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KAF



July 2, 1987
ESA 19750-L01

Mr. Peter Dawson, P.E.
Procter & Gamble Company
Winton Hill Technical Center
6110 Center Hill Road
Cincinnati, OH 45224

Dear Peter:

I am sending this letter to recap our telephone discussion on June 24, 1987, regarding problems associated with measuring NO_x emission from internal combustion engines and the recommended solutions to the measurement problem.

The problem ESA experienced during the attempted compliance tests on the gas compressor IC engine were manifested in NO_x (NO + NO₂) being indicated lower than indicated NO. The cause of the problem is now believed to be incompatibility of the low O₂ flue gas with a component in the NO_x analyzer (the NO₂ to NO converter).

The proposed solutions to the measurement problems have been arrived at following my discussions with the analyzer manufacturer technical staff and measurement specialists at the US EPA regarding their experiences measuring NO_x from similar sources.

I had a conversation with Mike Laney of Thermo Electron Corporation (instrument manufacturer). He admitted that although the literature regarding the analyzer boasts that species normally found in flue gas do not interfere with the analyzer high carbon monoxide concentrations and lack of oxygen in the sample could temporarily affect the reaction in the NO₂ to NO converter in the analyzer. The solution he offered was to use a dilution of the sample with ambient air. He also indicated that the converter could be reconditioned with air and the NO₂ and NO conversion efficiency be used as an indicator of its acceptability for use.

I also spoke with Jack Wasser and Richard Perry from US EPA's Research and Development group. They have been working on IC engine emissions for some time and experienced similar measurement problems using the Thermo Electron analyzer while testing under rich burn engine conditions. They indicated that their solution was not to direct the low O₂ stream through the NO₂ to NO converter for extended periods of time. They also indicated that the level of NO₂ in the exhaust during rich burn conditions was negligible and an occasional spot check should verify this without negatively affecting the performance of the NO₂ to NO converter.

Mr. Dawson
Procter and Gamble



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I also spoke with Peter Westlin of US EPA's Emission Measurement Systems Laboratory. Mr. Westlin is the author of EPA Method 20 which is the reference method specified to measure NO_x emissions from stationary internal combustion engines. He indicated that although no research was done on engines equipped with catalytic converters (as is the case at Sacramento) they found that virtually all of the NO_x found in the exhaust from engines operated in a fuel rich manner was in the form of NO. He concurred that it would be acceptable to operate the analyzer in the NO mode (bypassing the NO₂ to NO converter) with an occasional spot check for NO₂. I asked Mr. Westlin if he would recommend using EPA Method 7 to support the instrument data. He replied that it could provide data that may validate the instrument readings, although it is not a reference method for this source type.

Based on the information I gathered from the above sources and others, the following tactics are proposed for the retest of the engine at Sacramento on July 14th:

1. Operate the analyzer bypassing the NO₂ to NO converter except to spot check.
2. Verify the efficiency of the NO₂ to NO converter on site.
3. Collect Method 7 (grab samples) as back up data.

In addition to the above, ESA will attempt to have a spare NO₂ to NO converter on hand during the measurements and modify the analyzer to allow a converter change with little or no lost time.

I hope this information is useful to you. Please contact me if I can be of any assistance.

Sincerely,

ENERGY SYSTEMS ASSOCIATES

A handwritten signature in cursive script that reads "Robert A. Finken".

Robert A. Finken
Director, Testing Services

RAF:ch

cy: Rich Scollay, Procter & Gamble

SECTION 1.0
INTRODUCTION AND SUMMARY

Energy Systems Associates (ESA) was contracted by the Procter and Gamble Sacramento plant to conduct performance testing on a production gas-fired internal combustion (IC) engine. The engine drives a compressor which supplies high pressure production gas to a gas turbine. The emissions control system consists of a catalytic muffler installed on the unit. The performance tests were conducted to satisfy conditions stipulated in the Permit to Construct issued to Procter and Gamble on December 12, 1986, under the County of Sacramento APCD Application Nos. A/C 8592 and 8593.

The Permit specifies that the engine shall not emit NO_x in excess of 2.0 g/HP-hr.

The tests were conducted on July 15, 1987. Testing was supervised and conducted by Robert A. Finken, ESA's Director of Testing Services. Geoff Bogue assisted during the performance tests. Rich Scollay coordinated testing for Procter and Gamble.

The results of the tests are presented in Table 1-1. The results show that engine emissions were below the permit emission limit of 2.0 g/HP-hr.

TABLE 1-1.
RESULTS OF EMISSION TEST ON IC ENGINE

	Run 1	Run 2	Run 3	Average
Compressor Data:				
Gas Flow, mcfh	225	226	225	225
Gas Temperature, °F				
Inlet	86	90	92	89
Outlet	107	111	113	110
Gas Pressure, psig				
Inlet	90	90	90	90
Outlet	495	490	490	492
Brake Specific HP*	684	687	687	686
Engine Exhaust Data:				
Temperature, °F	1013	989	988	997
H ₂ O, %	19.1	19.8	20.4	19.8
Flow, wacfm	3,096	3,155	3,039	3,097
Flow, dscfm at 60 °F	881	906	865	884
O ₂ , %	0	0	0	0
NO _x , ppm	137	135	139	137
NO _x , ppm at 3% O ₂	117	116	119	117
NO _x , g/hr	399	404	397	400
NO _x , g/HP-hr	0.58	0.59	0.58	0.58

*Calculated value; see Appendix D.

SECTION 2.0

UNIT DESCRIPTION

The IC engine is located at the Procter and Gamble facility at 8201 Fruitridge Road in Sacramento. The engine drives a compressor which pressurizes a production gas from 85 to 470 psig prior to introduction to a 21 MW gas turbine generator. The engine is a Superior Model 8G-825 rated at 800 HP. NOx emissions are controlled with a catalytic muffler.

SECTION 3.0

TEST DESCRIPTION

3.1 TEST CONDITIONS

The IC engine was operated by Procter and Gamble at normal operating conditions during the test. The gas turbine unit, which is supplied with fuel gas by the engine/compressor, operated at steady maximum load (21 MW) throughout the test.

Unit operating data were recorded, and are furnished in Appendix C.

3.2 SAMPLE LOCATIONS

Emission sampling was conducted through ports installed in a horizontal extension to the engine's muffler exhaust. A diagram of the sample location is included in Appendix C. The extension is located three diameters downstream and two diameters upstream of flow disturbances to comply with EPA Method 1 criteria. Velocity traverses were performed using 12 sample points as specified by EPA Method 1.

A gaseous traverse performed at the start of testing showed no stratification, so single-point sampling was used for gaseous and moisture tests.

3.3 TEST PROCEDURES

NO_x and O₂ were measured by ESA's continuous emissions monitoring (CEM) system. The sampling system employs the supercooled moisture removal trap described in Appendix A to conserve any NO₂ present in the exhaust gas. This system meets EPA Method 20 requirements for conservation of NO₂. Velocity and moisture measurements were conducted in the duct to determine exhaust gas flow rates. The test procedures used are listed in Table 3-1. Measurement procedures are described in Appendix A. Quality assurance procedures for emission measurements are summarized in Appendix B.

During an initial test run on the engine on June 24, 1987, several problems were encountered with NOx measurements due to what is believed to be an incompatibility of the low O₂ flue gas with the NOx converter. Based on conversations with personnel from the instrument manufacturer, EPA's Research and Development Group, and EPA's Emission Measurement Laboratory, the following modifications were made to the test procedure:

1. Operate the NOx analyzer in the NO mode, bypassing the NO₂ to NO converter.
2. Spot check the NOx measurements at regular intervals.
3. Verify NO₂ to NO converter efficiency on-site.
4. Collect EPA Method 7 samples (PDS flasks) as back up data.

Details of the modifications are included in Appendix A.

TABLE 3-1.
SUMMARY OF TEST PROCEDURES

Parameter	Measurement Principle	Reference Method	Comments
NOx NOx	Chemiluminescence Grab sample/ colorimetric	ARB 1-100 EPA 7	Duplicate one-hour runs Three triplicate sets of flasks
O ₂	Electrochemical cell	ARB 1-100	Duplicate one-hour runs
Stack Flow	Pitot traverse	EPA 1 & 2	In conjunction with NOx and O ₂ tests.
H ₂ O	Condensation	EPA 4	Duplicate runs in conjunction with NOx and O ₂ tests.

NOx emissions were calculated and reported on a ppm, g/hr, and g/HP-hr basis. Emissions on a g/hr basis were determined from measured NOx and exhaust flow rate. Brake-specific NOx emissions (g/HP-hr) were calculated from the g/hr NOx emission rate and power output by the IC engine. Horsepower output from the engine was determined from measured compressor operating parameters with the following brake horsepower equation for compressors:

$$P_{\text{comp}} = \frac{0.0643 T_{\text{inlet}} kQ}{\eta 528 (k-1)} \left[\left(\frac{P_{\text{outlet}}}{P_{\text{inlet}}} \right)^{1-1/k} - 1 \right]$$

where

- P_{comp} = compressor brake horsepower, HP
- T_{inlet} = temperature of gas at compressor inlet, °R
- k = ratio of specific heats, C_p/C_v
- Q = gas flow rate, scfm at 528 °D
- η = compressor mechanical efficiency
- P_{inlet} = gas inlet pressure, psi
- P_{outlet} = gas outlet pressure, psi

Inlet and outlet temperatures and pressures were recorded during the NOx and velocity test to provide input to the brake horsepower calculation. Since there was no direct measurement of natural gas flow through the compressor, gas flow was determined based on fuel flow to the turbine. Natural gas analysis was performed by Zalco Laboratories, Inc. in Bakersfield, California.

SECTION 4.0

RESULTS

The results of the tests are summarized in Table 4-1. The results show that NO_x emissions were 0.58 gr/HP-hr, or 71% below the permit limit of 2.0g/HP-hr.

Raw data sheets and chain of custody documentation are included in Appendix C, calculation procedures and specialized calculations are in Appendix D, outside laboratory reports are in Appendix E, and gaseous strip charts are in Appendix F.

TABLE 4-1.
RESULTS OF EMISSION TEST ON IC ENGINE

	Run 1	Run 2	Run 3	Average
Compressor Data:				
Gas Flow, mcfh	225	226	225	225
Gas Temperature, °F				
Inlet	86	90	92	89
Outlet	107	111	113	110
Gas Pressure, psig				
Inlet	90	90	90	90
Outlet	495	490	490	492
Brake Specific HP*	684	687	687	686
Engine Exhaust Data:				
Temperature, °F	1013	989	988	997
H ₂ O, %	19.1	19.8	20.4	19.8
Flow, wacfm	3,096	3,155	3,039	3,097
Flow, dscfm at 60 °F	881	906	865	884
O ₂ , %	0	0	0	0
NO _x , ppm	137	135	139	137
NO _x , ppm at 3% O ₂	117	116	119	117
NO _x , g/hr	399	404	397	400
NO _x , g/HP-hr	0.58	0.59	0.58	0.58

*Calculated value; see Appendix D.

TABLE 4-2.
COMPARISON OF NO_x DATA BY CEM AND PDS FLASK

Run	NO _x , ppm		Diff, %
	CEM	PDS	
1	139	123	+13
2	138	123	+12
3	140	126	+11

APPENDIX A

MEASUREMENT PROCEDURES

Continuous Emissions Monitoring System
Oxygen (O₂) by Continuous Analyzer
NO/NO_x by Continuous Analyzer
Determination of Moisture in Stack Gases

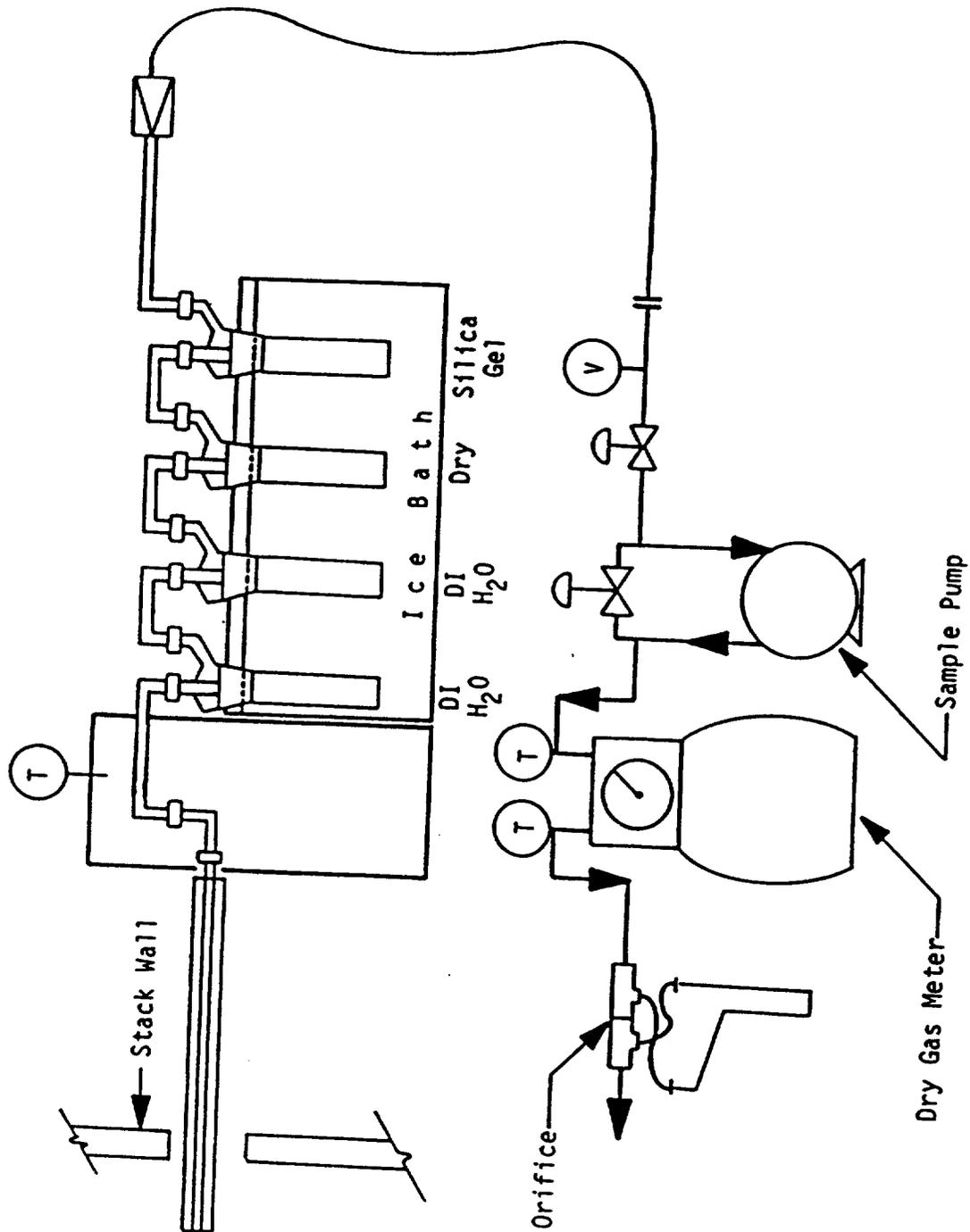
Continuous Emissions Monitoring System

O₂, CO, CO₂, NO, NO_x, and SO₂ are measured using an extractive continuous emissions monitoring (CEM) package, shown in the following figure. This package is comprised of three basic subsystems. They are: (1) the sample acquisition and conditioning system, (2) the calibration gas system, and (3) the analyzers themselves. This section presents a description of the sampling and calibration systems. Descriptions of the analyzers used in this program and the corresponding reference test methods follow. Information regarding quality assurance information on the system, including calibration routines and system performance data follows.

The sample acquisition and conditioning system contains components to extract a representative sample from the stack or flue, transport the sample to the analyzers, and remove moisture and particulate material from the sample. In addition to performing the tasks above, the system must preserve the measured species and deliver the sample for analysis intact. The sample acquisition system extracts the sample through a stainless steel probe. The probe is insulated or heated as necessary to avoid condensation. If the particulate loading in the stack is high, a sintered stainless steel filter is used on the end of the probe.

Where water soluble NO₂ and/or SO₂ are to be measured, the sample is drawn from the probe through a heated Teflon sample line into a supercooled (approximately -20 °C) water removal trap. The trap consists of stainless steel flasks in a bath of dry ice and antifreeze. If dry ice is not locally available, ice and rock salt are used. This design removes the water vapor by condensation and freezes the liquid quickly. The contact between the sample and liquid water is minimized. Since the solubility of the NO₂ and SO₂ in ice is negligible, these species are conserved. This system meets the requirements of EPA Method 20. The sample is then drawn through a Teflon transport line and particulate filter, into the sample pump. The pump is a dual head, diaphragm pump. All sample-wetted components of the pump are stainless steel or Teflon. The pressurized sample leaving the pump flows through a stainless steel refrigerated (38 °F) compressed air dryer for final moisture removal. A drain line and valve are provided to constantly expel any condensed moisture from the dryer. After the dryer, the sample is directed into a distribution manifold. Excess sample is vented through a back-pressure regulator, maintaining a constant pressure of 5-6 psig to the analyzers.

The calibration system is comprised of two parts: the analyzer calibration, and the system calibration check (dynamic calibration). The analyzer calibration equipment includes pressurized cylinders of certified span gas. The gases used are, as a minimum, certified to ±1% by the manufacturer where necessary, to comply with reference method requirements. EPA Protocol 1 gases are used. The cylinders are equipped with pressure regulators which supply the calibration gas to the analyzers at the same pressure and flow rate as the sample. The selection of zero, span, or sample gas directed to each analyzer is accomplished by operation of the sample/calibration selector valves.



Sample Train for Determination of Moisture by EPA Method 4.

The system calibration check is accomplished by transporting the same gases used to zero and span the analyzers to the sample conditioner inlet (probe exit). The span gas is exposed to the same elements as the sample and the system response is documented. Where the supercooled moisture removal system is used, water is added to the knockout flasks before the pre-test check. The analyzer indications for the system calibration check must agree within 3% of the analyzer calibration. Values are adjusted and changes/repairs are made to the system to compensate for any difference in analyzer readings. Specific information on the analytical equipment and test methods used is provided in the following pages.

Method: Oxygen (O₂) by Continuous Analyzer

Applicable Ref. Methods: EPA 3A, EPA 20, ARB 1-100, BA ST-14

Principle: A sample is continuously drawn from the flue gas stream, conditioned, and conveyed to the instrument for direct readout of O₂ concentration.

Analyzer: Teco Model 326A

Measurement Principle: Electrochemical cell

Ranges: 0-5, 0-10, 0-25% O₂

Accuracy: ±1% of full scale

Output: 0-100 mV, linear

Interferences: Halogens and halogenated compounds will cause a positive interference. Acid gases will consume the fuel cell and cause a slow calibration drift.

Response Time: 90% <7 seconds

Sampling Procedure: A representative flue gas sample is collected and conditioned using the CEM system described previously. If Method 20 is used, that method's specific procedures for selecting sample points are used. Otherwise, the procedures described in the report are used to select sample locations.

Analytical Procedure: An electrochemical cell is used to measure O₂ concentration. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally, and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give an output in percent O₂ by volume.

Special Calibration Procedure: The measurement cells used with the O₂ instrument have to be replaced on a regular basis. After extended use, the cells tend to produce a nonlinear response. Therefore, a three-point calibration is performed at the start of each test day to check for linearity. If the response is not linear (± 2% of scale), the cell is replaced.

Method: NO/NOx by Continuous Analyzer

Applicable
Ref. Methods: EPA 7E, EPA 20; ARB 1-100, BA ST-13A

Principle: A sample is continuously drawn from the flue gas stream, conditioned, and conveyed to the instrument for direct readout of NO or NOx.

Analyzer: Teco Model No. 10AR

Measurement
Principle: Chemiluminescence

Accuracy: $\pm 1\%$ of full scale

Ranges: 0-2.5, 0-10, 0-25, 0-100, 0-250, 0-1000, 0-2500,
0-10,000 ppm

Output: 0-10 mV

Inferences: Compounds containing nitrogen (other than ammonia) may cause interference.

Response
Time: 90%, 1.5 seconds (NO mode) and 1.7 seconds (NOx mode)

Sampling
Procedure: A representative flue gas sample is collected and conditioned using the CEM system described previously. If EPA Method 20 is used, that method's specific procedures for selecting sample points are used. Otherwise, the procedures described in the report are used to select sample locations.

Analytical
Procedure: The oxides of nitrogen monitoring instrument is a chemiluminescent nitric oxide analyzer. The operational basis of the instrument is the chemiluminescent reaction of NO and ozone (O₃) to form NO₂ in an excited state. Light emission results when excited NO₂ molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier tube, the output of which is electronically processed so it is linearly proportional to the NO concentration. The output of the instrument is in ppmV.

When NO_2 is expected to be present in the flue gas, a supercooled water drop-out flask will be placed in the sample line to avoid loss of NO_2 . Since NO_2 is highly soluble in water, "freezing out" the water will allow the NO_2 to reach the analyzers for analysis. The analyzer measures NO only. In the NO_x mode, the gas is passed through a moly converter which converts NO_2 to NO and a total NO_x measurement is obtained. NO_2 is determined as the difference between NO and NO_x . Use of a moly converter instead of a stainless steel converter eliminates NH_3 interference; NH_3 is converted to NO with a stainless converter, but not with a moly converter.

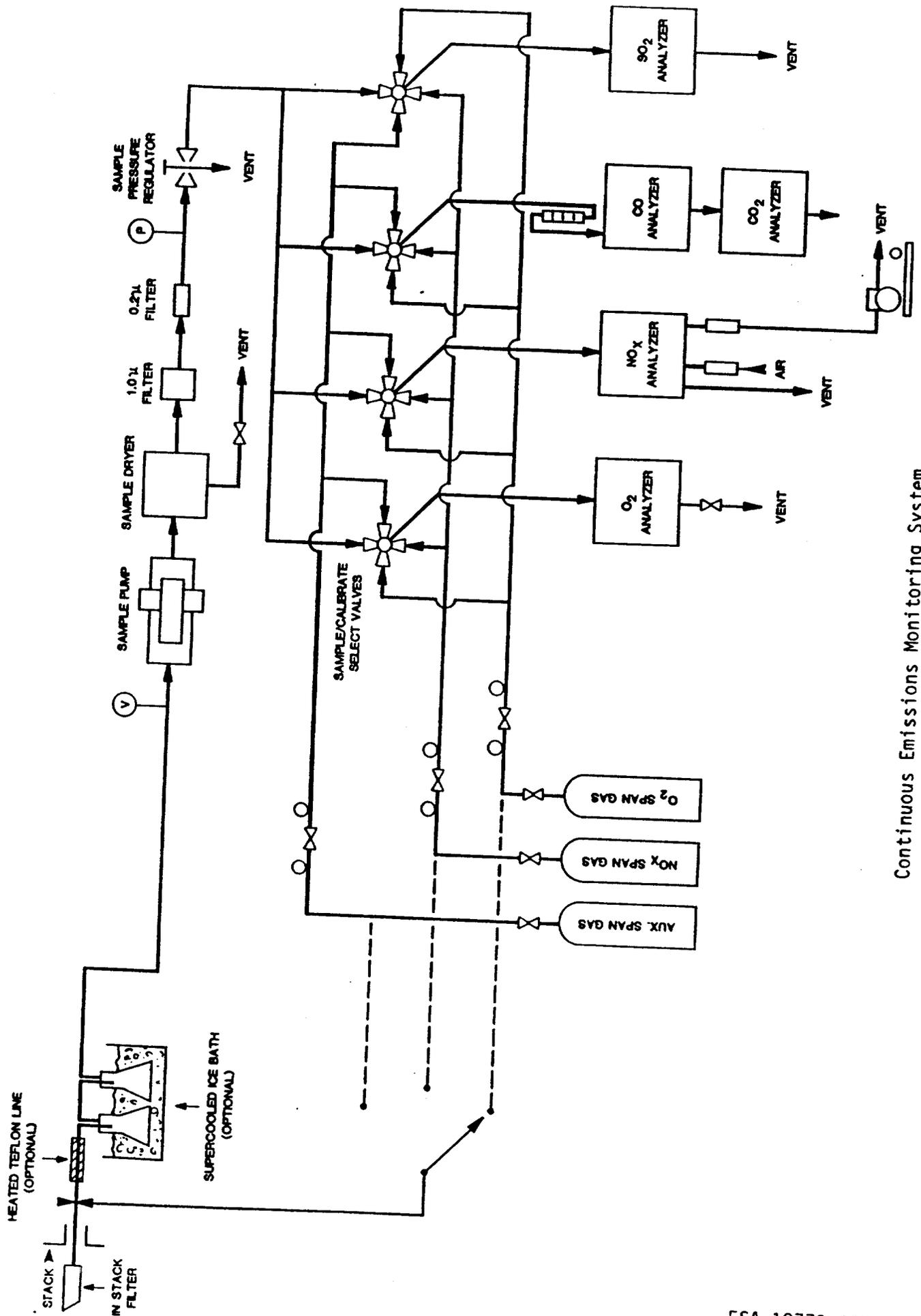
Method: Determination of Moisture in Stack Gases

Applicable Ref. Methods: EPA 4, ARB 1-4

Principle: A gas sample is extracted at a constant rate from the source; moisture is removed from the sample stream and determined volumetrically or gravimetrically.

Sampling Procedure: The sample train used in the tests is shown in the following figure. The sample is drawn at a constant rate through a stainless steel probe. The probe is connected to an impinger train by Teflon tubing. The train consists of two Smith-Greenburg impingers which contain 100 ml water, an empty impinger as a knockout, and an impinger containing silica gel to protect the pump from moisture.

Sample Recovery and Analysis: Following testing, moisture content is determined gravimetrically from initial and final impinger weights.



Continuous Emissions Monitoring System