SASS train, and EPA Method 5. Interestingly, the Andersen results compare quite well with the SASS measurement. However, both are significantly less than the EPA Method 5 solid (front half) result. The solid particulate collection temperature for each method is also noted in Table 3-7 (stack temperature for the in-stack Andersen impactors and filter oven temperature for SASS and Method 5). The relatively good agreement between SASS and Andersen particulate load is consistent with the similar high temperatures at which solid particulate is collected in these methods. The high Method 5 solid particulate results suggests that significant quantities of material condense in the temperature range from 120° to 230°C (250° to 450°F), the difference between the Method 5 oven temperature and the stack and SASS oven temperatures.

3.3 TRACE ELEMENT ANALYSIS RESULTS

The Kern County crude oil fuel samples and the SASS train samples from the steamer flue gas were analyzed for 73 trace elements using the spark source mass spectrometry (SSMS), supplemented by atomic absorption spectrometry (AAS). (Selective ion electrode, x-ray fluorescence spectrometry, and wet chemical methods were employed for selected elements in some samples.) Once the trace element concentrations were determined, trace element flowrates for fuel oil and flue gas vapor and condensed phases could be computed. Trace element concentrations and flowrates are presented in Appendix B.

Table 3-8 summarizes the calculated trace element flowrates corresponding to the fuel oil and flue gas samples. A mass balance closure measure based on the

Table 3-7. SUMMARY OF PARTICULATE LOADING MEASUREMENTS

Method	Particulate load, mg/dscm	Collection temperature, °C (°F)
Andersen Impactor		
Run 1: Solid Particulate	30.8	290 (550)[a]
Run 2: Solid Particulate	38.2	280 (530)[a]
SASS		
Solid Particulate	26	230 (450)[b]
Method 5		
Run 1: Solid Particulate	64	120 (250)[b]
Condensible Particulate	85	
Total	149	
Run 2: Solid Particulate	128	120 (250)[b]
Condensible Particulate	14	
Total	142	

[a]Stack temperature (in-stack impactor train)
[b]Filter oven nominal temperature

TABLE 3-8. TRACE ELEMENT FLOWRATES

Element[a]	Fuel oil Concentration[b] (μg/g)	Fuel oil Flowrate (μg/s)	Flue gas Concentration (μg/dscm)	Flue gas Flowrate (μg/s)	Mass balance closure flue gas flowrate/ fuel oil flowrate (percent)
Aluminum	5.0	1900	79	370	19
Antimony	--[c]	--	0.69	3.2	
Arsenic	0.006	2.3	2.0	9.1	390
Barium	0.55	210	6.9	32	15
Beryllium	<0.01	<3.9	0.0091	0.042	>11
Bismuth	--	--	0.0046	0.021	
Boron	0.14	54	3.3	15	28
Bromine	0.13	50	4.8	22	44
Cadmium	--	--	<0.49	<2.2	
Calcium	9.0	3500	6.2	290	8.2
Cerium	--	--	0.27	1.3	
Cesium	--	--	0.11	0.49	
Chlorine	23	8900	720	3300	37
Chromium	0.40	160	73	340	220
Cobalt	0.40	160	1.4	6.2	3.9
Copper	0.70	270	1700	8100	3000
Dysprosium	--	--	0.091	0.42	
Europium	--	--	0.0091	0.042	
Fluorine	16	6200	17	77	1.3
Gadolinium	--	--	0.091	0.42	
Gallium	0.20	78	1.2	5.4	7.9
Germanium	<0.02	<7.8	2.2	10.3	>130
Holmium	--	--	<4.9	<23	
Iodine	0.50	190	1.8	8.1	4.2
Iron	7.5	2900	310	1400	49
Lanthanum	--	--	0.36	1.7	
Lead	0.55	210	2.4	11	5.2
Lithium	0.35	140	2.1	9.6	7.0
Lutecium	--	--	0.0091	0.042	
Magnesium	6.5	2500	41	190	7.5
Manganese	0.35	140	5.6	26	19
Mercury	<0.4	<160	0.77	3.5	>2.3
Molybdenum	1.2	470	24	110	24
Neodymium	--	--	0.27	1.3	
Nickel	13	5000	610	2600	56

(continued)

[a]Erbium, gold, hafnium, iridium, osmium, palladium, rhenium, rhodium, and ruthenium were also analyzed for but not found above the detection limit in any sample.
[b]Average of duplicate analyses.
[c]Dashes indicate element not found above detection limit. See Appendix B for detection limits.

TABLE 3-8. (continued)

Element[a]	Fuel oil Concentration[b] (μg/g)	Fuel oil Flowrate (μg/s)	Flue gas Concentration (μg/dscm)	Flue gas Flowrate (μg/s)	Mass balance closure flue gas flowrate/ fuel oil flowrate (percent)
Niobium	0.06	23	<0.89	2.1	<18
Phosphorus	3.0	1200	34	160	13
Platinum	1.0	390	1.7	8.0	2.1
Potassium	4.0	1600	90	420	27
Praesodymium	--	--	0.33	1.5	
Rubidium	0.02	7.8	0.26	1.2	15
Samarium	--	--	0.091	0.42	
Scandium	0.06	23	12	56	240
Selenium	0.45	170	12	56	32
Silicon	14	5400	83	380	7.0
Silver	--	--	2.2	10.2	
Sodium	120	46,000	120,000	560,000	1200
Strontium	0.20	78	3.3	15	19
Tantalum	--	--	0.046	0.21	
Tellurium	--	--	2.1	9.7	
Terbium	--	--	0.018	0.084	
Thallium	--	--	0.0091	0.042	
Thorium	--	--	0.18	0.84	
Thulium	--	--	0.0091	0.042	
Tin	--	--	0.091	0.42	
Titanium	0.35	140	24	110	81
Tungsten	--	--	0.0091	0.042	
Uranium	--	--	150	670	
Vanadium	0.40	160	23	100	67
Ytterbium	--	--	0.023	0.105	
Yttrium	0.050	19	0.77	3.6	18
Zinc	2.0	780	740	3400	440
Zirconium	0.13	50	1.2	5.6	11

[a]Erbium, gold, hafnium, tridium, osmium, palladium, rhenium, rhodium, and rutherium were also analyzed for but not found above the detection limit in any sample.
[b]Average of duplicate analyses.
[c]Dashes indicate element not found above detection limit. See Appendix B for detection limits.

ratio of flue gas output to fuel input flowrates for each element is also presented. Laboratory analysis results for fuel oil are based on the average of results obtained for two separate oil samples collected during the SASS test.

Trace elements found in the fuel oil at levels greater than 10 µg/g (corresponding to flowrates greater than about 4 mg/s) were chlorine, fluorine, nickel, silicon, and sodium. Sodium was measured at the highest level. The source of this sodium is most likely the salt water brine in the produced crude. The residual moisture content of the fuel was 0.57 percent by proximate analysis.

Trace elements emitted at levels exceeding 100 µg/dscm (corresponding to flowrates greater than about 0.45 mg/s) in the exhaust were chlorine condensed chlorides. copper, iron, nickel, sodium, and zinc. Copper and sodium were present in the flue gas at much higher levels than could be accounted for by the fuel oil. Additional sodium may have been introduced through suspended salts in the combustion air. Reasonably good mass balance closure for several metals was obtained, including iron, nickel, titanium, and vanadium. However, in general, mass balance closure was poor, with less element in the flue gas than introduced with the fuel.

3.4 ORGANIC EMISSION RESULTS

Total organics and organic species emissions were measured using two methods (see Appendix A for complete method description). The volatile organic priority pollutant compounds (those having boiling points generally less than 110°C (230°F) were analyzed by thermal desorption, purge and trap, gas chromatography mass spectrometry (GC/MS) of VOST traps in accordance with

the EPA VOST protocol (Reference 3-1). The volatile organic compounds sought in the analysis are listed in Table 3-9.

Organic analyses of SASS train samples were performed according to an extended EPA Level 1 protocol (Reference 3-2). The SASS train particulate (filter), organic module sorbent (XAD-2), and organic module condensate (OMC) samples were extracted with methylene chloride in a Soxhlet apparatus. The extracts (the XAD-2 and OMC extracts were combined) were then subjected to total chromatographable organic (TCO) and gravimetric (GRAV) analyses to determine the total concentration of organics within the 100° to 300°C (212° to 572°F) and greater than 300°C (572°F) boiling point ranges, respectively. Infrared (IR) spectra of the GRAV residue of the extracts were also obtained.

In addition, the SASS train organic sorbent module extract was analyzed for the semivolatile organic priority pollutant compounds (a category which contains several polynuclear aromatic hydrocarbon (PAH) species) by GC/MS in accordance with EPA Method 625. (Reference 3-4). Semivolatile organic compounds sought by GC/MS are listed in Table 3-10. A discussion of the analytical results follows.

3.4.1 Volatile Organic Emissions

Table 3-11 summarizes volatile organic species emissions detected in the VOST measurement (three trap pairs were sampled and analyzed, denoted "run" in table). Only three compounds were detected: benzene, toluene, and ethylbenzene. Flue gas concentrations were 60 µg/dscm (18 ppb) for benzene and less than 4 µg/dscm (1 ppb) for toluene and ethylbenzene, on the average.

TABLE 3-9. VOLATILE ORGANIC COMPOUNDS SOUGHT IN GC/MS ANALYSIS

Halogenated Aliphatics	Ethers
Chloromethane	Ethylene oxide
Dichloromethane	Propylene oxide
Chloroform	
Tetrachloromethane	**Chlorinated Ethers**
Chloroethane	
1,1-dichloroethane	2-chloroethyl vinyl ether
1,2-dichloroethane	
1,1,1-trichloroethane	**Aldehydes**
1,1,2-trichloroethane	
1,1,2,2-tetrachloroethane	Acrolein
1,2-dichloropropane	
Vinyl chloride	**Amines and Nitriles**
1,1-dichloroethylene	
1,2-dichloroethylene	Acrylonitrile
Trichloroethylene	
Tetrachloroethylene	**Aromatic Hydrocarbons**
Alkyl chloride	
1,3-dichloropropene	Benzene
Bromomethane	Toluene
Bromodichloromethane	Ethyl benzene
Dibromochloromethane	Xylenes
Bromoform	
Trichlorofluoromethane	**Chlorinated Aromatics**
	Chlorobenzene

TABLE 3-10. COMPOUNDS SOUGHT IN THE EPA METHOD 625 GC/MS ANALYSIS AND THEIR DETECTION LIMITS[a]

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)carbazole	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
Acenaphthylene	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

[a]In nanograms per microliter injected

TABLE 3-11. VOLATILE ORGANIC SPECIES EMISSIONS

	Stack Gas Concentration				
Compound	Run 1 (μg/dscm)	Run 2 (μg/dscm)	Run 3 (μg/dscm)	Average (μg/dscm)	(ppb)
Benzene	128	42	9	60	18
Toluene	6.3	1.1	2.3	3.2	0.83
Ethylbenzene	3.2	<1	<1	1.7	0.39

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

Table 3-12 summarizes organic emissions results based on the TCO, GRAV, and GC/MS analyses for semivolatile organics. Total organic emissions were relatively low, about 300 µg/dscm, and roughly equally split among the semivolatile (TCO) and nonvolatile (GRAV) boiling point ranges. The levels noted reflect the sorbent module extract analysis; the particulate (filter) extract contained negligible organic content. The emissions noted are of the same order of magnitude as emissions measured from recent tests of a steamer equipped with another low-NO_x burner design (the MHI burner, Reference 3-5). Semivolatile priority pollutants detected were naphthalene, phenol, and dimethylphthalate, all at concentrations well below 10 µg/dscm. The dimethylphthalate noted is most likely a sample contaminant.

Table 3-13 summarizes results of the IR spectroscopy analysis of the SASS train extracts. The organic sorbent module extract spectrum suggests the presence of aliphatic hydrocarbons and oxygenated hydrocarbons such as aldehydes and/or ketones. As noted in the table, the filter extract spectrum showed no peaks. A weak spectrum for the blank suggests the presence of small quantities of aliphatic hydrocarbons.

3.5 EXTENDED CONTINUOUS EMISSIONS MONITORING

Continuous monitoring of stack gas O_2, CO_2, CO, NO_x, and SO_2 was performed for a period extending from January 21 to February 24, 1984. Figures 3-3 through 3-5 illustrate the emission trends over this test period. The points plotted represent hourly averages of data taken at 5- to 15-minute intervals. Test periods where data gaps appear correspond to shutdown of the steamer. The first shutdown occurred during the period of February 12 to February 15. This was caused by concerns from the site personnel relating to

TABLE 3-12. TOTAL ORGANIC AND SEMIVOLATILE ORGANIC PRIORITY POLLUTANT EMISSIONS

	Emission level[a] (μg/dscm)	(pg/J)
Total semivolatile organics (C_7 to C_{16}) by TCO	170	50
Total nonvolatile organics (C_{16+}) by gravimetry	130	35
Total organics	300	85
Semivolatile organic priority pollutants[b]:		
Naphthalene	1.4	0.40
Phenol	0.7	0.20
Dimethylphthalate	3.6	1.0
Other priority pollutants	<0.4	<0.1

[a]Blank corrected. Levels noted correspond to the sorbent module extract analysis; the filter particulate extract contained negligible organic content.
[b]Average of duplicate analyses

TABLE 3-13. IR SPECTRA SUMMARY

Sample	Wave number (cm^{-1})	Intensity[a]	Assignment	Possible compound categories present
XAD-2 extract	2930	M	CH alkyl	Aliphatic hydrocarbons, oxygenated hydrocarbons such as aldehydes and/or ketones
	1732	S	C=O stretch	
	1438	W	C-H bend	
	1255	W	C-O stretch	
	1165	W	C-O stretch	
	1125	W	C-O stretch	
Filter		No peaks		
XAD-2 blank[b]	2928	S	C-H aliphatic	Small amounts of aliphatic hydrocarbons

[a]S = strong; M = medium; W = weak
[b]Very weak spectrum

accelerated tube corrosion. These concerns turned out to be unfounded upon inspection. The second shutdown, starting on February 16 and lasting to February 21, was caused by electrical problems. Steady operation of the steamer was not again reached until February 21.

The O_2 and CO_2 traces shown in Figure 3-3 indicate quite steady operation of the steamer over the entire test period. Flue gas O_2 levels were maintained at about 3 percent. Only during the final day (February 24) did the flue gas O_2 increase to over 4 percent, with a corresponding drop in CO_2 concentration. It is not known whether this increase in O_2 was caused by higher secondary or primary air flow. NO_x emissions, shown in Figure 3-4, indicate levels generally below 80 ppm, corrected to 3 percent O_2. Average NO_x emissions for the entire test period were about 70 ppm at 3 percent O_2. O measurements, available only to February 11 due to subsequent instrument malfunction, indicate levels generally below 30 ppm at 3 percent O_2. SO_2 emissions, shown in Figure 3-5, indicate emissions in the range of about 500 to 750 ppm at 3 percent O_2. An increase in SO_2 emissions seems evident, starting at about the half-way point of the extended test period. This increase might be attributable to increased sulfur levels in the crude oil, although fuel oil samples were not collected during this time period to verify this.

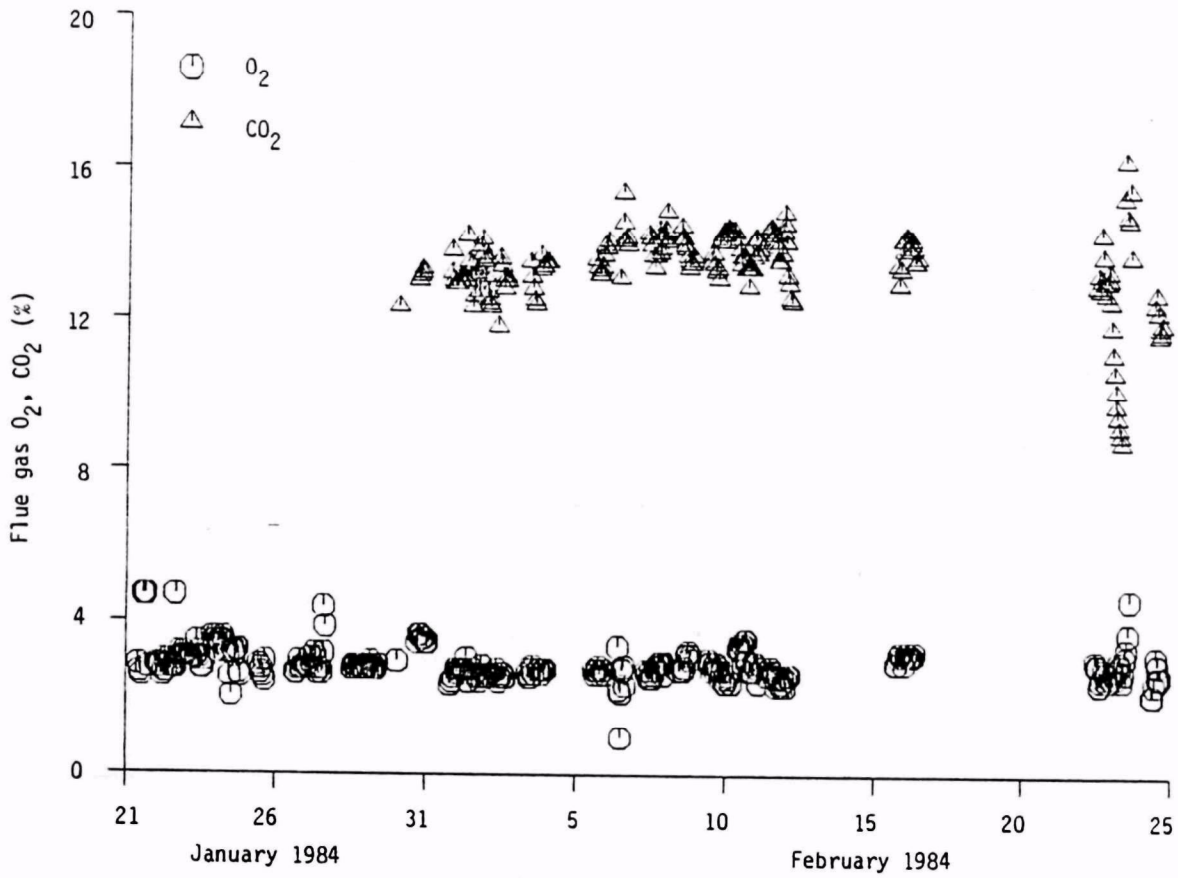


Figure 3-3. Flue gas O_2 and CO_2 for the extended test period.

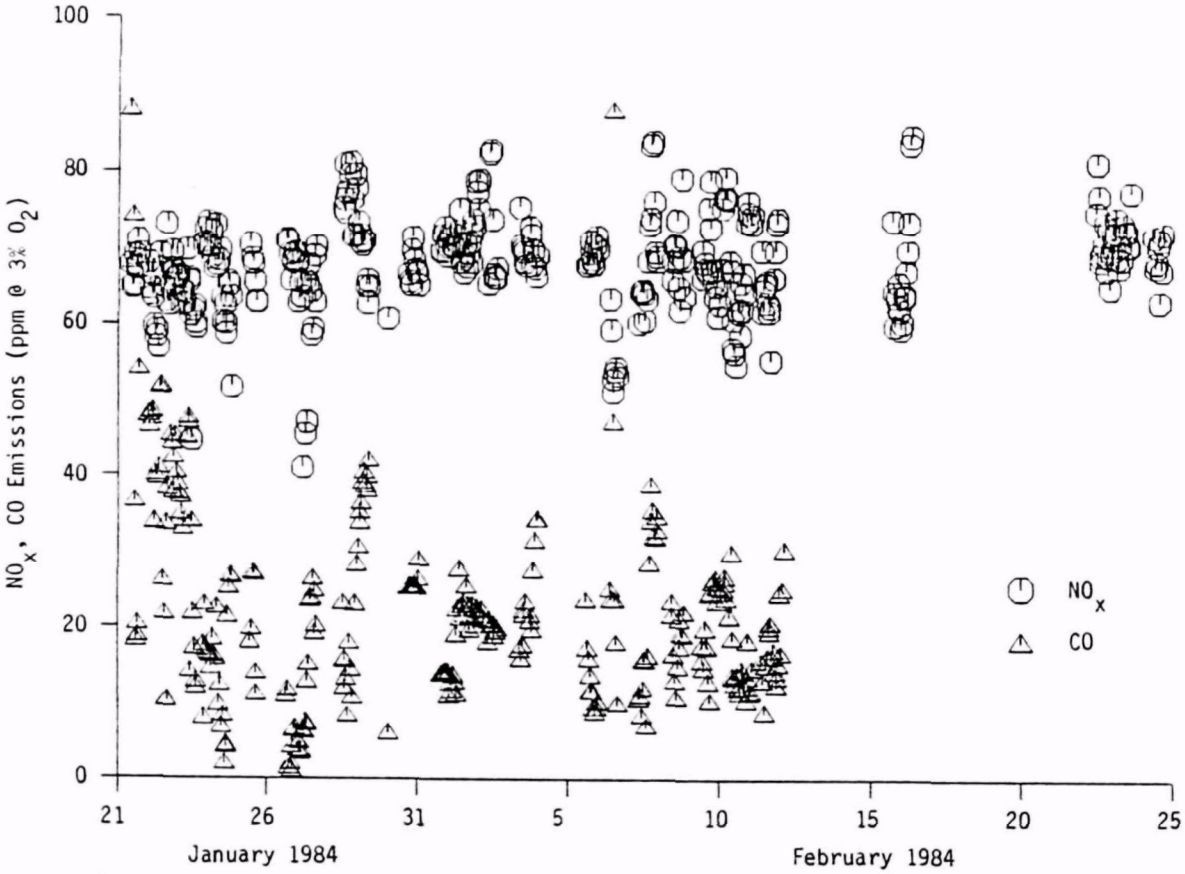


Figure 3-4. Flue gas NO_x and CO for the extended test period.

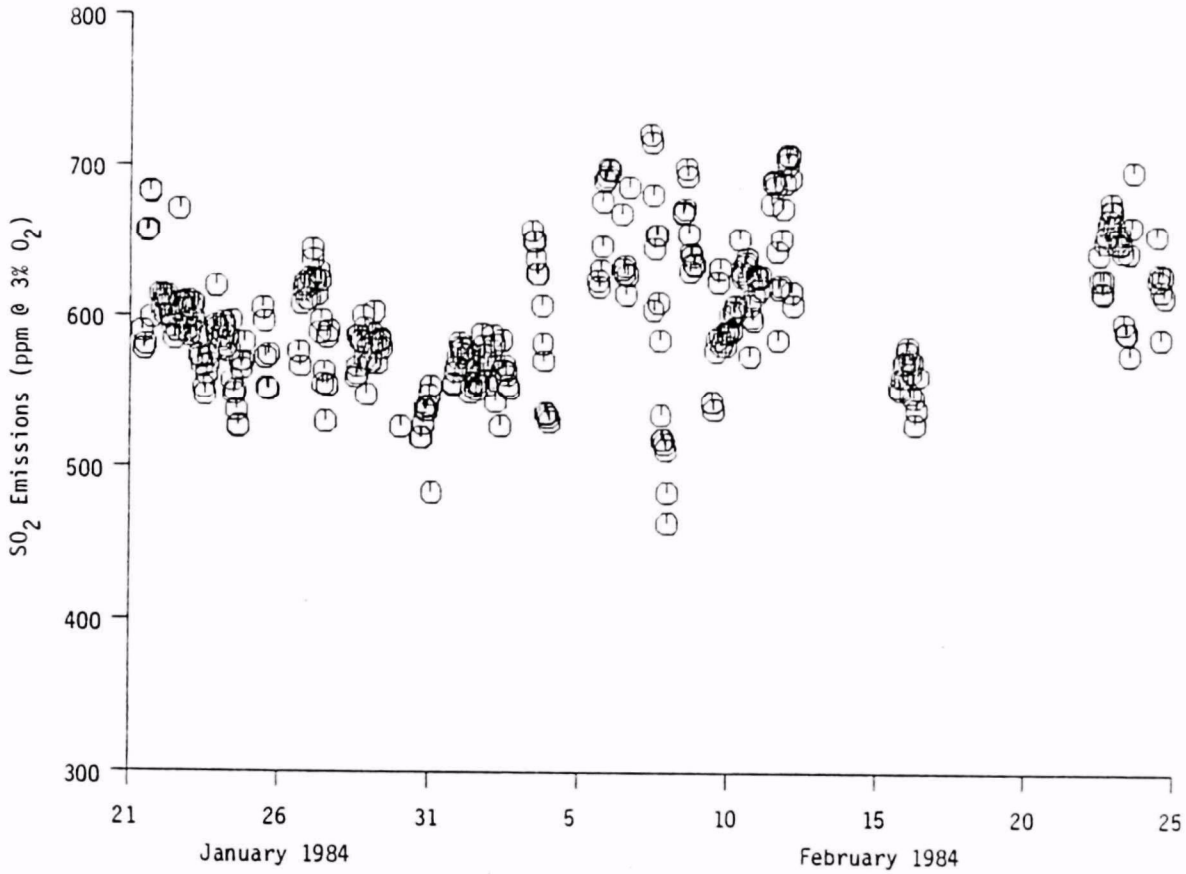


Figure 3-5. Flue gas SO_2 for the extended test period.

REFERENCES FOR SECTION 3

3-1. "Protocol for the Collection and Analysis of Volatile POHC's Using VOST," EPA-600/8-84-007, NTIS PB84-170042, March 1984.

3-2. Lentzen, D.E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB 293795, October 1978.

3-3. Waterland, L. R., et al., "Environmental Assessment of Industrial Boilers Firing Coal-Liquid Mixtures and Wood," in Proceedings of the 1982 Joint Symposium on Stationary Combustion NO_x Control, Volume II, EPA 600/9-85-022b, NTIS PB 85-235612, July 1985.

3-4. 44 CFR 69532, December 3, 1979.

3-5. Castaldini, C., et al., "Environmental Assessment of an Enhanced Oil Recovery Steam Generator Equipped with a Low-NO_x Burner," EPA 600/7-86-003 a/b, February 1986.

SECTION 4

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 the NO_x monitor readings
- Duplicate SSMS analysis of the fuel sample and duplicate GC/MS analysis of SASS extract sample for determination of analytical precision
- Duplicate Method 5/8 and controlled condensation system (CCS) measurements of steamer flue gas particulate, SO_2, and SO_3 concentrations under relatively constant operation
- Analysis of blind spiked XAD-2 resin blank for TCO, GRAV, and GC/MS analytical precision
- Use of EPA/EMSL audit sample in the laboratory analysis of Method 7, Method 8, and controlled condensation system samples for determination of analytical accuracy.

The following paragraphs discuss the results of these QA activities.

4.1 NO_x MONITOR CERTIFICATION TEST RESULTS

The EPA Method 7 test protocol was used three times during the extended continuous monitoring period to certify the accuracy of the NO_x analyzer. Tables 4-1, 4-2, and 4-3 show the results of the certification tests

TABLE 4-1. METHOD 7 CERTIFICATION RESULTS: JANUARY 24, 1984

Test no.	NO_x reference method results (ppm)				Average analyzer reading (ppm)	Difference (ppm)
	Sample 1	Sample 2	Sample 3	Sample average		
1	68	80	65	71	65	6
2	--[a]	--[a]	--[a]	--	--	--
3	69	59	--[b]	64	62	2
4	77	43	55	58	59	(1)
5	45	83	34	53	58	(5)
6	56	93	47	65	65	0
7	53	192	32	92	64	28
8	30	63	53	49	64	(15)
9	46	28	40	38	48	(10)
Mean reference method test value				61		
Mean of differences						0.62

95 percent confidence interval of the differences = 10.8

Relative accuracy =

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

= 19 percent

[a]Suspected sample contamination during analysis
[b]Sample lost during recovery

TABLE 4-2. METHOD 7 CERTIFICATION RESULTS: FEBRUARY 8, 1984

Test no.	NO_x reference method results (ppm)				Average analyzer reading (ppm)	Difference (ppm)
	Sample 1	Sample 2	Sample 3	Sample average		
1	50	32	24	36	69	33
2	80	100	64	81	72	(9)
3	64	72	62	66	70	4
4	82	95	96	91	75	(16)
5	84	16	80	60	61	1
6	80	13	88	60	65	5
7	88	63	54	68	78	10
8	59	60	54	58	68	10
9	41	63	--[a]	52	63	11
Mean reference method test value				64		
Mean of differences						11

95 percent confidence interval of the differences = 7.2

Relative accuracy =

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

= 28 percent

[a]Sample lost during recovery

TABLE 4-3. METHOD 7 CERTIFICATION RESULTS: FEBRUARY 24, 1984

Test no.	NO_x reference method results (ppm)				Average analyzer reading (ppm)	Difference (ppm)
	Sample 1	Sample 2	Sample 3	Sample average		
1	65	55	53	58	68	10
2	70	72	99	81	73	(8)
3	75	33	63	57	67	10
Mean reference method test value				65		
Mean of differences						9.3

95 percent confidence interval of the differences = 2.9

Relative accuracy =

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

= 19 percent

conducted on January 24 and February 8 and 24, respectively. Tests performed on February 24 were abbreviated (only three sets of three flasks were taken during this certification test, as shown in Table 4-3). Results of the Method 7 NO_x monitor certification tests performed on January 24 and on February 24 indicated that the meter relative accuracy was within the performance specification of 20 percent. The relative accuracy as determined by the tests on February 8 (Table 4-2) was not. However, if results from the first set of samples are disregarded, the indicated relative accuracy of the NO_x meter is improved to 15 percent. NO_x readings indicating concentrations below 45 ppm can be considered suspect. Two of the three samples in the first set of Method 7 flasks in the February 8 tests show NO_x concentrations of 32 and 24 ppm. Sample leakage may have caused these low values.

4.2 DUPLICATE ANALYSES

4.2.1 Trace Element Analyses

Blind duplicate fuel samples were submitted for analysis for trace elements by SSMS, supplemented by atomic absorption analysis for mercury and sodium, x-ray fluorescence for sulfur, and specific ion electrode analysis for chlorine. Precision of the analysis was then determined based on the relative standard deviation of the replicate samples. Table 4-4 summarizes the results of these SSMS duplicate analyses. The average relative standard deviation for all the trace elements was 42 percent; the maximum relative standard deviation was 113 percent. Both are within the implied precision of Level 1 analyses of a factor of 2 or 3.

4.2.2 Organic Analyses

The organic sorbent module extract from the SASS test was analyzed in duplicate by GC/MS for the semivolatile organic priority pollutants. Results

TABLE 4-4. DUPLICATE SSMS ANALYSES OF TEST FUEL[a], ppm

Element	Sample 901440	Sample 901441	Relative standard deviation (percent)
Aluminum	9	1	113
Barium	0.8	0.3	64
Boron	0.2	0.08	61
Bromine	0.2	0.06	76
Calcium	13	5	63
Chlorine	25	21	12
Chromium	0.4	0.4	0
Cobalt	0.6	0.2	71
Copper	0.7	0.7	0
Fluorine	27	4	105
Gallium	0.2	0.2	0
Iodine	0.5	0.5	0
Iron	10	5	47
Lead	0.6	0.5	13
Lithium	0.5	0.2	61
Magnesium	8	5	33
Manganese	0.4	0.3	20
Molybdenum	2	0.3	105
Nickel	6	20	76
Niobium	0.09	0.03	71
Phosphorus	4	2	47
Potassium	5	3	35
Rubidium	0.02	0.02	0
Selenium	0.5	0.4	16
Silicon	19	9	51
Sodium	132	104	17
Strontium	0.2	0.2	0
Sulfur	11,700	11,600	0.61
Titanium	3	4	20
Vanadium	6	2	22
Yttrium	0.06	0.04	28
Zinc	2	2	0
Zirconium	0.2	0.06	76
Average relative standard deviation			42

[a]Only elements reported present at greater than the method detection limit are noted

of these analyses are summarized in Table 4-5. The average relative standard deviation for these duplicate analyses was 32 percent; the maximum relative standard deviation was 47 percent. Both are within the project precision goal of 50 percent for these measurements (Reference 4-1).

4.2.3 Particulate, SO_2, and SO_3 Emission Measurements

Two sequential combined Methods 5 and 8 tests were performed on February 1, 1984, with the steamer operating under relatively constant conditions. Both solid (front half) and condensible (back half) particulate emission levels were obtained, as well as SO_2 and SO_3 emissions from wet chemical analyses of appropriate impinger solutions. In addition, two sequential CCS tests were performed on February 23, 1984, again under relatively constant steamer operation, giving duplicate SO_2 and SO_3 emission measurements. Results of all these tests are summarized in Table 4-6.

The project precision goal for all these measurements is 20 percent (Reference 4-1). The precision suggested by Table 4-6 for total particulate, SO_2 by both methods, and SO_3 by CCS fall well within this goal. The precision of the Method 8 SO_3 measurement exceeds the goal; however, the apparent SO_3 levels were quite low.

The precision of each of the particulate emission fraction measurements (solid and condensible) exceeded the project goal, although the total particulate result had very good precision. Discussion in Section 3.2 suggests that changes in steamer operating conditions between the two Method 5 runs could have affected the split between solid and condensible particulate fractions. These changes could similarly have affected SO_3 emissions as well.

TABLE 4-5. RESULTS OF DUPLICATE GC/MS ANALYSES OF THE SASS ORGANIC SORBENT MODULE EXTRACT[a]

Compound	Analysis results, (μg/train) Run 1	Run 2	Relative standard deviation (percent)
Dibutylphthalate	50	50	0
Dimethylphthalate	100	60	35
Naphthalene	40	20	47
Phenol	20	10	47
Average relative standard deviation			32

[a]Only compounds reported present at greater than the method detection limit are noted

TABLE 4-6. RESULTS OF DUPLICATE PARTICULATE, SO_2, AND SO_3 MEASUREMENTS

Method	Parameter	Result (μg/dscm) Run 1	Run 2	Relative standard deviation (percent)
Method 5 (February 1, 1984)	Solid particulate	64	128	47
	Condensible particulate	85	14	101
	Total particulate	149	142	3.4
Method 8 (February 1, 1984)	SO_2	1676	1606	3.0
	SO_3	43.6	14.8	70
CCS (February 23, 1984)	SO_2	1599	1627	1.2
	SO_3	158	169	4.8

Finally, duplicate impinger solution aliquots were analyzed to give the back half (condensible) particulate result noted in Table 4-6. Results of these analyses are given in Table 4-7. As noted, analytical precision for these analyses was within 20 percent.

4.3 ANALYTICAL RECOVERY OF BLIND SPIKES

As part of quality assurance procedures, a sample of blank XAD-2 resin was spiked with a mixture of polynuclear aromatic hydrocarbons (naphthalene, phenanthrene, and pyrene), TCO compounds (dodecane, hexadecane and the naphthalene), and GRAV compounds (bis(2-ethylhexyl)phthalate, plus the phenanthrene and pyrene noted). This spiked resin was then extracted and analyzed as a separate sample to obtain recovery and analytical accuracy information. Table 4-8 summarizes these data. As shown in the table, the recovery and analytical accuracy for all components spiked was excellent. The maximum deviations were +28 percent and -35 percent, well within the project accuracy goal of -50, +100 percent for this analysis.

4.4 REFERENCE METHOD AUDIT SAMPLES

Audit samples supplied by EPA's Environmental Monitoring and Support Laboratory (EMSL) were analyzed along with the laboratory analysis of Method 7 and Method 8 samples collected in the field to establish the analytical accuracy of these analyses. Results of the audit sample analyses are summarized in Table 4-9. Excellent accuracy is evidenced.

TABLE 4-7. DUPLICATE METHOD 5 CONDENSIBLE PARTICULATE ANALYSIS RESULTS

Method 5 train	Analysis result (μg/train)		Relative standard deviation (percent)
	Test 1	Test 2	
1	13.70	13.42	1.5
2	26.31	20.92	16

TABLE 4-8. SPIKE XAD-2 RESIN ANALYSIS RESULTS

Analyte spiked	Spiked amount (mg)	Recovered amount (mg)	Percent recovery
TCO compounds			
(400 μg dodecane, 400 μg hexadecane, 400 μg naphthalene)	1.20	0.784	65
GRAV compounds			
(10 mg bis(2-ethylhexyl) phthalate, 400 μg pyrene, 400 μg phenanthrene)	10.8	11.0	102
Polynuclear aromatics			
Naphthalene	0.40	0.42	105
Phenanthrene	0.40	0.40	100
Pyrene	0.40	0.51	128

TABLE 4-9. EMSL AUDIT SAMPLE ANALYSIS RESULTS

Pollutant	Audit sample		Reported value (mg/dscm)	Known value[a] (mg/dscm)	Percent difference
	Lot no.	Sample no.			
SO_2	0881	2337	1294.9	1296.4	0.12
	0881	3333	200.7	190.7	5.2
NO_2	0481	5501	297.3	298.6	0.44

[a]As certified by EMSL

REFERENCE FOR SECTION 4

4-1. "Quality Assurance Plan for the Combustion Modification Environmental Assessment," Acurex Corporation under EPA Contract 68-02-2160, September 10, 1982.

SECTION 5

SUMMARY

Field tests were performed on a 16-MW (55 X 10^6 Btu/hr) thermally enhanced oil recovery (EOR) steamer equipped with the EPA low-NO_x burner. This burner was developed under EPA sponsorship to achieve NO_x emissions at or below 85 ppm at 3 percent O_2 with acceptable CO and smoke emissions when burning high-nitrogen fuel oils. These tests were performed in conjunction with the field demonstration tests by the Energy and Environmental Research Corporation (EERC), the burner developers. Two series of tests were performed: a comprehensive test program to characterize flue gas emissions from the steamer with burner operating conditions set to achieve the field demonstration goals of less than 85 ppm NO_x and low combustible emissions, and an extended flue gas monitoring program spanning about 30 days to measure the low-NO_x burner performance under typical steamer operation.

During the 1-day comprehensive tests, NO_x emissions averaged about 70 ppm at 3 percent O_2, with CO emissions below 30 ppm while burning Kern County crude oil with a nitrogen content of about 1 percent. SO_2 emissions measured by a continuous monitor averaged about 550 ppm, also at 3 percent O_2. Other SO_2 measurements with extractive sampling trains indicate relatively good agreement between the continuous monitor and these methods. Solid particulate emissions were measured at about 27 ng/J (96 mg/dscm). Condensible particulate emissions were at about 14 ng/J (50 mg/dscm). These

results correspond to the average of two separate measurements. Particle size distribution data indicate that about 90 percent of the particulate had a mean particle diameter less than 1 to 10 μm (two determinations). Trace element analyses performed on the fuel oil indicate sodium, silicon, nickel, fluorine, and chlorine are the major elements present at levels greater than 10 μg/g. In the flue gas, sodium, chlorine (condensed chlorides), copper, iron, nickel, and zinc contributed the highest emission levels, with emission concentrations greater than 100 μg/dscm.

Volatile organic analyses of flue gas samples indicated benzene, toluene, and ethylbenzene as the detected compounds, with emissions in the 2 to 60 μg/dscm (0.4 to 20 ppb) range. Semivolatile organic compounds detected were naphthalene and phenol in the 1 μg/dscm (0.3 ppb) range. Total organic emissions were relatively low, at 300 μg/dscm, and relatively evenly distributed between the semivolatile (boiling point of about 100° to 300°C) and nonvolatile (boiling point of greater than about 300°C) categories.

Extended continuous monitoring of flue gas criteria emissions spanned a period of 33 days. During this monitoring period, NO_x emissions were generally below 80 ppm, with an average of about 70 ppm at 3 percent O_2. CO emissions were also low, generally less than 30 ppm at 3 percent O_2.

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 source assessment sampling system (SASS) train for particulate mass, trace elements, and semivolatile and nonvolatile organics; the EPA Method 5 with modified impingers for SO_2 and SO_3 measurements by EPA Method 8; a volatile organic sampling train (VOST) for volatile organic species; a controlled condensation system (CCS) sampling train for SO_2 and sulfuric acid mist measurement; gas grab sampling equipment for determining N_2O emissions by subsequent laboratory gas chromatography and sampling equipment for validation of NO_x analyzer 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

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, and SO_2. The heated sample gas was treated for moisture removal using a permeation dryer. 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.

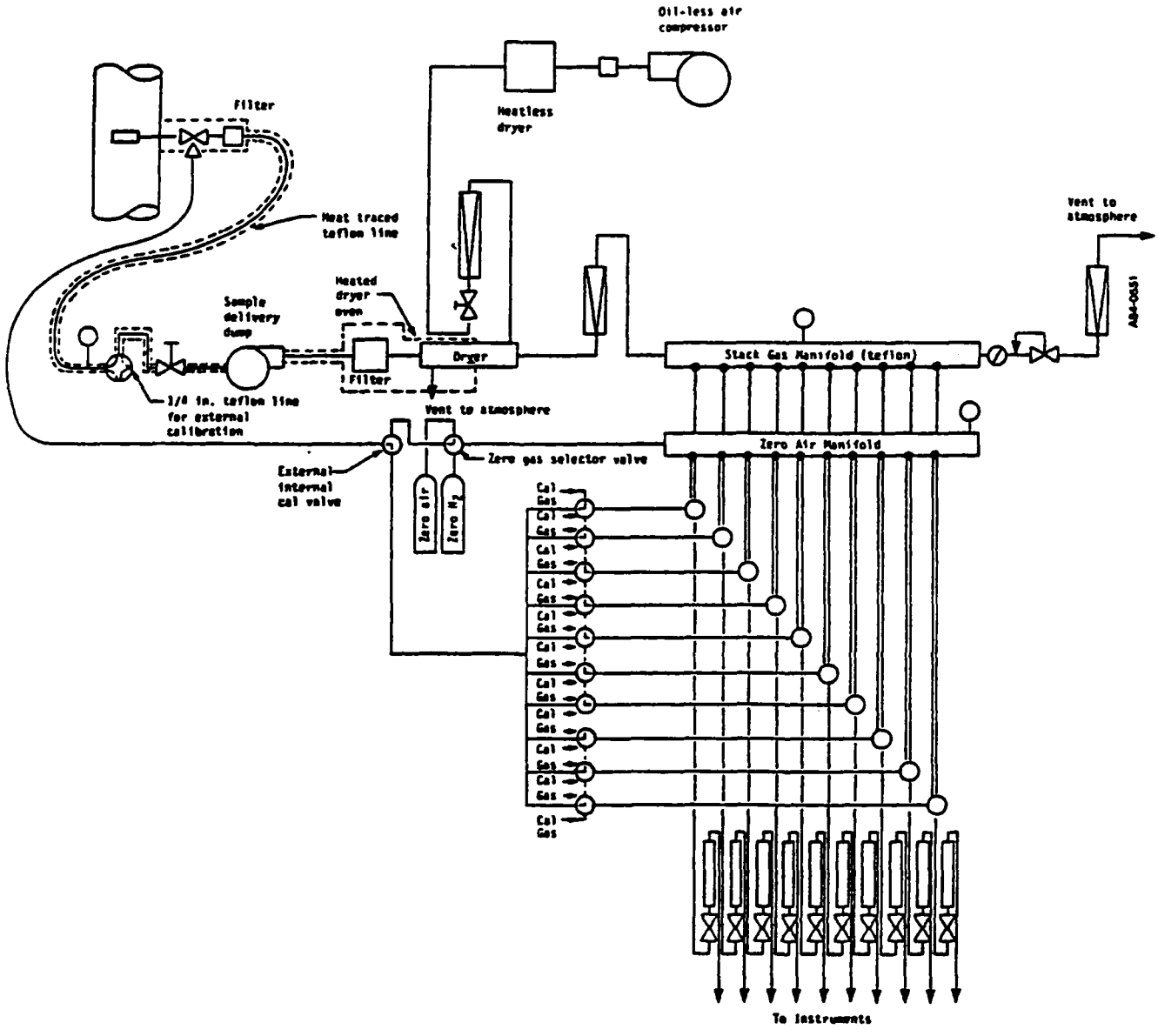


Figure A-1. Schematic for continuous extractive sampling system.

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

Instrument	Principle of operation	Manufacturer	Instrument model	Range
NO NO_x	Chemiluminescence	Thermo Electron	10 AR	0-2.5 ppm 0-10 ppm 0-25 ppm 0-100 ppm 0-250 ppm 0-1,000 ppm 0-2,500 ppm 0-10,000 ppm
CO (1)	Nondispersive infrared (NDIR)	ANARAD	500R	0-1,000 ppm
CO (2)	Nondispersive infrared (NDIR)	ANARAD	500R	0-10 percent (10,000 ppm)
CO_2	Nondispersive infrared (NDIR)	ANARAD	AR500	0-20 percent
SO_2	Pulsed Fluorescence	Thermo Electron	40	0-100 ppm 0-1,000 ppm 0-5,000 ppm 0-10,000 ppm
O_2	Fuel cell	Teledyne		0-5 percent 0-10 percent 0-25 percent
Datalogger	Electronic	[1]Acurex/Autodata	10	99 channels
Sample gas conditioner	Permeation dryer	Permapure	E-4G-SS	10 scfm
Strip chart recorders	Dual pen analog	Linear	400	0-10 mV 0-100 mV 0-1V 0-10V

A.2 TRACE ELEMENT AND SEMIVOLATILE AND NONVOLATILE ORGANIC EMISSIONS

Emissions of semivolatile and nonvolatile organics 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 for inorganic and organic emissions.

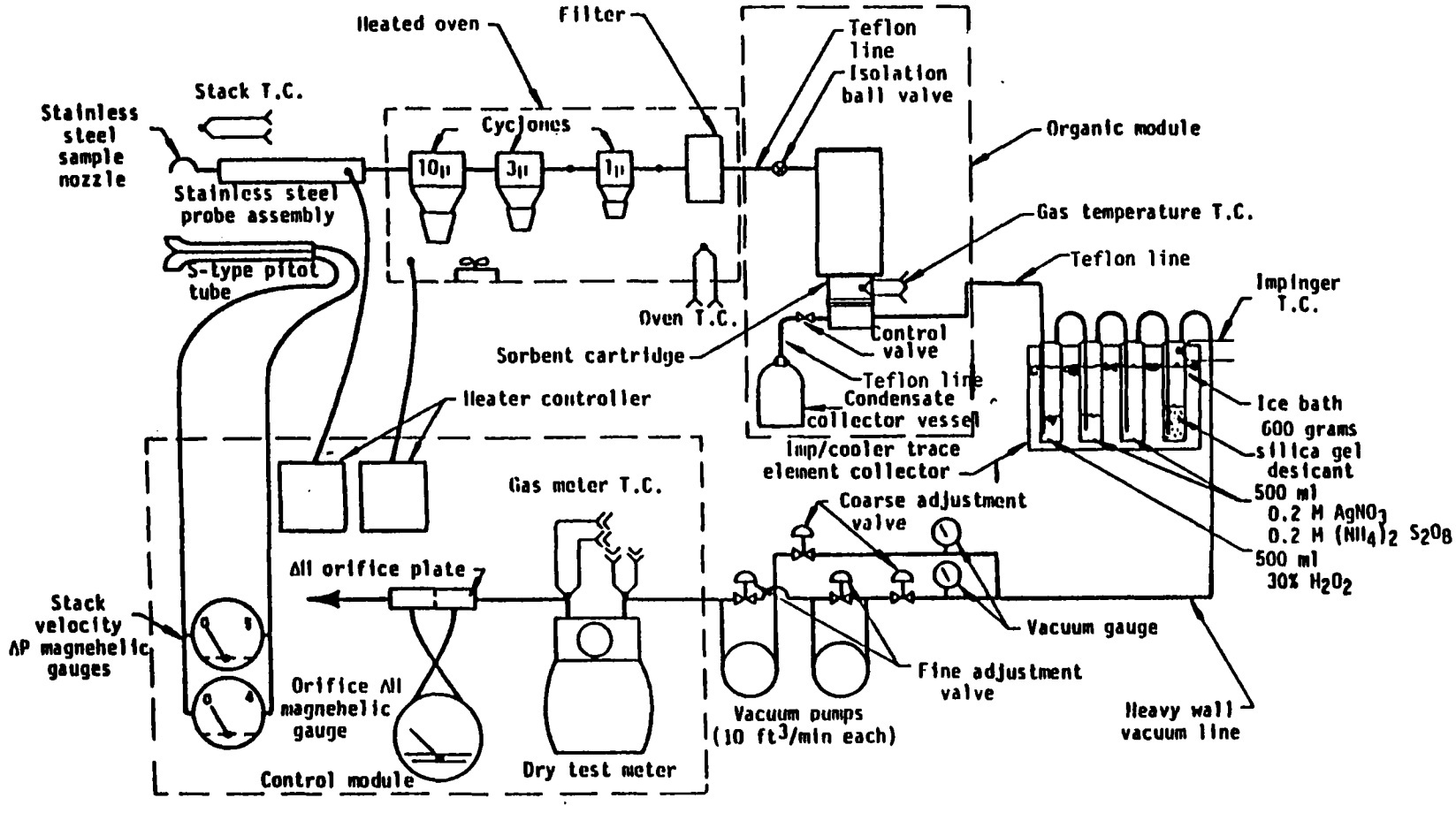
The SASS, illustrated in Figure A-2, is generally similar to the system utilized for total particulate mass emission tests (a high-volume Method 5 train), with the exception of:

- 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.

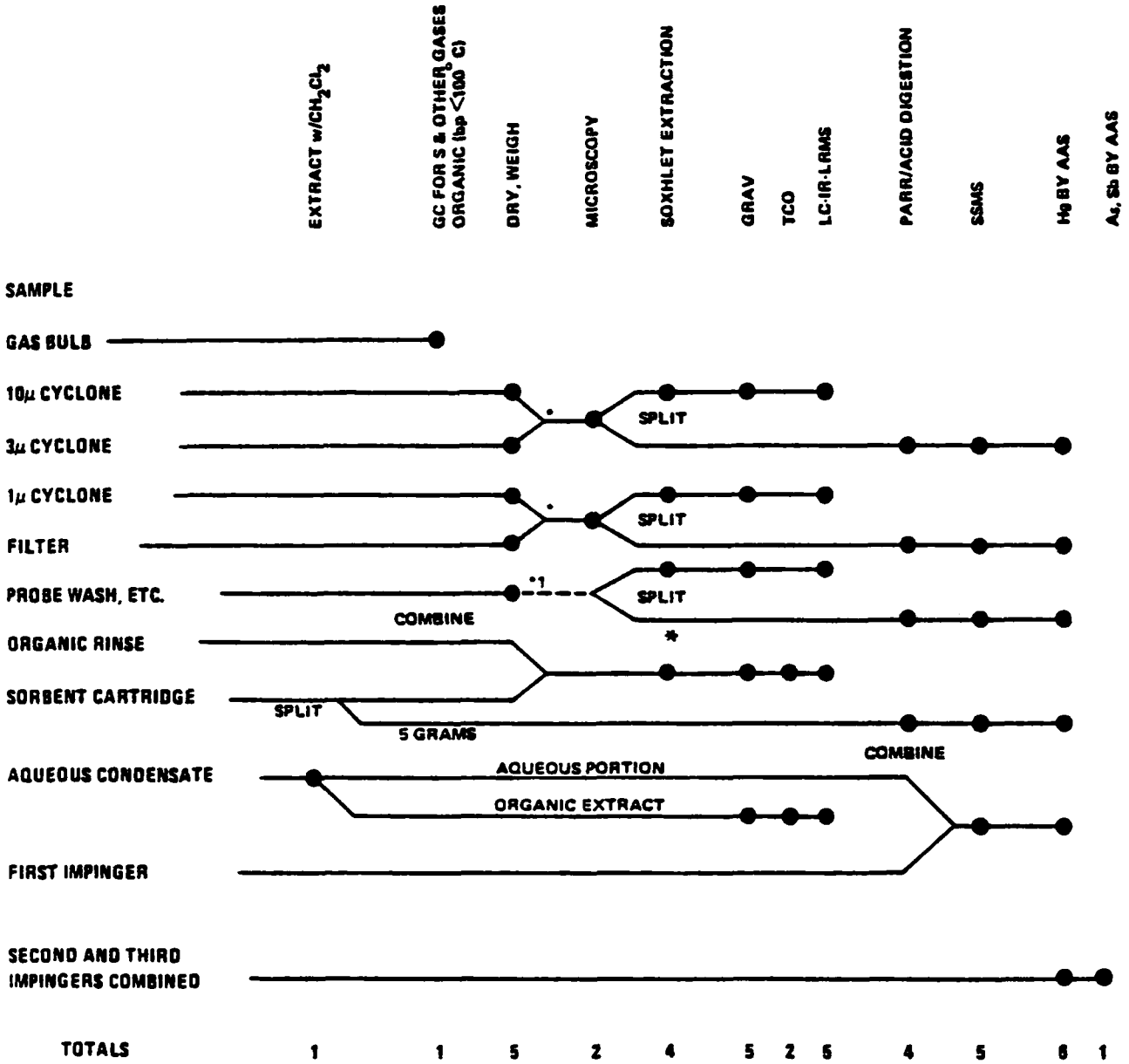
Schematics outlining the standard sampling and analytical procedures using the SASS equipment are presented in Figures A-3 and A-4. The following paragraphs briefly describe analytical procedures used in measuring trace elements and organic emissions.

Inorganic analyses of solid (particulate and organic sorbent) and liquid (impinger solution) samples from the SASS train were performed with 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) and for backup analyses for those elements identified as major components by SSMS. Additional backup techniques used to quantitate elements identified as major components by SSMS were specific ion



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.

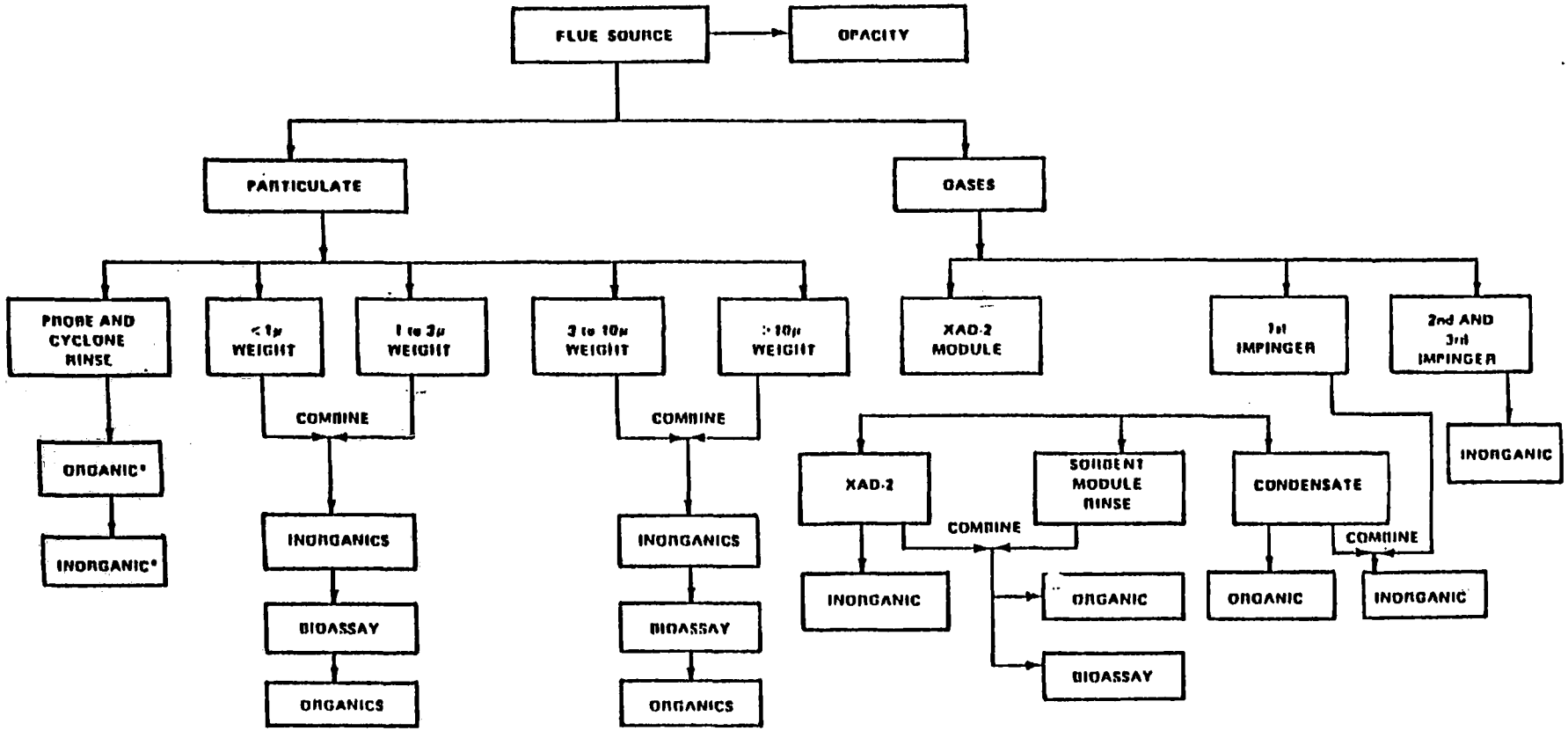


Figure A-4. Flue gas sample analysis protocol.

electrode methods for fluorine and chlorine, x-ray fluorescence for sulfur, and a wet chemical (colorimetric) method for phosphorous.

Quantitative information on total organic emissions was obtained by gas chromatography/flame ionization detector for total chromatographable organics (TCO), that fraction with boiling point between about 100° and 300°C, and by gravimetry (GRAV) of sample extracts for that fraction with boiling point greater than 300°C. Infrared spectroscopy (IR) was used for identification of organic functional groups in the GRAV residue of extract samples and gas chromatography/mass spectroscopy (GC/MS) was used to quantitate the semivolatile organic priority pollutant species in extract samples. This class contains several of the polynuclear aromatic hydrocarbon (PAH) compounds of interest from combustion sources. 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 VOLATILE ORGANIC EMISSIONS

A volatile organic sampling train (VOST), shown schematically in Figure A-6, was used to measure the low-molecular-weight volatile organic compounds (boiling points $\leq$110°C) in the flue gas according to the EPA protocol (Reference A-2). The train consists of two organic sorbent traps connected in series. The first trap contained ~1.6g of the porous polymer Tenax-GC; 35/60 mesh. The second trap consisted of ~1.0g each of Tenax-GC

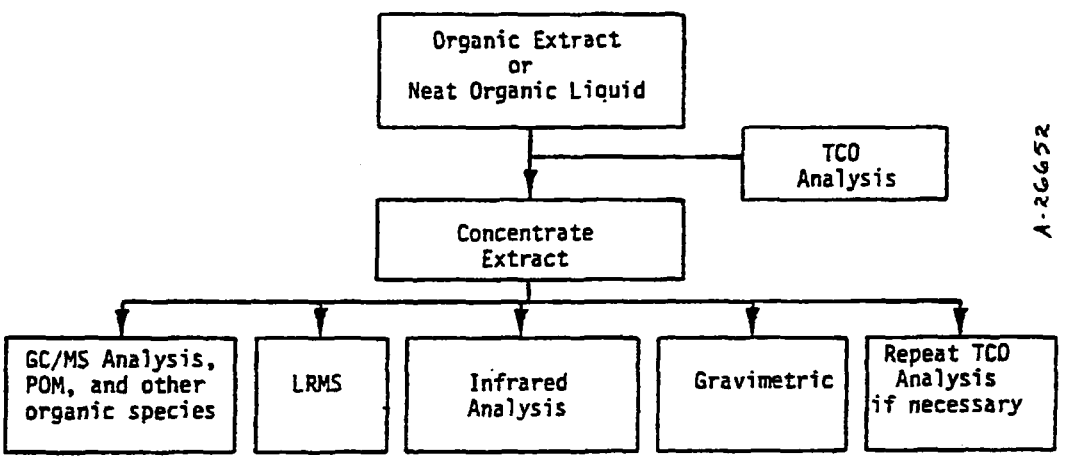


Figure A-5. Organic analysis methodology.

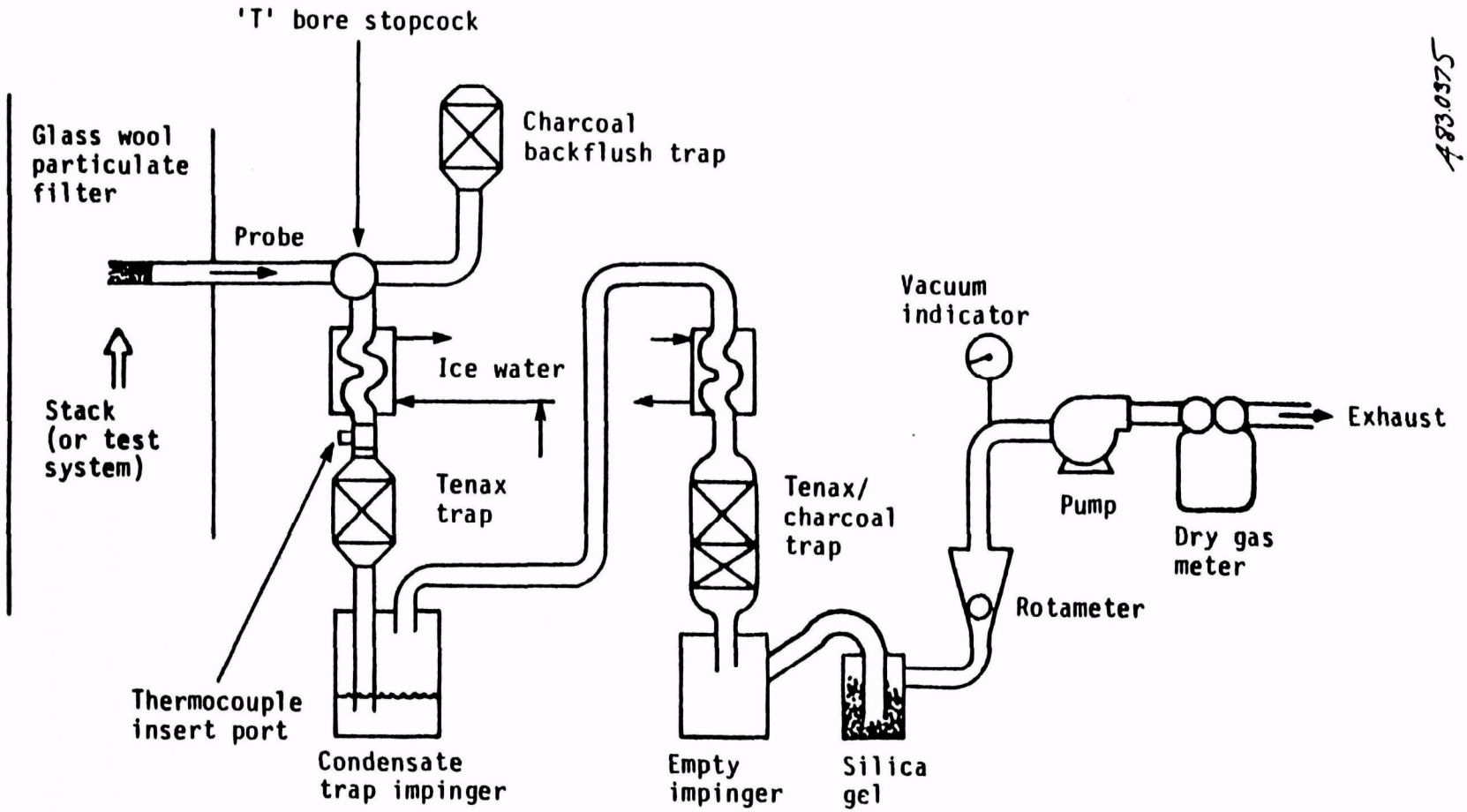


Figure A-6. Schematic of volatile organic sampling train (VOST).

and petroleum-based charcoal. Prior to their use in the field, each trap was conditioned to remove organic compounds. Conditioning consisted of baking each trap at 190°C with a N_2 purge for an 8-hr period. The traps were then desorbed at 190°C directly into a GC/FID. If a trap showed no contaminant peaks greater than 20 ng as benzene or toluene, it was considered ready for sampling. The trap was then sealed at each end with compression fittings, placed in clean, muffled culture tubes, and sealed in a metal can with a charcoal packet for shipping.

Before the field testing, the entire system was leak-checked at ~15 to 20 in. of vacuum. A leakage rate of 0.05 l/min was considered acceptable. Ambient air was drawn through a charcoal-filled tube to prevent organic contamination while bringing the system back to ambient pressure.

One set of samples (three trap pairs), a field blank, a trip blank, and a lab blank were obtained for the test program. The gas sample was obtained at the stack location. A total sample volume of 20 l was taken over a 40-min period (0.5 l/min) for each trap pair. Upon completion of the test, the sample traps were removed from the train, sealed, returned to their original culture tubes, and stored in a metal can on ice. The VOST samples were analyzed by thermal desorption, purge and trap GC/MS according to the EPA VOST protocol. Each pair of traps used was analyzed for the EPA Method 624 (volatile) priority pollutants (Reference A-3). Each trap in a trap pair was analyzed separately.

A.4 PARTICULATE TESTS

Particulate mass emission tests were performed using the EPA Method 5 with the impinger train modified according to EPA Method 8 for SO_2 and SO_3 measurements. The sampling train used is illustrated in Figure A-7. Solid

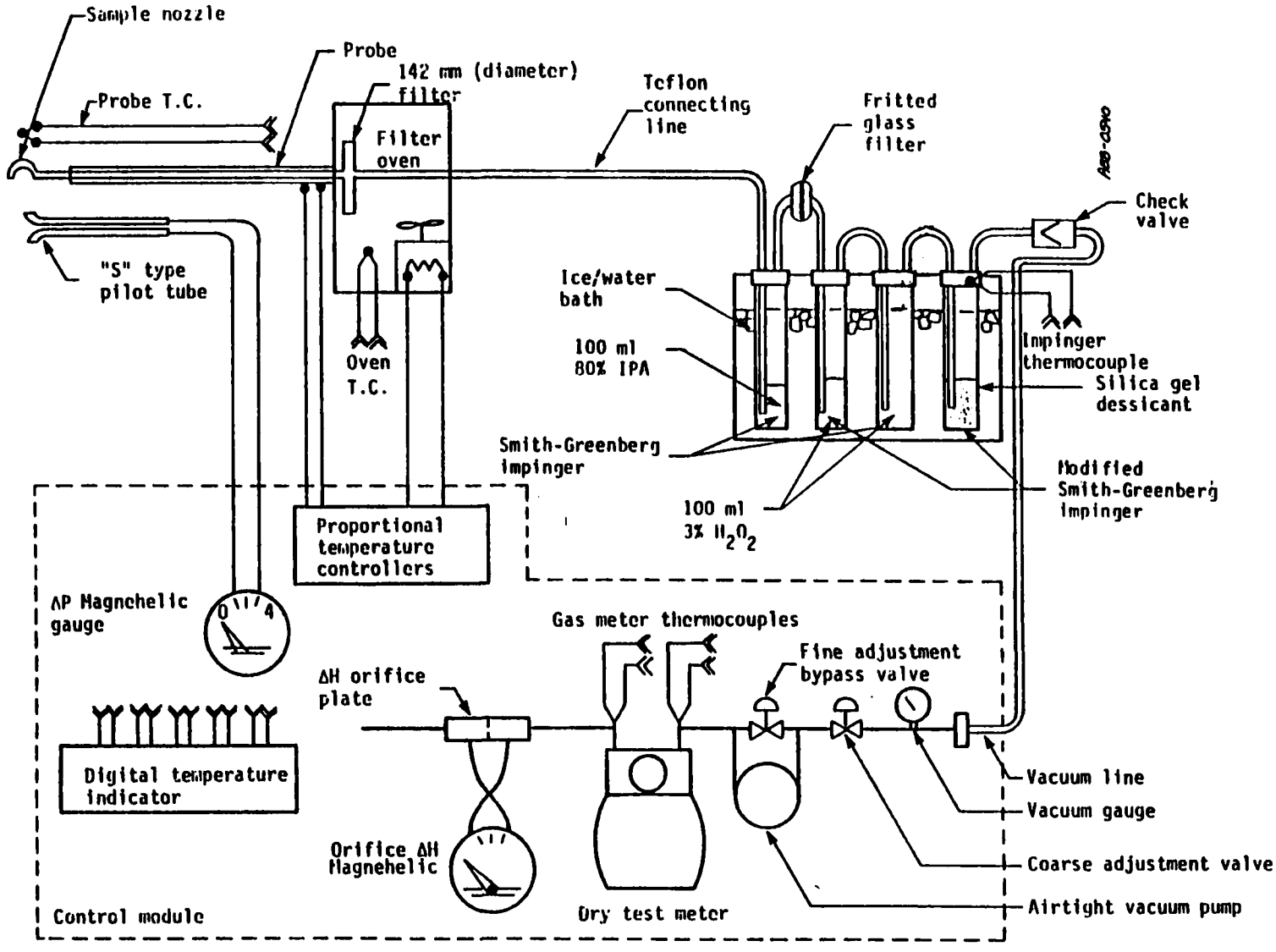


Figure A-7. Particulate and SO_x sampling train (EPA Method 5 and 8).

particulate matter collected in the probe, cyclone, and filter were determined by gravimetric analyses of these samples. Condensible particulate matter was obtained from gravimetric analysis of impinger liquids and impinger rinses. Sulfur oxide emissions were determined by bariun-thorin titration of appropriate impinger solutions per EPA Method 8 protocol.

A.5 SULFUR OXIDE EMISSIONS

Sulfur oxide emissions (SO_2 and SO_3) were also measured using the controlled condensation system illustrated in Figure A-8. This sampling system, designed primarily to measure vapor phase concentrations of SO_3 as H_2SO_4, consists of a heated Vycor probe, a Goksoyr/Ross condenser (condensation coil), impingers, a pump, and a dry gas test meter. By using the Goksoyr/Ross condenser, the gas is cooled to the dew point where SO_3 condenses as H_2SO_4. SO_2 interference is prevented by maintaining the temperature of the gas above the water dew point. Sulfur dioxide is collected in a 3 percent hydrogen peroxide solution. Both SO_2 and SO_3 (as H_2SO_4) are measured by titration with a 0.02 N NaOH, using bromophenol blue as the indicator. A more detailed discussion of the sampling and analytical techniques for the controlled condensation system is given in Reference A-4.

A.6 N_2O SAMPLING AND ANALYSIS

The stack gas grab samples were extracted into stainless-steel cylinders for laboratory analysis for N_2O using the sampling apparatus illustrated in Figure A-9. 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 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

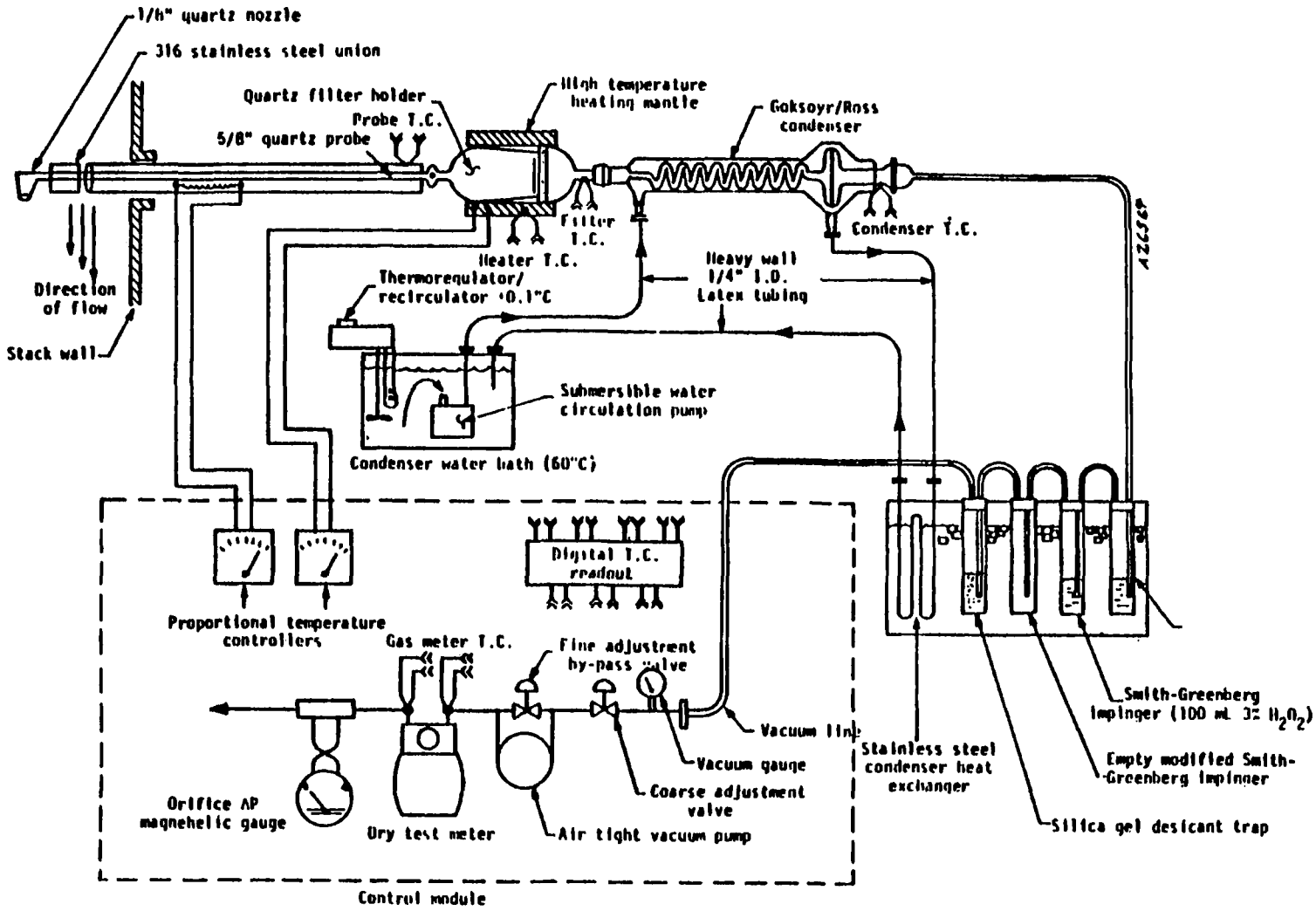


Figure A-8. Controlled condensation system.

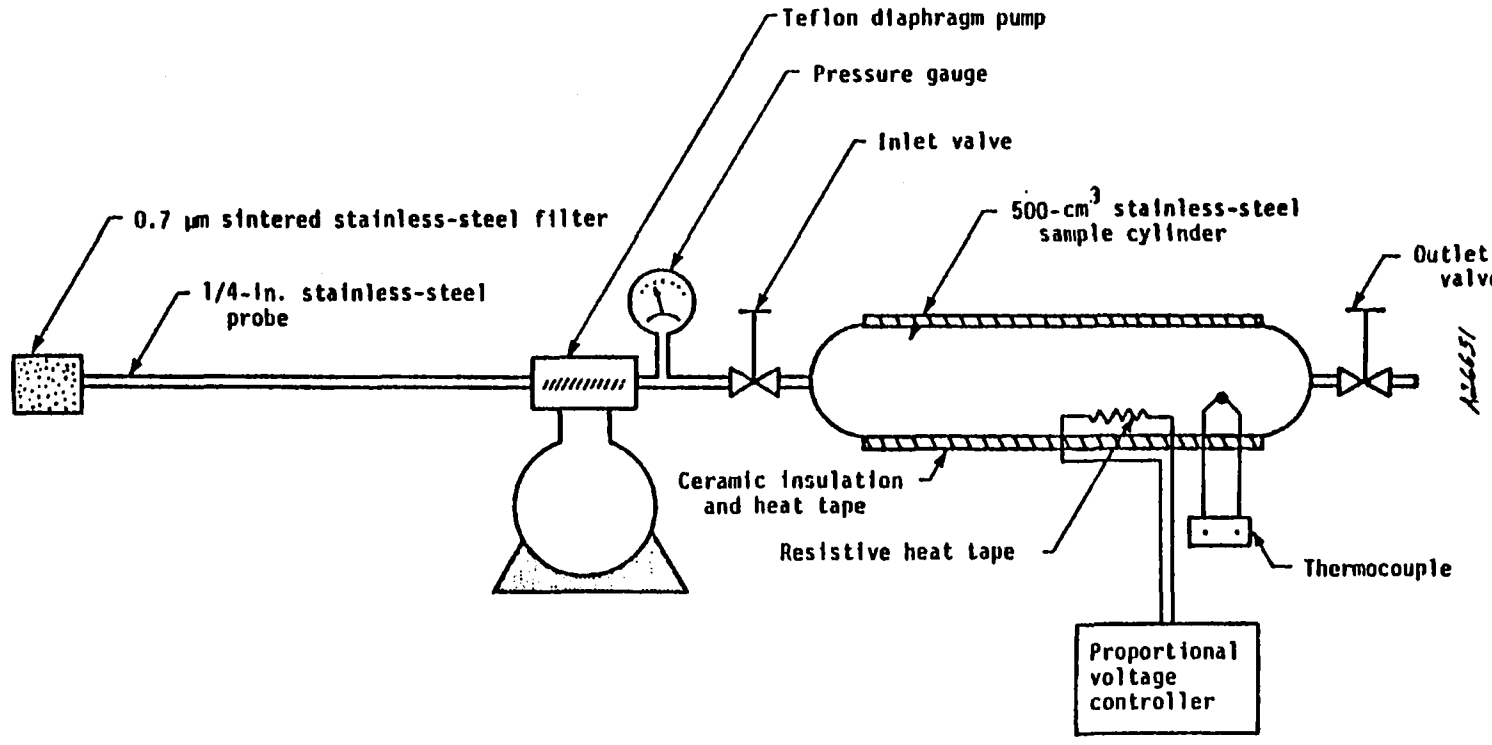


Figure A-9. N_2O sampling system.

20 ml/min with the column kept at 45°C (112°F). Elution time for N_2O was approximately 5 min.

A.7 NO_x MONITOR CERTIFICATION SAMPLING AND ANALYSIS

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 PB 293795, October 1978.

A-2. "Protocol for the Collection and Analysis of Volatile POHC's Using VOST," EPA-600/8-84-007, NTIS PB84-170042, March 1984.

A-3. "Methods for Chemical Analysis of Water and Wastes," EPA-600/4-79-020, NTIS PB 297686, March 1979.

A-4. Maddalone, R. and N. Gainer, "Process Measurement Procedures: H_2SO_4 Emissions," EPA-600/7-79-156, NTIS PB80-115959, July 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 elemental analysis results (μg/g or μg/ml) for each sample analyzed. Compositions for the steamer crude oil and all SASS train samples (filter, XAD-2 resin, and first impinger) are noted. Other tables give corresponding sample element concentrations in units of μg/dscm (labeled MCG/DSCM) and ng/J (labeled NG/J) heat input. A final set of tables gives corresponding trace element flowrates in μg/s (labeled MCG/SEC), with the mass balance ratio (out/in) noted in the last table (labeled STEAMER MASS BALANCE).

Symbols appearing in the table include:

DSCM	Dry standard cubic meter at 1 atm and 20°C
MCG	Microgram
PPM	Parts per million by weight
SEC	Second
<	Less than
>	Greater than

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

Detection limits for the various SASS samples were:

- Filter: <0.1 μg/g
- XAD-2: <0.08 μg/g
- Impinger and organic module condensate: <0.008 μg/ml
- Fuel oil: <0.7 μg/g

SASS and steamer operating data used for the calculation of trace element emissions were as follows:

- Fuel flowrate -- 388 ml/s (3,073 lb/hr)
- Heat input -- 16.6 MW (56.63 x 10^6 Btu/hr)
- Flue gas flowrate -- 4.62 dscm/s (9,779 dscfm)
- SASS gas volume collected -- 22.5 dscm (796 dscf)
- Particulate on filter -- 0.5129 g
- XAD weight -- 130 g
- Impinger 1 volume -- 547 ml
- Impinger 2 and 3 volume -- 840 ml
- Heating value of fuel -- 42.78 MJ/kg (18,430 Btu/lb)

PPM BLANK CORRECTED

EOR STEAMER
BASELINE
PPM

ELEMENT	FUEL	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS
ALUMINUM	.500E+01	.232E+04	.100E+01	.850E+00	.000E+00
ANTIMONY	.000E+00	.800E+01	.000E+00	.210E-01	.000E+00
ARSENIC	.600E-02	.158E+02	.300E-01	.480E-01	.700E-02
BARIUM	.550E+00	.800E+01	.400E+00	.180E+00	.000E+00
BERYLLIUM	<.100E-01	.400E+00	.000E+00	.000E+00	.000E+00
BISMUTH	.000E+00	.200E+00	.000E+00	.000E+00	.000E+00
BORON	.140E+00	.000E+00	.500E+00	.180E-01	.000E+00
BROMINE	.130E+00	.600E+01	.000E+00	.192E+00	.000E+00
CADMIUM	.000E+00	.000E+00	.000E+00	<.200E-01	.000E+00
CALCIUM	.900E+01	U.000E+00	.400E+01	.160E+01	.000E+00
CERIUM	.000E+00	.119E+02	.000E+00	.000E+00	.000E+00
CESIUM	.000E+00	.400E+00	.000E+00	.400E-02	.000E+00
CHLORINE	.230E+02	.315E+05	.000E+00	.000E+00	.000E+00
CHROMIUM	.400E+00	.280E+02	.000E+00	.299E+01	.000E+00
COBALT	.400E+00	.557E+02	.000E+00	<.600E-02	.000E+00
COPPER	.700E+00	.600E+01	.000E+00	.719E+02	.000E+00
DYSPROSIUM	.000E+00	.400E+01	.000E+00	.000E+00	.000E+00
ERBIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
EUROPIUM	.000E+00	.400E+00	.000E+00	.000E+00	.000E+00
FLUORINE	.160E+02	.106E+03	.000E+00	.590E+00	.000E+00
GADOLINIUM	.000E+00	.400E+01	.000E+00	.000E+00	.000E+00
GALLIUM	.200E+00	.117E+02	.000E+00	.370E-01	.000E+00
GERMANIUM	<.200E-01	.190E+01	.100E-01	.880E-01	.000E+00
HOLMIUM	.000E+00	.200E+01	.000E+00	<.200E+00	.000E+00
IODINE	.500E+00	.000E+00	.100E-01	.700E-01	.000E+00
IRON	.750E+01	.715E+04	.000E+00	.594E+01	.000E+00
LANTHANUM	.000E+00	.158E+02	.000E+00	.000E+00	.000E+00
LEAD	.550E+00	.300E+01	.400E+00	.000E+00	.000E+00
LITHIUM	.350E+00	.162E+02	.000E+00	.700E-01	.000E+00
LUTETIUM	.000E+00	.400E+00	.000E+00	.000E+00	.000E+00
MAGNESIUM	.650E+01	.154E+04	.100E+01	.000E+00	.000E+00
MANGANESE	.350E+00	.180E+02	.100E+00	.190E+00	.000E+00
MERCURY	<.400E+00	.200E-01	.120E+00	.000E+00	.200E-02
MOLYBDENUM	.120E+01	.100E+02	.100E+00	.970E+00	.000E+00
NEODYMIUM	.000E+00	.120E+02	.000E+00	.000E+00	.000E+00
NICKEL	.130E+02	.236E+05	.100E+00	.299E+01	.000E+00
NIOBIUM	.600E-01	.600E+00	.000E+00	<.360E-01	.000E+00
PHOSPHORUS	.300E+01	.408E+03	.000E+00	.100E+01	.000E+00
PLATINUM	.100E+01	.000E+00	.300E+00	.000E+00	.000E+00
POTASSIUM	.400E+01	.100E+01	.800E+01	.180E+01	.000E+00
PRASEODYMIUM	.000E+00	.380E+01	.000E+00	.100E-01	.000E+00
RUBIDIUM	.200E-01	.700E+00	.000E+00	.100E-01	.000E+00
SAMARIUM	.000E+00	.400E+01	.000E+00	.000E+00	.000E+00
SCANDIUM	.600E-01	.370E+01	.000E+00	.495E+00	.000E+00
SELENIUM	.450E+00	.380E+01	.000E+00	494E+00	.000E+00

PPM BLANK CORRECTED

EOR STEAMER
BASELINE
PPM

ELEMENT	FUEL	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS
SILICON	.140E+02	.000E+00	.000E+00	.340E+01	.000E+00
SILVER	.000E+00	.100E+01	.000E+00	.900E-01	.000E+00
SODIUM	.118E+03	.113E+04	.000E+00	.496E+04	.000E+00
STRONTIUM	.200E+00	.120E+02	.110E+00	.970E-01	.000E+00
SULFUR	.104E+04	.650E+02	.500E+01	.687E+04	.000E+00
TANTALUM	.000E+00	.200E+01	.000E+00	.000E+00	.000E+00
TELLURIUM	.000E+00	.300E+01	.000E+00	.840E-01	.000E+00
TERBIUM	.000E+00	.800E+00	.000E+00	.000E+00	.000E+00
THALLIUM	.000E+00	.400E+00	.000E+00	.000E+00	.000E+00
THORIUM	.000E+00	.800E+01	.000E+00	.000E+00	.000E+00
THULIUM	.000E+00	.400E+00	.000E+00	.000E+00	.000E+00
TIN	.000E+00	.400E+01	.000E+00	.000E+00	.000E+00
TITANIUM	.350E+00	.200E+02	.000E+00	.960E+00	.000E+00
TUNGSTEN	.000E+00	.400E+00	.000E+00	.000E+00	.000E+00
URANIUM	.000E+00	.100E+01	.000E+00	.600E+01	.000E+00
VANADIUM	.400E+00	.937E+03	.200E-01	.470E-01	.000E+00
YTTERBIUM	.000E+00	.100E+01	.000E+00	.000E+00	.000E+00
YTTRIUM	.500E-01	.232E+02	.000E+00	.100E-01	.000E+00
ZINC	.200E+01	.600E+02	.230E+01	.300E+02	.000E+00
ZIRCONIUM	.130E+00	.000E+00	.000E+00	.500E-01	.000E+00

CONCENTRATION — EOR STEAMER BASELINE MCG/DSCM

ELEMENT	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS	STACK OUTLET
ALUMINUM	.528E+02	.577E+01	.206E+02	.000E+00	.792E+02
ANTIMONY	.182E+00	.000E+00	.510E+00	.000E+00	.692E+00
ARSENIC	.360E+00	.173E+00	.116E+01	.261E+00	.196E+01
BARIUM	.182E+00	.231E+01	.437E+01	.000E+00	.686E+01
BERYLLIUM	.910E-02	.000E+00	.000E+00	.000E+00	.910E-02
BISMUTH	.455E-02	.000E+00	.000E+00	.000E+00	.455E-02
BORON	.000E+00	.288E+01	.437E+00	.000E+00	.332E+01
BROMINE	.137E+00	.000E+00	.466E+01	.000E+00	.480E+01
CADMIUM	.000E+00	.000E+00	< .485E+00	.000E+00	< .485E+00
CALCIUM	U .000E+00	.231E+02	.388E+02	.000E+00	.619E+02
CERIUM	.271E+00	.000E+00	.000E+00	.000E+00	.271E+00
CESIUM	.910E-02	.000E+00	.971E-01	.000E+00	.106E+00
CHLORINE	.716E+03	.000E+00	.000E+00	.000E+00	.716E+03
CHROMIUM	.637E+00	.000E+00	.726E+02	.000E+00	.732E+02
COBALT	.127E+01	.000E+00	< .146E+00	.000E+00	.127E+01<X<.141E+01
COPPER	.137E+00	.000E+00	.174E+04	.000E+00	.174E+04
DYSPROSIUM	.910E-01	.000E+00	.000E+00	.000E+00	.910E-01
ERBIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
EUROPIUM	.910E-02	.000E+00	.000E+00	.000E+00	.910E-02
FLUORINE	.241E+01	.000E+00	.143E+02	.000E+00	.167E+02
GADOLINIUM	.910E-01	.000E+00	.000E+00	.000E+00	.910E-01
GALLIUM	.266E+00	.000E+00	.898E+00	.000E+00	.116E+01
GERMANIUM	.432E-01	.577E-01	.214E+01	.000E+00	.224E+01
HOLMIUM	.455E-01	.000E+00	< .485E+01	.000E+00	.455E-01<X<.490E+01
IODINE	.000E+00	.577E-01	.170E+01	.000E+00	.176E+01
IRON	.163E+03	.000E+00	.144E+03	.000E+00	.307E+03
LANTHANUM	.360E+00	.000E+00	.000E+00	.000E+00	.360E+00
LEAD	.683E-01	.231E+01	.000E+00	.000E+00	.238E+01
LITHIUM	.369E+00	.000E+00	.170E+01	.000E+00	.207E+01
LUTETIUM	.910E-02	.000E+00	.000E+00	.000E+00	.910E-02
MAGNESIUM	.350E+02	.577E+01	.000E+00	.000E+00	.408E+02
MANGANESE	.410E+00	.577E+00	.461E+01	.000E+00	.560E+01
MERCURY	.455E-03	.692E+00	.000E+00	.745E-01	.767E+00
MOLYBDENUM	.228E+00	.577E+00	.235E+02	.000E+00	.243E+02
NEODYMIUM	.273E+00	.000E+00	.000E+00	.000E+00	.273E+00
NICKEL	.536E+03	.577E+00	.726E+02	.000E+00	.609E+03
NIOBIUM	.137E-01	.000E+00	< .874E+00	.000E+00	.137E-01<X<.887E+00
PHOSPHORUS	.928E+01	.000E+00	.243E+02	.000E+00	.336E+02
PLATINUM	.000E+00	.173E+01	.000E+00	.000E+00	.173E+01
POTASSIUM	.228E-01	.461E+02	.437E+02	.000E+00	.898E+02
PRASEODYMIUM	.865E-01	.000E+00	.243E+00	.000E+00	.329E+00
RUBIDIUM	.159E-01	.000E+00	.243E+00	.000E+00	.259E+00
SAMARIUM	.910E-01	.000E+00	.000E+00	.000E+00	.910E-01
SCANDIUM	.842E-01	.000E+00	.120E+02	.000E+00	.121E+02
SELENIUM	.865E-01	.000E+00	.120E+02	.000E+00	.121E+02

CONCENTRATION EOR STEAMER BASELINE MCG/DSCM

ELEMENT	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS	STACK OUTLET
SILICON	.000E+00	.000E+00	.825E+02	.000E+00	.825E+02
SILVER	.228E-01	.000E+00	.218E+01	.000E+00	.221E+01
SODIUM	.258E+02	.000E+00	.120E+06	.000E+00	.120E+06
STRONTIUM	.273E+00	.634E+00	.235E+01	.000E+00	.326E+01
SULFUR	.148E+01	.288E+02	.167E+06	.000E+00	.167E+06
TANTALUM	.455E-01	.000E+00	.000E+00	.000E+00	.455E-01
TELLURIUM	.683E-01	.000E+00	.204E+01	.000E+00	.211E+01
TERBIUM	.182E-01	.000E+00	.000E+00	.000E+00	.182E-01
THALLIUM	.910E-02	.000E+00	.000E+00	.000E+00	.910E-02
THORIUM	.182E+00	.000E+00	.000E+00	.000E+00	.182E+00
THULIUM	.910E-02	.000E+00	.000E+00	.000E+00	.910E-02
TIN	910E-01	.000E+00	.000E+00	.000E+00	.910E-01
TITANIUM	.455E+00	.000E+00	.233E+02	.000E+00	.238E+02
TUNGSTEN	.910E-02	.000E+00	.000E+00	.000E+00	.910E-02
URANIUM	.228E-01	.000E+00	.146E+03	.000E+00	.146E+03
VANADIUM	.213E+02	.115E+00	.114E+01	.000E+00	.226E+02
YTTERBIUM	.228E-01	.000E+00	.000E+00	.000E+00	.228E-01
YTTRIUM	.528E+00	.000E+00	.243E+00	.000E+00	.771E+00
ZINC	.137E+01	.133E+02	.728E+03	.000E+00	.742E+03
ZIRCONIUM	.000E+00	.000E+00	.121E+01	.000E+00	.121E+01

MASS/HEAT INPUT

EOR STEAMER
BASELINE
NG/J

ELEMENT	FUEL	STACK OUTLET
ALUMINUM	.117E+00	.220E-01
ANTIMONY	.000E+00	.192E-03
ARSENIC	.140E-03	.545E-03
BARIUM	.128E-01	.191E-02
BERYLLIUM	< .233E-03	.253E-05
BISMUTH	000E+00	.127E-05
BORON	.327E-02	.923E-03
BROMINE	.303E-02	.133E-02
CADMIUM	.000E+00	< .135E-03
CALCIUM	.210E+00	.172E-01
CERIUM	.000E+00	.753E-04
CESIUM	.000E+00	.295E-04
CHLORINE	.537E+00	.199E+00
CHROMIUM	.933E-02	.204E-01
COBALT	.933E-02	.352E-03<X<.393E-03
COPPER	.163E-01	.485E+00
DYSPROSIUM	.000E+00	.253E-04
ERBIUM	.000E+00	.000E+00
EUROPIUM	.000E+00	.253E-05
FLUORINE	.373E+00	.465E-02
GADOLINIUM	.000E+00	.253E-04
GALLIUM	.467E-02	.324E-03
GERMANIUM	< .467E-03	.622E-03
HOLMIUM	.000E+00	.127E-04<X<.136E-02
IODINE	.117E-01	.488E-03
IRON	.175E+00	.853E-01
LANTHANUM	.000E+00	.100E-03
LEAD	.128E-01	.661E-03
LITHIUM	.816E-02	.575E-03
LUTETIUM	.000E+00	.253E-05
MAGNESIUM	.152E+00	.113E-01
MANGANESE	.816E-02	.156E-02
MERCURY	< .933E-02	.213E-03
MOLYBDENUM	.280E-01	.677E-02
NEODYMIUM	.000E+00	.759E-04
NICKEL	.303E+00	.169E+00
NIOBIUM	.140E-02	.380E-05<X<.247E-03
PHOSPHORUS	.700E-01	.933E-02
PLATINUM	.233E-01	.481E-03
POTASSIUM	.933E-01	.250E-01
PRASEODYMIUM	.000E+00	.915E-04
RUBIDIUM	.467E-03	.719E-04
SAMARIUM	.000E+00	.253E-04
SCANDIUM	.140E-02	.336E-02
SELENIUM	.105E-01	.336E-02

MASS/HEAT INPUT

EOR STEAMER
BASELINE
NG/J

ELEMENT	FUEL	STACK OUTLET
SILICON	.327E+00	.229E-01
SILVER	.000E+00	.614E-03
SODIUM	.275E+01	.335E+02
STRONTIUM	.467E-02	.907E-03
SULFUR	.243E+02	.464E+02
TANTALUM	.000E+00	127E-04
TELLURIUM	.000E+00	.586E-03
TERBIUM	.000E+00	.506E-05
THALLIUM	.000E+00	.253E-05
THORIUM	.000E+00	.506E-04
THULIUM	.000E+00	.253E-05
TIN	.000E+00	.253E-04
TITANIUM	.816E-02	.661E-02
TUNGSTEN	.000E+00	.253E-05
URANIUM	.000E+00	.405E-01
VANADIUM	.933E-02	.628E-02
YTTERBIUM	.000E+00	.633E-05
YTTRIUM	.117E-02	.214E-03
ZINC	.467E-01	.206E+00
ZIRCONIUM	.303E-02	.337E-03

MASS/HEAT INPUT — EOR STEAMER BASELINE NG/J

ELEMENT	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS	STACK OUTLET
ALUMINUM	.147E-01	.160E-02	.574E-02	.000E+00	.220E-01
ANTIMONY	.506E-04	.000E+00	.142E-03	.000E+00	.192E-03
ARSENIC	.100E-03	.481E-04	.324E-03	.726E-04	.545E-03
BARIUM	.506E-04	.642E-03	.121E-02	.000E+00	.191E-02
BERYLLIUM	.253E-05	.000E+00	.000E+00	.000E+00	.253E-05
BISMUTH	.127E-05	.000E+00	.000E+00	.000E+00	.127E-05
BORON	.000E+00	.802E-03	.121E-03	.000E+00	.923E-03
BROMINE	.380E-04	.000E+00	.130E-02	.000E+00	.133E-02
CADMIUM	.000E+00	.000E+00	< .135E-03	.000E+00	< .135E-03
CALCIUM	U .000E+00	.642E-02	.108E-01	.000E+00	.172E-01
CERIUM	.753E-04	.000E+00	000E+00	.000E+00	.753E-04
CESIUM	.253E-05	.000E+00	.270E-04	.000E+00	.295E-04
CHLORINE	.199E+00	.000E+00	.000E+00	.000E+00	.199E+00
CHROMIUM	.177E-03	.000E+00	.202E-01	.000E+00	.204E-01
COBALT	.352E-03	.000E+00	< .405E-04	.000E+00	.352E-03<X<.393E-03
COPPER	.380E-04	.000E+00	.485E+00	.000E+00	.485E+00
DYSPROSIUM	.253E-04	.000E+00	.000E+00	.000E+00	.253E-04
ERBIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
EUROPIUM	.253E-05	.000E+00	.000E+00	.000E+00	.253E-05
FLUORINE	.671E-03	.000E+00	.398E-02	.000E+00	.465E-02
GADOLINIUM	.253E-04	.000E+00	.000E+00	.000E+00	.253E-04
GALLIUM	.740E-04	.000E+00	.250E-03	.000E+00	.324E-03
GERMANIUM	.120E-04	.160E-04	.594E-03	.000E+00	.622E-03
HOLMIUM	.127E-04	.000E+00	< .135E-02	.000E+00	.127E-04<X<.136E-02
IODINE	.000E+00	.160E-04	.472E-03	.000E+00	.488E-03
IRON	.452E-01	.000E+00	.401E-01	.000E+00	.853E-01
LANTHANUM	.100E-03	.000E+00	.000E+00	.000E+00	.100E-03
LEAD	.190E-04	.642E-03	.000E+00	.000E+00	.661E-03
LITHIUM	.103E-03	.000E+00	.472E-03	.000E+00	.575E-03
LUTETIUM	.253E-05	.000E+00	.000E+00	.000E+00	.253E-05
MAGNESIUM	.975E-02	.160E-02	.000E+00	.000E+00	.113E-01
MANGANESE	.114E-03	.160E-03	.128E-02	.000E+00	.156E-02
MERCURY	.127E-06	.192E-03	.000E+00	.207E-04	.213E-03
MOLYBDENUM	.633E-04	.160E-03	.655E-02	.000E+00	.677E-02
NEODYMIUM	.759E-04	.000E+00	.000E+00	.000E+00	.759E-04
NICKEL	.149E+00	.160E-03	.202E-01	.000E+00	.169E+00
NIOBIUM	.380E-05	.000E+00	< .243E-03	.000E+00	.380E-05<X<.247E-03
PHOSPHORUS	.258E-02	.000E+00	.675E-02	.000E+00	.933E-02
PLATINUM	.000E+00	.481E-03	.000E+00	.000E+00	.481E-03
POTASSIUM	.633E-05	.128E-01	.121E-01	.000E+00	.250E-01
PRASEODYMIUM	.240E-04	.000E+00	.675E-04	.000E+00	.915E-04
RUBIDIUM	.443E-05	.000E+00	.675E-04	.000E+00	.719E-04
SAMARIUM	.253E-04	.000E+00	.000E+00	.000E+00	.253E-04
SCANDIUM	.234E-04	.000E+00	.334E-02	.000E+00	.336E-02
SELENIUM	.240E-04	.000E+00	.333E-02	.000E+00	.336E-02

MASS/HEAT INPUT EOR STEAMER BASELINE NG/J

ELEMENT	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS	STACK OUTLET
SILICON	.000E+00	.000E+00	.229E-01	.000E+00	.229E-01
SILVER	.633E-05	.000E+00	.607E-03	.000E+00	.614E-03
SODIUM	.718E-02	.000E+00	.335E+02	.000E+00	.335E+02
STRONTIUM	.759E-04	.176E-03	.655E-03	.000E+00	.907E-03
SULFUR	.411E-03	.802E-02	.464E+02	.000E+00	.464E+02
TANTALUM	.127E-04	.000E+00	.000E+00	.000E+00	.127E-04
TELLURIUM	.190E-04	.000E+00	.567E-03	.000E+00	.586E-03
TERBIUM	.506E-05	.000E+00	.000E+00	.000E+00	.506E-05
THALLIUM	.253E-05	.000E+00	.000E+00	.000E+00	.253E-05
THORIUM	.506E-04	.000E+00	.000E+00	.000E+00	.506E-04
THULIUM	.253E-05	.000E+00	.000E+00	.000E+00	.253E-05
TIN	.253E-04	.000E+00	.000E+00	.000E+00	.253E-04
TITANIUM	.127E-03	.000E+00	.648E-02	.000E+00	.661E-02
TUNGSTEN	.253E-05	.000E+00	.000E+00	.000E+00	.253E-05
URANIUM	.633E-05	.000E+00	.405E-01	.000E+00	.405E-01
VANADIUM	.593E-02	.321E-04	.317E-03	.000E+00	.628E-02
YTTERBIUM	.633E-05	.000E+00	.000E+00	.000E+00	.633E-05
YTTRIUM	.147E-03	.000E+00	.675E-04	.000E+00	.214E-03
ZINC	.380E-03	.369E-02	.202E+00	.000E+00	.206E+00
ZIRCONIUM	.000E+00	.000E+00	.337E-03	.000E+00	.337E-03

MASS FLOWRATE — EOR STEAMER BASELINE MCG/SEC

ELEMENT	FUEL	STACK OUTLET
ALUMINUM	.194E+04	.366E+03
ANTIMONY	.000E+00	.320E+01
ARSENIC	.233E+01	.905E+01
BARIUM	.213E+03	.317E+02
BERYLLIUM	< .388E+01	.421E-01
BISMUTH	.000E+00	.210E-01
BORON	.543E+02	.153E+02
BROMINE	.504E+02	.222E+02
CADMIUM	.000E+00	< .224E+01
CALCIUM	.349E+04	.286E+03
CERIUM	.000E+00	.125E+01
CESIUM	.000E+00	.491E+00
CHLORINE	.891E+04	.331E+04
CHROMIUM	.155E+03	.338E+03
COBALT	.155E+03	.586E+01<X<.653E+01
COPPER	.271E+03	.806E+04
DYSPROSIUM	.000E+00	.421E+00
ERBIUM	.000E+00	.000E+00
EUROPIUM	.000E+00	.421E-01
FLUORINE	.620E+04	.773E+02
GADOLINIUM	.000E+00	.421E+00
GALLIUM	.775E+02	.538E+01
GERMANIUM	< .775E+01	.103E+02
HOLMIUM	.000E+00	.210E+00<X<.226E+02
IODINE	.194E+03	.811E+01
IRON	.291E+04	.142E+04
LANTHANUM	.000E+00	.166E+01
LEAD	.213E+03	.110E+02
LITHIUM	.136E+03	.955E+01
LUTETIUM	.000E+00	.421E-01
MAGNESIUM	.252E+04	.189E+03
MANGANESE	.136E+03	.259E+02
MERCURY	< .155E+03	.354E+01
MOLYBDENUM	.465E+03	.112E+03
NEODYMIUM	.000E+00	.126E+01
NICKEL	.504E+04	.281E+04
NIOBIUM	.233E+02	.631E-01<X<.410E+01
PHOSPHORUS	.116E+04	.155E+03
PLATINUM	.388E+03	.799E+01
POTASSIUM	.155E+04	.415E+03
PRASEODYMIUM	.000E+00	.152E+01
RUBIDIUM	.775E+01	.119E+01
SAMARIUM	.000E+00	.421E+00
SCANDIUM	.233E+02	.559E+02
SELENIUM	.174E+03	.558E+02

MASS FLOWRATE

EOR STEAMER
BASELINE
MCG/SEC

ELEMENT	FUEL	STACK OUTLET
SILICON	.543E+04	.381E+03
SILVER	.000E+00	.102E+02
SODIUM	.457E+05	.556E+06
STRONTIUM	.775E+02	.151E+02
SULFUR	.403E+06	.770E+06
TANTALUM	.000E+00	.210E+00
TELLURIUM	.000E+00	.973E+01
TERBIUM	.000E+00	.841E-01
THALLIUM	.000E+00	.421E-01
THORIUM	.000E+00	.841E+00
THULIUM	.000E+00	.421E-01
TIN	.000E+00	.421E+00
TITANIUM	.136E+03	.110E+03
TUNGSTEN	.000E+00	.421E-01
URANIUM	.000E+00	.673E+03
VANADIUM	.155E+03	.104E+03
YTTERBIUM	.000E+00	.105E+00
YTTRIUM	.194E+02	.356E+01
ZINC	.775E+03	.343E+04
ZIRCONIUM	.504E+02	.561E+01

MASS FLOWRATE — EOR STEAMER BASELINE MCG/SEC

ELEMENT	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS	STACK OUTLET
ALUMINUM	.244E+03	.266E+02	.953E+02	.000E+00	.366E+03
ANTIMONY	.841E+00	.000E+00	.235E+01	.000E+00	.320E+01
ARSENIC	.166E+01	.799E+00	.538E+01	.121E+01	.905E+01
BARIUM	.841E+00	.107E+02	.202E+02	.000E+00	.317E+02
BERYLLIUM	.421E-01	.000E+00	.000E+00	.000E+00	.421E-01
BISMUTH	.210E-01	.000E+00	.000E+00	.000E+00	.210E-01
BORON	.000E+00	.133E+02	.202E+01	.000E+00	.153E+02
BROMINE	.631E+00	.000E+00	.215E+02	.000E+00	.222E+02
CADMIUM	.000E+00	.000E+00	< .224E+01	.000E+00	< .224E+01
CALCIUM	U .000E+00	.107E+03	.179E+03	.000E+00	.286E+03
CERIUM	.125E+01	.000E+00	.000E+00	.000E+00	.125E+01
CESIUM	.421E-01	000E+00	.448E+00	.000E+00	.491E+00
CHLORINE	.331E+04	.000E+00	.000E+00	.000E+00	.331E+04
CHROMIUM	.294E+01	.000E+00	.335E+03	.000E+00	.338E+03
COBALT	.586E+01	.000E+00	< .673E+00	.000E+00	.586E+01<X<.653E+01
COPPER	.631E+00	.000E+00	.806E+04	.000E+00	.806E+04
DYSPROSIUM	.421E+00	.000E+00	.000E+00	.000E+00	.421E+00
ERBIUM	.000E+00	.000E+00	.000E+00	.000E+00	.000E+00
EUROPIUM	.421E-01	.000E+00	.000E+00	.000E+00	.421E-01
FLUORINE	.111E+02	.000E+00	.661E+02	.000E+00	.773E+02
GADOLINIUM	.421E+00	.000E+00	.000E+00	.000E+00	.421E+00
GALLIUM	.123E+01	.000E+00	.415E+01	.000E+00	.538E+01
GERMANIUM	.200E+00	.266E+00	.987E+01	.000E+00	.103E+02
HOLMIUM	.210E+00	.000E+00	< .224E+02	.000E+00	.210E+00<X<.226E+02
IODINE	.000E+00	.266E+00	.785E+01	.000E+00	.811E+01
IRON	.751E+03	.000E+00	.666E+03	.000E+00	.142E+04
LANTHANUM	.166E+01	.000E+00	.000E+00	.000E+00	.166E+01
LEAD	.315E+00	.107E+02	.000E+00	.000E+00	.110E+02
LITHIUM	.170E+01	.000E+00	.785E+01	.000E+00	.955E+01
LUTETIUM	.421E-01	.000E+00	.000E+00	.000E+00	.421E-01
MAGNESIUM	.162E+03	.266E+02	.000E+00	.000E+00	.189E+03
MANGANESE	.189E+01	.266E+01	.213E+02	.000E+00	.259E+02
MERCURY	.210E-02	.320E+01	.000E+00	.344E+00	.354E+01
MOLYBDENUM	.105E+01	.266E+01	.109E+03	.000E+00	.112E+03
NEODYMIUM	.126E+01	.000E+00	.000E+00	.000E+00	.126E+01
NICKEL	.248E+04	.266E+01	.335E+03	.000E+00	.281E+04
NIOBIUM	.631E-01	.000E+00	< .404E+01	.000E+00	.631E-01<X<.410E+01
PHOSPHORUS	.429E+02	.000E+00	.112E+03	.000E+00	.155E+03
PLATINUM	.000E+00	.799E+01	.000E+00	.000E+00	.799E+01
POTASSIUM	.105E+00	.213E+03	.202E+03	.000E+00	.415E+03
PRASEODYMIUM	.399E+00	.000E+00	.112E+01	.000E+00	.152E+01
RUBIDIUM	.736E-01	.000E+00	.112E+01	.000E+00	.119E+01
SAMARIUM	.421E+00	.000E+00	.000E+00	.000E+00	.421E+00
SCANDIUM	.389E+00	.000E+00	.555E+02	.000E+00	.559E+02
SELENIUM	.399E+00	.000E+00	.554E+02	.000E+00	.558E+02

MASS FLOWRATE

EOR STEAMER
BASELINE
MCG/SEC

ELEMENT	FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS	STACK OUTLET
SILICON	.000E+00	.000E+00	.381E+03	.000E+00	.381E+03
SILVER	.105E+00	.000E+00	.101E+02	.000E+00	.102E+02
SODIUM	.119E+03	.000E+00	.556E+06	.000E+00	.556E+06
STRONTIUM	.126E+01	.293E+01	.109E+02	.000E+00	.151E+02
SULFUR	.683E+01	.133E+03	.770E+06	.000E+00	.770E+06
TANTALUM	.210E+00	.000E+00	.000E+00	.000E+00	.210E+00
TELLURIUM	.315E+00	.000E+00	.942E+01	.000E+00	.973E+01
TERBIUM	.841E-01	.000E+00	.000E+00	.000E+00	.841E-01
THALLIUM	.421E-01	.000E+00	.000E+00	.000E+00	.421E-01
THORIUM	.841E+00	.000E+00	.000E+00	.000E+00	.841E+00
THULIUM	.421E-01	.000E+00	.000E+00	.000E+00	.421E-01
TIN	.421E+00	.000E+00	.000E+00	.000E+00	.421E+00
TITANIUM	.210E+01	.000E+00	.108E+03	.000E+00	.110E+03
TUNGSTEN	.421E-01	.000E+00	.000E+00	.000E+00	.421E-01
URANIUM	.105E+00	.000E+00	.673E+03	.000E+00	.673E+03
VANADIUM	.985E+02	.533E+00	.527E+01	.000E+00	.104E+03
YTTERBIUM	.105E+00	.000E+00	.000E+00	.000E+00	.105E+00
YTTRIUM	.244E+01	.000E+00	.112E+01	.000E+00	.356E+01
ZINC	.631E+01	.613E+02	.336E+04	.000E+00	.343E+04
ZIRCONIUM	.000E+00	.000E+00	.561E+01	.000E+00	.561E+01

EOR STEAMER
BASELINE

STEAMER

STEAMER MASS BALANCE INPUT = FUEL OUTPUT = STACK GAS

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
ALUMINUM	.194E+04	.366E+03	.189E+00
ANTIMONY		.320E+01	*
ARSENIC	.233E+01	.905E+01	.389E+01
BARIUM	.213E+03	.317E+02	.149E+00
BERYLLIUM	X< 388E+01	.421E-01	.109E-01 <X
BISMUTH		.210E-01	*
BORON	.543E+02	.153E+02	.283E+00
BROMINE	.504E+02	.222E+02	.440E+00
CADMIUM		X<.224E+01	*
CALCIUM	.349E+04	.286E+03	.820E-01
CERIUM		.125E+01	*
CESIUM		.491E+00	*
CHLORINE	.891E+04	.331E+04	.371E+00
CHROMIUM	.155E+03	.338E+03	.218E+01
COBALT	.155E+03	.586E+01<X<.653E+01	.378E-01<X<.421E-01
COPPER	.271E+03	.806E+04	.297E+02
DYSPROSIUM		.421E+00	*
ERBIUM			*
EUROPIUM		.421E-01	*
FLUORINE	.620E+04	.773E+02	.125E-01
GADOLINIUM		.421E+00	*
GALLIUM	.775E+02	.538E+01	.694E-01
GERMANIUM	X<.775E+01	.103E+02	.133E+01 <X
HOLMIUM		.210E+00<X<.226E+02	*
IODINE	.194E+03	.811E+01	.419E-01
IRON	.291E+04	.142E+04	.488E+00
LANTHANUM		.166E+01	*
LEAD	.213E+03	.110E+02	.515E-01
LITHIUM	.136E+03	.955E+01	.704E-01
LUTETIUM		.421E-01	*
MAGNESIUM	.252E+04	.189E+03	.749E-01
MANGANESE	.136E+03	.259E+02	.191E+00
MERCURY	X<.155E+03	.354E+01	.229E-01 <X
MOLYBDENUM	.465E+03	.112E+03	.242E+00
NEODYMIUM		.126E+01	*
NICKEL	.504E+04	.281E+04	.559E+00
NIOBIUM	.233E+02	.631E-01<X<.410E+01	.271E-02<X<.176E+00
PHOSPHORUS	.116E+04	.155E+03	.133E+00
PLATINUM	.388E+03	.799E+01	.206E-01
POTASSIUM	.155E+04	.415E+03	.268E+00
PRASEODYMIUM		.152E+01	*
RUBIDIUM	.775E+01	.119E+01	.154E+00
SAMARIUM		.421E+00	*
SCANDIUM	.233E+02	.559E+02	.240E+01
SELENIUM	.174E+03	.558E+02	.320E+00

EOR STEAMER
BASELINE

STEAMER

STEAMER MASS BALANCE INPUT = FUEL OUTPUT = STACK GAS

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
SILICON	.543E+04	.381E+03	.703E-01
SILVER		.102E+02	*
SODIUM	.457E+05	.556E+06	.122E+02
STRONTIUM	.775E+02	.151E+02	.194E+00
SULFUR	.403E+06	.770E+06	.191E+01
TANTALUM		.210E+00	*
TELLURIUM		.973E+01	*
TERBIUM		.841E-01	*
THALLIUM		.421E-01	*
THORIUM		.841E+00	*
THULIUM		.421E-01	*
TIN		.421E+00	*
TITANIUM	.136E+03	.110E+03	.809E+00
TUNGSTEN		.421E-01	*
URANIUM		.673E+03	*
VANADIUM	.155E+03	.104E+03	.673E+00
YTTERBIUM		.105E+00	*
YTTRIUM	.194E+02	.356E+01	.184E+00
ZINC	.775E+03	.343E+04	.442E+01
ZIRCONIUM	.504E+02	.561E+01	.111E+00

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-86-013a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Environmental Assessment of an Enhanced Oil Recovery Steam Generator Equipped with an EPA Heavy-oil Low-NOx Burner; Volume I*		5. REPORT DATE April 1986
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) C. Castaldini, L.R. Waterland, and R. De Rosier		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Acurex Corporation Energy and Environmental Division P.O. Box 7044 Mountain View, California 94039		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-3188
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 1/84 - 1/85
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Joseph A. McSorley, Mail Drop 65, 919/541-2920. Volume II is a data supplement. (*) Volume I is Technical Results.

16. ABSTRACT The report gives results of comprehensive emission measurements and 30-day flue gas monitoring on a 16-MW (55 million Btu/hr) enhanced oil recovery steam generator equipped with the EPA low-NOx burner firing high-nitrogen crude. The 1-day comprehensive measurements included quantification of semivolatile organics and 73 trace elements; volatile organic sampling train quantitation of volatile organic priority pollutants; EPA Method 5/8 for particulate and SOx; controlled condensation for SOx; Andersen impactors for particle size distribution; grab samples for N2O; and continuous flue gas monitoring. NOx emissions averaged 70 ppm at 3% O2, well below the target of 85 ppm. CO emissions were below 30 ppm, and SO2 averaged about 550 ppm. Solid particulates were emitted at about 27 ng/J (96 mg/dscm); condensible particulates were about half that. Volatile organics (benzene, toluene, and ethylbenzene) were measured in the 0.4 to 20 ppb range. Semivolatile organics (naphthalene and phenol) were detected at about 0.3 ppb. Subsequent continuous monitoring of flue gas criteria emissions showed NOx below 80 ppm at 3% O2 with an average of 70 ppm. CO emissions were generally less than 30 ppm.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Assessments	Stationary Sources	14B
Boilers	Environmental Assessment	13A
Oil Recovery		08I, 11H
Crude Oil	Low-NOx Burners	
Combustion		21B

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 100
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)