DRI STANDARD OPERATING PROCEDURE

Performance Audit of Continuous Gas Analyzers

DRI SOP #4-101.3

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1.0 GENERAL DISCUSSION

1.1 Purpose of Procedure

This standard operating procedure is intended to provide the procedures for conducting a performance audit of the continuous gas analyzers that measure ambient concentrations of carbon monoxide (CO), sulfur dioxide (SO_2), nitric oxide and nitrogen dioxide (NO/NO_2), and oxides of nitrogen plus nitric acid (NO_Y^*/NO_Y) as operated by Atmospheric Research and Analysis (ARA), Inc. at the Southeastern Aerosol Research Characterization (SEARCH) study sites.

This procedure will be followed by all audit personnel of the Division of Atmospheric Science of the Desert Research Institute.

1.2 Underlying Principles

The continuous gas analyzers measure the ambient concentrations of trace gases using physical methods that are specific to the particular gases that are measured. One minute averages are collected by the site computer data acquisition system. The ambient sample is collected at a level above the ground of approximately 9 meters.

The performance audit consists of two methods to introduce gases of known concentrations to the continuous gas analyzers and determining their responses. The first audit method (Gas Addition Audit) introduces a known concentration of a specific trace gas at a known rate to the inlet of the analyzer where it is mixed with the ambient sample. The response of the instrument to air with and without the audit gas is compared to the concentration of gas that is introduced. The second audit method (Gas Replacement Audit) dilutes known concentrations and amounts of the trace gas with known amounts of clean, dry air to the inlet of the analyzer. The response of the analyzer is compared to the audit input concentrations.

1.3 Method Interferences and Their Minimization

Highly variable ambient concentrations present difficulties in determining the instrument response to the audit gas during the Gas Addition Audit. This can be minimized by conducting the audit during period when changes may be slower such as midday

The response of the instruments to dry air during the Gas Replacement Audit may differ from the response to humid ambient air.

1.4 Ranges and Typical Values of Measurements

The concentration of ambient SO_2 ranges from 0 to 200 ppb in urban areas and 0 to 100 ppb in rural areas. The concentration of NO/NO_2, and NO_Y/NO_Y^* range from 0 to 300 in urban areas and 0 to 150 in rural areas. The concentration of CO ranges from 0 to 10 ppm in urban areas and 0 to 2 ppm in rural areas. The audit concentrations of the Gas Addition Audits are 50 to 80% of the full scale of the instrument. The audit concentrations for the Gas Replacement Audits cover a range of 10 to 90% of full scale.

1.5 Typical Lower Quantifiable Limits, Precision, and Accuracy

The accuracy of the audit mass flow meters is ±1%. The accuracy of the gases in the audit cylinders is ±1 %. The overall accuracy for the Gas Addition Audit is 3% for a concentration of 80 ppb (2000 ppb for CO). The overall accuracies for the Gas Replacement Audit concentrations are 3% at an audit input of 200 ppb (25 ppm for CO) and 10% at an audit input of 20 ppb (3 ppm for CO).

1.6 Audit Criteria

The following set of flags is used notify the operator of the audit results and the recommended action:

Measurement	CRITERIA/FLAGS (W, R, S)			
	None	Warning	Recalibrate	Suspect
Difference (%)	0-5	±5-10	±10-15	> ±15
Slope (deviation from 1.00)	< ±0.05	±0.05-0.10	±0.10-0.15	> ±0.15
Intercept (deviation from zero)	< ±1% full scale	±1%-2% full scale	±2%-3% full scale	> ±3% full scale

From U.S. EPA (1984): "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume II".

1.7 Personnel Responsibilities

The Field Auditors should read and understand the entire standard operating procedure prior to conducting a performance audit. Familiarity with the operation of the sampling equipment and the audit equipment is necessary for valid measurements. In addition the Field Auditor generates a preliminary report of the audit results at the time of the audit to be presented to the site operator.

It is the responsibility of the Audit Supervisor to ensure the audit procedures are properly followed, to examine and document all documentation, to arrange for maintenance and repair of audit equipment, to maintain the supplies necessary to insure uninterrupted measurements, and to generate a report summarizing the audit results.

1.8 Definitions

The following terms are used in this document:

Performance audit: Comparison of instrument response to audit standards.
Audit standards: Standards provided by auditor for comparison.

1.9 Related Procedures
DRI SOP #4-204.1: Calibration of Tylan Mass Flow Controllers
DRI SOP #4-208.1: Calibration of Gilibrator Bubble Flow Meter
DRI SOP #4-209.1: Calibration of Pressure Transfer Standard
DRI SOP #4-210.1: Calibration of Temperature Transfer Standard

2.0 APPARATUS, INSTRUMENTATION, REAGENTS, AND FORMS

2.1 Apparatus and Instrumentation

2.1.1 Description

Tylan Mass Flow Controllers for Addition Audits, 30 and 50 cm^3/min
Audit Dilution System with Tylan Mass Flow Controllers, 10 l/min for air and 30 cm^3/min for gas
Scott-Marrin gas cylinder with CO/SO_2 mixture in N_2 with approximate concentrations of 300/10 ppm
Scott-Marrin gas cylinders with NO, NO_2, and NPN in N_2 with approximate concentrations of 10 ppm
Scott-Marrin gas cylinder with $NO/CO/SO_2$ mixture in N_2 with approximate concentrations of 50/50/5000 ppm
Zero air system with silica gel to remove water vapor, Purafil to oxidize NO to NO_2, activated charcoal to remove SO_2 and NO_2, and palladium on alumina pellets catalyst to oxidize CO to CO_2
Audit flow meter: Gilibrator bubble meter, model S (0.1-6 l/min) with printer
Audit pressure sensor: Thommen altimeter
Audit temperature sensor: Fluke Thermocouple Model 52 K/J
Teflon tubing, ¼ inch diameter, PFA grade 440 or 450
Teflon fittings, ¼ inch, PFA

2.1.2 Maintenance

Mass flow Controllers are calibrated before the audit.
Silica gel is changed when color changes from blue to clear.
Purifil is changed when color changes from purple to brown.
Charcoal is changed once a year.
Palladium on alumina catalyst is changed when CO zero increases
Containers are inspected for cracks each use.

2.1.3 Spare Parts and Supplies

Silica gel, Fisher Scientific, 750 Laurelwood Rd., Santa Clara, CA 95054
Purafil Chemisorbent Media RP 1/8 in, Air Filter Controls, 585 Charcot Ave, San Jose, CA 95131
Activated charcoal, P/N 05-685B, Fisher Scientific, 750 Laurelwood Rd., Santa Clara, CA 95054

Palladium (0.5%) on Alumina pellets, Engelhard COCat oxidation catalyst:

2.2 Forms and Paperwork

Audit forms for Gas Addition Audits
Audit forms for Gas Replacement Audits
Electronic copy of audit forms on portable computer that includes computation formulas.
The following pages contain blank worksheets for the Gas Addition and Replacement Audits.

CARBON MONOXIDE ADDITION AUDIT RECORD

desert research institute — REV 01/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # : NA		End :	EST

Site Instrument Data:

Manufacturer :	TEI			
Model No. :	48			
Analyzer S/N :				
Equivalency No. :	NA			
Analyzer Type :	Gas Filter Correlation			
Range Zero :		FS :		ppb
Chart Zero :		FS :		%
Analyzer Slope :		Int. :		
Zero Setting :				
Span Setting :				
Filter :				

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :

	SN	Cal Date	Slope	Intercept	Std T
Gas MFC(0-30):					
Gas MFC(0-50):					
Air MFC(0-5):					

Audit Cylinder:

NO		ppm in N2
NO2		ppm in N2
npn		ppm in N2
SO2		ppm in N2
CO		**ppm in N2**

Audit Results

---- Gas ---- VDC	sccm	----- Air ---- sccm	Audit Input ppb	ppb	Adj Response ppb	% Dev.	Time

Average	
Std Dev	

Comments: ______________________________

Figure 2-1: Blank Worksheet for CO Addition Audit Input

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SULFUR DIOXIDE ADDITION AUDIT RECORD

REV 01/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :	NA	End :	EST

Site Instrument Data:

Manufacturer :	TEI				
Model No. :	43C				
Analyzer S/N :					
Equivalency No. :					
Analyzer Type :	Pulsed Flourescense				
Range Zero :		FS :		ppb	
Chart Zero :		FS :		%	
Analyzer Slope :		Int. :			
Zero Setting :					
Span Setting :					
Filter :					

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :

	SN	Cal Date	Slope	Intercept	Std T
Gas MFC(0-30):					
Gas MFC(0-50):					
Air MFC(0-5):					

Audit Cylinder:

NO		ppm in N2
NO2		ppm in N2
npn		ppm in N2
SO2		**ppm in N2**
CO		ppm in N2

Audit Results

----- Gas ----- VDC	sccm	----- Air ----- sccm	Audit Input ppb	ppb	Adj Response ppb	% Dev.	Time

Average	
Std Dev	

Comments:

Figure 2.2: Blank Worksheet for SO_2 Addition Audit Record

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NITRIC OXIDE AUDIT RECORD **REV 01/99**

NITRIC OXIDE ADDITION

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :	NA	End :	EST

Site Instrument Data:

Manufacturer :	TEI		
Model No. :	42C		
Analyzer S/N :			
Equivalency No. :	NA		
Analyzer Type :	Gas Chemiluminescence		
Range Zero :		FS :	ppb
NO Slope :		Int. :	
NO2 Slope :		Int. :	
Zero Setting :			
Span Setting :			
Filter :			

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :	
Date :	
Conc/Bal :	ppm in N2
Press. :	psig

Audit Instrument Information:

Audit System:

Mfg/Model :

	SN	Cal Date	Slope	Intercept	Std T
Gas MFC(0-30):					
Gas MFC(0-50):					
Air MFC(0-5):					

Audit Cylinder:

NO	**ppm in N2**
NO2	ppm in N2
npn	ppm in N2
SO2	ppm in N2
CO	ppm in N2

Audit Results

----- Gas -----		----- Air -----		Audit Input		---------- NO ----------			---------- NO2 ----------			
							Adj Response			Adj Response		
VDC	sccm	VDC	sccm	ppb		ppb	ppb	% Dev.	ppb	ppb	% Dev.	Time

Average		Average	
Std Dev		Std Dev	

Comments: ______________________________

Figure 2.3: Blank Worksheet for NO to NO/NO_2 Analyzer Addition Audit Record

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NOy*/NOy ADDITION AUDIT RECORD

Nitric Oxide Addition

REV 01/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :	NA	End :	EST

Site Instrument Data:

Manufacturer :	TEI		
Model No. :	42C NOy*/NOy		
Analyzer S/N :			
Equivalency No. :			
Analyzer Type :	Gas Chemiluminescence		
Range Zero :		FS :	ppb
NOy* Slope :		Int. :	
NOy Slope :		Int. :	
Zero Setting :			
Span Setting :			
Filter :			

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :	
Date :	
Conc/Bal :	ppm in N2
Press. :	psig

Audit Instrument Information:

Audit System:

Mfg/Model :

	SN	Cal Date	Slope	Intercept	Std T
Gas MFC(0-30):					
Gas MFC(0-50):					
Air MFC(0-5):					

Audit Cylinder:

NO	**ppm in N2**
NO2	ppm in N2
npn	ppm in N2
SO2	ppm in N2
CO	ppm in N2

Audit Results

----- Gas ----- VDC	sccm	----- Air ----- VDC	sccm	Audit Input ppb		---------- NOy* ---------- ppb	Adj Response ppb	% Dev.	---------- NOy ---------- ppb	Adj Response ppb	% Dev.	Time

Average		Average	
Std Dev		Std Dev	

Comments: ______________________________

Figure 2.4: Blank Worksheet for NO to NO_Y/NO_Y^* Analyzer Addition Audit Record

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NITROGEN DIOXIDE AUDIT RECORD

REV 01/99

NITROGEN DIOXIDE ADDITION

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :		End :	EST

Site Instrument Data:

Manufacturer :	TEI		
Model No. :	42C		
Analyzer S/N :			
Equivalency No. :	NA		
Analyzer Type :			
Range Zero :		FS :	ppb
NO Slope :		Int. :	
NO2 Slope :		Int. :	
Zero Setting :			
Span Setting :			
Filter :			

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :	
Date :	
Conc/Bal :	ppm in N2
Press. :	psig

Audit Instrument Information:

Audit System:

Mfg/Model :

	SN	Cal Date	Slope	Intercept	Std T
Gas MFC(0-30):					
Gas MFC(0-50):					
Air MFC(0-5):					

Audit Cylinder:

NO	ppm in N2
NO2	**ppm in N2**
npn	ppm in N2
SO2	ppm in N2
CO	ppm in N2

Audit Results

----- Gas ----- VDC	sccm	----- Air ----- VDC	sccm	Audit Input ppb	NO ppb	NOX ppb	NO2 ppb	Adj NO2 ppb	------ NO2 ------ Deviation	Time

Average

Std Dev

Comments: ______________________

Figure 2.5: Blank Worksheet for NO_2 to NO/NO_2 Analyzer Addition Audit Record

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NOy*/NOy ADDITION AUDIT RECORD

NPN ADDITION

REV 01/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :	NA	End :	EST

Site Instrument Data:

Manufacturer :	TEI		
Model No. :	42C NOy*/NOy		
Analyzer S/N :			
Equivalency No. :	NA		
Analyzer Type :	Gas Chemiluminescence		
Range Zero :		FS :	ppb
NOy* Slope :		Int. :	
NOy Slope :		Int. :	
Zero Setting :			
Span Setting :			
Filter :			

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :

	SN	Cal Date	Slope	Intercept	Std T
Gas MFC(0-30):					
Gas MFC(0-50):					
Air MFC(0-5):					

Audit Cylinder:

NO		ppm in N2
NO2		ppm in N2
NPN		**ppm in N2**
SO2		ppm in N2
CO		ppm in N2

Audit Results

----- Gas ----- VDC	----- Gas ----- sccm	----- Air ----- VDC	----- Air ----- sccm	Audit Input ppb		NOy* ppb	NOy* Adj Response ppb	NOy* % Dev.	NOy ppb	NOy Adj Response ppb	NOy % Dev.	Time

Average		Average	
Std Dev		Std Dev	

Comments:

Figure 2.6: Blank Worksheet for NPN to NO_Y/NO_Y^* Analyzer Addition Audit Record

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CARBON MONOXIDE AUDIT INPUT

REV 01/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :	NA	End :	EST

Site Instrument Data:

Manufacturer :	TEI			
Model No. :	48			
Analyzer S/N :				
Equivalency No. :	NA			
Analyzer Type :	Gas Filter Correlation			
Range Zero :		Fullscale :		ppb
Chart Zero :		Fullscale :		%
Analyzer Slope :		Intercept :		
Zero Setting :				
Span Setting :				
Filter :				

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :	
System ID :	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN :		
Conc./balance :		ppm in N2
Pressure :		psig

Audit Results

Audit Flow					Analyzer Response				Deviation		
Gas		Air		Conc	Instrument		DAS	Adj Zero	Inst	DAS	Adj Zero
VDC	sccm	VDC	sccm	ppb	VDC	ppb	ppb	ppb	%	%	%
								Average			
								Standard Deviation			

	Instr	DAS	Adj Zero
Slope			
Intercept			
Correlation			

Comments: ____

Figure 2-7: Blank Worksheet for CO Gas Replacement Audit Input

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SULFUR DIOXIDE AUDIT INPUT

REV 02/99

Sampling Network :	SEARCH	Site Name :		Date :			
Auditor :		Site ID :		Start Time :		EST	
Operator :	ARA	AIRS # :	NA	End :		EST	

Site Instrument Data:

Manufacturer :	TEI				
Model No. :	43C				
Analyzer S/N :					
Equivalency No. :	NA				
Analyzer Type :	Pulsed Flourescence				
Range Zero :		FS :		ppb	
Chart Zero :		FS :		%	
Analyzer Slope :		Int. :			
Zero Setting :					
Span Setting :					
Filter :					

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	NA

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :	
System ID :	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN :		
Conc./balance :		ppm in N2
Pressure :		psig

Audit Results

Audit Flow					Analyzer Response				Deviation		
Gas		Air		Conc	Instrument		DAS	Adj zero	Inst	DAS	Adj zero
VDC	sccm	VDC	sccm	ppm	VDC	ppb	ppm	ppm	%	%	%
								Average			
								Std Deviation			

	Instr	DAS	Adj Zero
Slope			
Intercept			
Correlation			

Comments: ______________________________________

Figure 2-8: Blank Worksheet for SO_2 Gas Replacement Audit Input

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NITRIC OXIDE AUDIT INPUT

REV 02/99

Sampling Network	SEARCH	Site Name		Date			
Auditor		Site ID		Start Time		EST	
Operator	ARA	AIRS #		End		EST	

Site Instrument Data:

Manufacturer	TEI			
Model No.	42C NO/NO2			
Analyzer S/N				
Equivalency Number				
Analyzer Type	Gas Chemiluminesence			
Range Zero/Fullscale		Fullscale		ppb
Chart Zero/Fullscale		Fullscale		%
Analyzer Slope		Intercept		
Zero Setting				
Span Setting				
Filter				

Calibration System:

Manufacturer	
Model No.	
SN	
Cert. Date	

Calibration Cylinder:

SN		
Date		
Conc/Bal		ppm in N2
Press.		psig

Audit Instrument Information:

Audit System:

Mfg/Model	
System ID	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN:		
NO Concentration		ppm in N2
NOx Conc.		ppm in N2
Pressure		psig

Audit Results

Audit Flow					Analyzer Response				Deviation		
Gas		Air		Conc	Instrument		DAS	Adj DAS	Inst	DAS	Adj DAS
VDC	sccm	VDC	sccm	ppb	VDC	ppb	ppb	ppb	%	%	%
								Average Deviation			
								Standard Deviation			

	Instr	DAS	Chart
Slope			
Intercept			
Correlation			

Comments: ______________________________

Figure 2-9: Blank Worksheet for NO to NO Channel of NO/NO_2 Gas Replacement Audit Input

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OXIDES OF NITROGEN AUDIT INPUT

REV 02/99

Sampling Network	SEARCH	Site Name		Date		
Auditor		Site ID		Start Time		EST
Operator	ARA	AIRS #		End		EST

Site Instrument Data:

Manufacturer	TEI			
Model No.	42C NO/NO2			
Analyzer S/N				
Equivalency Number				
Analyzer Type	Gas Chemiluminesence			
Range Zero		Fullscale		ppb
Chart Zero		Fullscale		%
Analyzer Slope		Intercept		
Zero Setting				
Span Setting				
Filter				

Calibration System:

Manufacturer	
Model No.	
SN	
Certification Date	

Calibration Cylinder:

SN		
Date		
Conc/Bal		ppm in N2
Press.		psig

Audit Instrument Information:

Audit System:

Mfg/Model	
System ID	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN:		
NO Concentration		ppm in N2
NOx Conc.		ppm in N2
Pressure		psig

Audit Results

Audit Flow					Analyzer Response				Deviation		
Gas		Air		Conc	Instrument		DAS	Adj DAS	Inst	DAS	Adj DAS
VDC	sccm	VDC	sccm	ppb	VDC	ppb	ppb	ppb	%	%	%
								Average Deviation			
								Standard Deviation			

	Instr	DAS	Chart
Slope			
Intercept			
Correlation			

Comments:

Figure 2-10: Blank Worksheet for NO to NO_2 Channel of NO/NO_2 Gas Replacement Audit Input

NITROGEN DIOXIDE AUDIT INPUT REV 02/99

Sampling Network	SEARCH	Site Name		Date	
Auditor		Site ID		Start Time	EST
Operator	ARA	AIRS #		End	EST

Site Instrument Data:

Manufacturer	TEI		
Model No.	42C NO/NO2		
Analyzer S/N			
Equivalency No.			
Analyzer Type	Gas Chemiluminesence		
Range Zero/Fullscale		Fullscale	ppb
Chart Zero/Fullscale		Fullscale	%
Analyzer Slope		Intercept	
Zero Setting			
Span Setting			
Filter			

Calibration System:

Manufacturer	
Model No.	
SN	
Cert. Date	

Calibration Cylinder:

SN ____________
Date ____________
Conc/Bal ____________ ppm in N2
Press. ____________ psig

Audit Instrument Information:

Audit System:

Mfg/Model				
System ID				
	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN:		
NO Concentration		ppm in N2
NOx Conc.		ppm in N2
Pressure		psig

Audit Results

Audit Flow						Analyzer Response					Deviation
Ozone Setting		Air		NO2 Conc.	NO2 Conv.	NO Initial	NOx Initial	NO Final	NOx Final	NO2 Resp	DAS
Set Point	Setting	VDC	sccm	ppb	ppb	ppb	ppb	ppb	ppb	ppb	%
off	0										
~80	40										
~180	150										
~400	550										
										Average Deviation	

Converter Efficiency: Slope ____ %
Average ____ %

	DAS
Slope	
Intercept	
Correlation	

Comments: ____

Figure 2-11: Blank Worksheet for NO_2 by GPT to NO/NO_2 Gas Replacement Audit Input

NITRIC OXIDE AUDIT INPUT (NOy*)

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Sampling Network	SEARCH	Site Name		Date	
Auditor		Site ID		Start Time	EST
Operator	ARA	AIRS #	NA	End	EST

Site Instrument Data:

Manufacturer	TEI		
Model No.	42C NOy*/NOy		
Analyzer S/N			
Equivalency Number	NA		
Analyzer Type	Gas Chemiluminesence		
Range Zero/Fullscale		Fullscale	ppb
Chart Zero/Fullscale		Fullscale	%
Analyzer Slope		Intercept	
Zero Setting			
Span Setting			
Filter			

Calibration System:

Manufacturer	
Model No.	
SN	
Cert. Date	

Calibration Cylinder:

SN		
Date		
Conc/Bal		ppm in N2
Press.		psig

Audit Instrument Information:

Audit System:

Mfg/Model	
System ID	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN:		
NO Concentration		ppm in N2
NOx Conc.		ppm in N2
Pressure		psig

Audit Results

Audit Flow					Analyzer Response				Deviation		
Gas		Air		Conc	Instrument		DAS	Adj	Inst	DAS	Adj
VDC	sccm	VDC	sccm	ppb	VDC	ppb	ppb	ppb	%	%	%
								Average Deviation			
								Standard Deviation			

	Instr	DAS	Adj
Slope			
Intercept			
Correlation			

Comments: ____________________

Figure 2-12: Blank Worksheet for NO to NO_Y^* Channel for NO_Y/NO_Y^* Gas Replacement Audit

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NITRIC OXIDE AUDIT INPUT (NOy)

REV 02/99

Sampling Network	SEARCH	Site Name		Date	
Auditor		Site ID		Start Time	EST
Operator	ARA	AIRS #	NA	End	EST

Site Instrument Data:

Manufacturer	TEI			
Model No.	42C NOy*/NOy			
Analyzer S/N				
Equivalency Number	NA			
Analyzer Type	Gas Chemiluminesence			
Range Zero		Fullscale		ppb
Chart Zero		Fullscale		%
Analyzer Slope		Intercept		
Zero Setting				
Span Setting				
Filter				

Calibration System:

Manufacturer	
Model No.	
SN	
Certification Date	

Calibration Cylinder:

SN		
Date		
Conc/Bal		ppm in N2
Press.		psig

Audit Instrument Information:

Audit System:

Mfg/Model	
System ID	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN:		
NO Concentration		ppm in N2
NOx Conc.		ppm in N2
Pressure		psig

Audit Results

Audit Flow					Analyzer Response				Deviation		
Gas		Air		Conc	Instrument		DAS	Adj	Inst	DAS	Adj
VDC	sccm	VDC	sccm	ppb	VDC	ppb	ppb	ppb	%	%	%
								Average Deviation			
								Standard Deviation			

	Instr	DAS	Adj
Slope			
Intercept			
Correlation			

Comments: ____________________

Figure 2-13: Blank Worksheet for NO to NO_Y Channel for NO_Y/NO_Y^* Gas Replacement Audit

desert research institute

NITROGEN DIOXIDE (GPT) AUDIT INPUT (NOy*/NOy) REV 02/99

Sampling Network	SEARCH	Site Name		Date	
Auditor		Site ID		Start Time	EST
Operator	ARA	AIRS #	NA	End	EST

Site Instrument Data:

Manufacturer	TEI			
Model No.	42C NOy*/NOy			
Analyzer S/N				
Equivalency Number	NA			
Analyzer Type	Gas Chemiluminesence			
Range Zero		Fullscale		ppb
Chart Zero		Fullscale		%
Analyzer Slope		Intercept		
Zero Setting				
Span Setting				
Filter				

Calibration System:

Manufacturer	
Model No.	
SN	
Certification Date	

Calibration Cylinder:

SN		
Date		
Conc/Bal		ppm in N2
Press.		psig

Audit Instrument Information:

Audit System:

Mfg/Model	
System ID	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN:	0	
NO Concentration	0.00	ppm in N2
NOx Conc.	0.00	ppm in N2
Pressure	0	psig

Audit Results

Audit Input		Analyzer Response				Converter Efficiency	
	NO2 Input	NOy*		NOY		NOy*	NOy
Ozone level	ppb	Initial	Final	Initial	Final	%	%
40							
150							
450							

	NOy*	NOy
Average Converter Efficiency		
Standard Deviation		

Comments: ______________________________

Figure 2-14: Blank Worksheet for NO_2 by GPT to NO_Y/NO_Y^* Analyzer Gas Replacement Audit

desert research institute

NITROGEN DIOXIDE AUDIT RECORD (NO2)

REV 02/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :		End :	EST

Site Instrument Data:

Manufacturer :	TEI			
Model No. :	42C NO/NO2			
Analyzer S/N :				
Equivalency No. :	NA			
Analyzer Type :	Gas Chemiluminescense			
Range Zero :		FS :		ppb
Chart Zero :		FS :		%
Analyzer Slope :		Int. :		
Zero Setting :				
Span Setting :				
Filter :				

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :	
System ID :	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN :		
Conc./balance :		ppm in N2
Pressure :		psig

Audit Results

|------------------------------ Audit Flow ------------------------|-------- Analyzer Response -----------| |----- Deviation -----|

Gas VDC	Gas sccm	Air VDC	Air sccm	Conc ppb	Corr ppb	DAS ppb NO	NOx	NO2	Corr NO3	DAS %	Corr %

Average Deviation		
Standard Deviation		

	Instr	DAS	Corr DAS
Slope			
Intercept			
Correlation			

Comments: ____

Figure 2-15: Blank Worksheet for NO_2 to NO/NO_2 Analyzer Gas Replacement Audit

desert research institute

NITRIC OXIDE AUDIT RECORD (NOy*/NOy-NPN)

REV 02/99

Sampling Network :	SEARCH	Site Name :		Date :	
Auditor :		Site ID :		Start Time :	EST
Operator :	ARA	AIRS # :		End :	EST

Site Instrument Data:

Manufacturer :	TEI			
Model No. :	42C NOy*/NOy			
Analyzer S/N :				
Equivalency No. :	NA			
Analyzer Type :	Gas Chemiluminescense			
Range Zero :		FS :		ppb
Chart Zero :		FS :		%
Analyzer Slope :		Int. :		
Zero Setting :				
Span Setting :				
Filter :				

Calibration System:

Manufacturer :	
Model No. :	
SN :	
Cert. Date :	

Calibration Cylinder:

SN :		
Date :		
Conc/Bal :		ppm in N2
Press. :		psig

Audit Instrument Information:

Audit System:

Mfg/Model :	
System ID :	

	SN	Cal Date	Slope	Intercept
Air MFC:				
Gas MFC:				

Audit Cylinder:

Cylinder SN :		
Conc./balance :		ppm in N2
Pressure :		psig

Audit Results

Audit Flow: Gas VDC	Gas sccm	Air VDC	Air sccm	Conc ppb	Corr conc ppb	Analyzer Response: NOy* ppb	NOy ppb	Corrected Deviation: NOy* %	NOy %

	NOy*	NOy
Average Deviation		
Standard Deviation		

Instr	NOy*	NOy
Slope		
Intercept		
Correlation		

Comments: ____________________

Figure 2-16: Blank Worksheet for NPN to NO_Y/NO_Y^* Analyzer Gas Replacement Audit

3.0 CALIBRATION STANDARDS

3.1 Preparation, Ranges, and Traceability of Standards

The Tylan mass flow controllers (MFC) in the audit dilution systems are calibrated with Brooks Vol-u-met mercury-sealed piston flow meters. The 30 and 50 cm^3/min MFCs are calibrated with Vol-u-met model 1053-A2A with a 100 cm^3 tube. The 5 and 10 l/min MFCs are calibrated with Vol-u-met model B-924!-007-WAA with a 1200 cm^3 tube. Both Vol-u-mets have been fitted with electronic sensors that measure the time required for the piston to move a fixed distance. The volumes associated with the movement of the pistons are determined with Hastings bubblemeters that are NIST-traceable.

The Gilibrator Bubble Flow Meter is calibrated with a Hastings Bubble flow meter, model HBM-1A, 100 cm^3 tube, S/N 1426, that is NIST-traceable.

The Thommen altimeter is checked with a Fortin-type mercury-in-glass barometer. The barometer reading is corrected for temperature and altitude using corrections provided by the Smithsonian Meteorological Tables (List, 1951).

The Fluke thermocouple is calibrated at approximately 0 and 30 °C in a water bath using a Brooklyn Thermometer (29 – 31 °C) S/N 10772 NIST-traceable.

3.2 Use of Standards

The audit Mass Flow Controllers are calibrated prior to the field audit. If questions arise as to audit results, the MFCs are calibrated after the audit.

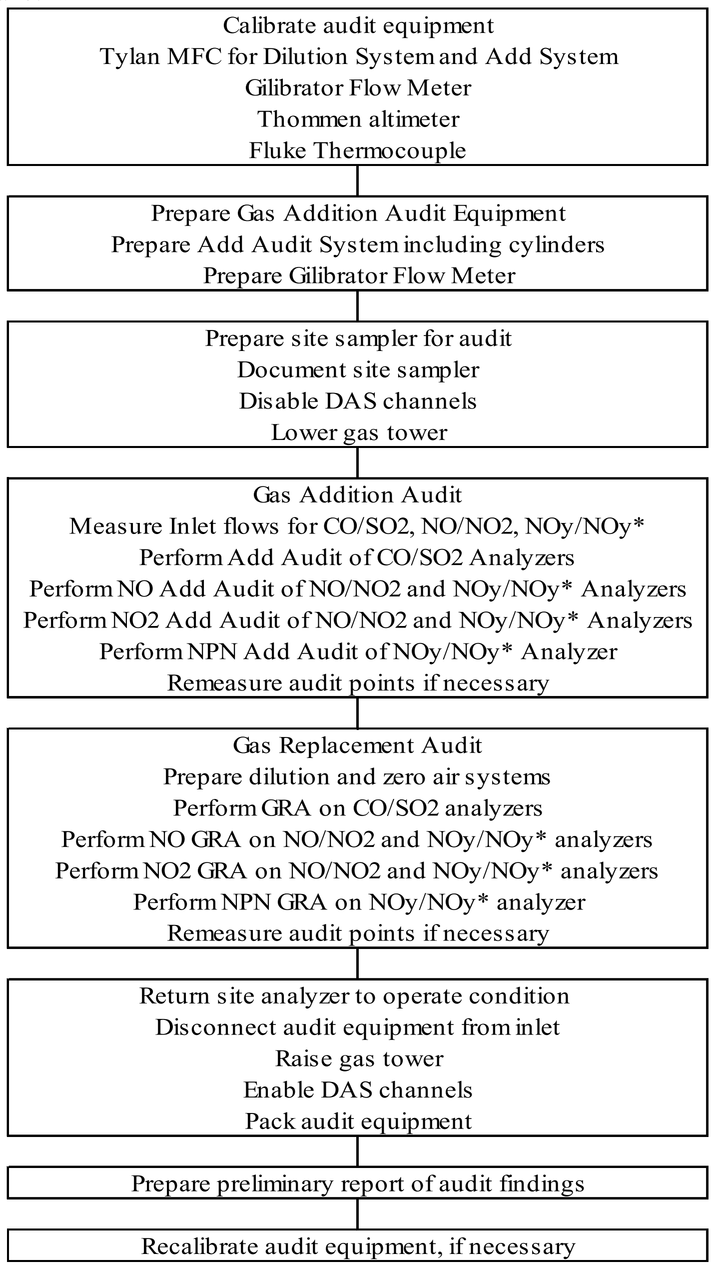
3.3 Typical Accuracy of Calibration Standards

The accuracy of the Brooks Vol-u-mets is ±1%. The accuracy of the pressure standard is ±1 mb. The accuracy of the temperature standard is ±0.01 °C.

4.0 PROCEDURES

4.1 General Flow Diagram

The typical flow of the audit procedures for the continuous gas analyzers is depicted in the following figure.



4.2 Audit Procedures

The following sections describe in detail the audit procedures for the continuous gas analyzers. It should be reviewed before each audit so that all necessary tasks will be accomplished.

During the audit of the continuous gas analyzers, audit gases are introduced to the instrument at the instrument inlet. The Audit Dilution System (ADS) is operated near the base of the tower under a tent that protects it from direct sunlight and rain. Zero air and/or trace gas concentrations are introduced to the analyzers by the ADS through Teflon tubing attached to the sample inlets.

The gas addition audits (GAA) are done first, followed by the gas replacement audits (GRA). During the GAA, trace gas is introduced directly to the sample inlet and diluted by the sample flow. During the GRA, trace gas is diluted with clean, dry air and then introduced to the sample inlet. The following procedures contain one section for the GAA and a second section for the GRA.

4.2.1 Gas Addition Audits (GAA)

The CO and SO_2 analyzers use the same inlet with the separate MFC's. These analyzers are audited at the same time by introducing trace gases from a cylinder containing a mixture of CO and SO_2. The NO/NO_2 and NO_Y/NO_Y^* analyzers have separate inlets and separate MFC's. These analyzers can be audited at the same time by supplying trace gas to their inlets through a two-way solenoid valve that switches gas between one inlet and the other inlet. The GAA are done with NO for both analyzers, NO_2 for the NO/NO_2 analyzer, and n-propyl nitrate (NPN) for the NO_Y/NO_Y^* analyzer.

The order of the GAA is the (1) CO/SO_2 analyzers, (2) NO to the NO/NO_2 and NO_Y/NO_Y^* analyzers, (3) NO_2 to the NO/NO_2 analyzer, and (4) NPN to the NO_Y/NO_Y^* analyzer. In each case, the analyzer samples 9 minutes of ambient air followed by 9 minutes of ambient air plus a trace gas for 8 to 10 cycles ending with 9 minutes of ambient air. The instrument response to the known audit concentration for a particular 9 minute period is determined by subtracting the average of the ambient readings before and after the period. If the ambient readings have too much variation from one period to the next, one or the other may no be used. The ambient readings need to be relatively constant or at least slowly changing during the audit for the Gas Addition method to provide meaningful results.

1) Prepare audit forms or audit notebook by entering site name and date of audit.
2) Prepare portable computer and Excel Addition audit worksheet

3) Record serial numbers of instruments and mass flow controllers.
4) Record information regarding the site gas cylinders including serial number, gas concentration, pressure, and certification date.
5) Unpack the gas addition MFC enclosure, gas addition switching valve, various cylinders that will be used for the GAA, regulators, tubing and fittings, and Gilibrator flow meter.
6) Place the GAA MFC on small table or box under tent. Remove caps from fittings. Attach 1/8th in Teflon tubing from outlet of 30 cm^3/min MFC to common side of gas addition switching valve
7) For the gas that is to be introduced, attach regulator to its designated gas cylinder. Attach Teflon tubing to outlet of regulator. Purge each regulator of air using the following procedure: turn regulator valve counter-clockwise to close; open cylinder valve to pressurize high pressure side of regulator; close cylinder valve; open regulator valve by turning clockwise to release pressure; close regulator valve; repeat process at least 4 more times. Leave cylinder valve closed. Connect tubing from regulator to gas inlet fitting on GAA MFC box.
8) Prepare Gilibrator flow meter to use to measure the sample flow rate at the instrument inlets. Use the S-size (6 l/min) flow cell since the inlet flows are approximately 2.5 to 3 l/min.
9) When the GAA and Gilibrator equipment are ready, disable the Gas Analyzer channels on data acquisition system (DAS). Record time that channels were disabled.
10) Lower Gas Sample Inlet tower so that the inlet box is near the ground at a level that it can be under the edge of the tent. This protects the inlets to the instruments in case of rain. Move tent over inlet box.
11) Remove the small funnels on the CO/SO_2, the NO/NO_2, and the NO_Y/NO_Y^* inlets. Attach short piece of Teflon tubing to each inlet and measure the flow rate at each inlet. Collect at least 3 sets of 10 readings with the Gilibrator. As with other flow measurements, the flow rate measured by the Gilibrator tends to decrease from its initial value for the first few sets of readings as the temperature in the cell equilibrates. The three sets of 10 readings are obtained should vary less than ±0.01 l/min. Measure and record the ambient pressure and temperature with each set of flow rate measurements. Calculate the audit flow rates at standard conditions of 1 atm for pressure and 298.15 °K (25 °C). Compare the audit flow rates to the MFC flow rates displayed on the site DAS.
12) Enter the audit flow rates in the Excel Gas Addition worksheets. Enter or check the values for the concentrations of the audit cylinders and the coefficients for the Add MFC. Confirm that the coefficients correctly convert voltage to the standard flow rate at 1 atm and 298.15 °K (25 °C)
13) The Excel Addition worksheet calculates the concentration of the trace gas that is added to the instrument by determining the dilution ratio and then multiplying that by

the cylinder concentration of the gas. For the sample flow rates and the cylinder concentrations, determine the flow rate of the Add MFC to obtain concentrations in the upper half of the expected range of each analyzer. Turn on power to Add MFC box and enter desired flow rate value in thumbwheel switches. Attach digital volt meter to front panel of Add MFC box and check output voltage of the 30 cm^3/min MFC. Enter flow voltage in Excel Addition worksheet and check expected concentration. Adjust if outside range of instrument.

14) For the CO/SO_2 analyzer, connect a Teflon tube from the normally closed side of the switching valve to a Teflon "T". Attach one side of the "T" to the short piece of tube connected to the CO/SO_2 inlet. Connect a short piece of Teflon tubing to the inlet side of the "T". Set the timer to 999sec and enter 540 into the switches. Connect timer to 110 VAC and record time of start of addition audit. The light on the timer will be steady indicating that flow is going through the normally open port and the analyzer is sampling ambient air. After 9 minutes, the valve will switch, the light will blink indicating that flow is going through the normally closed side and that the analyzer is sampling ambient air plus audit gas.
15) For the NO/NO_2 and NO_Y/NO_Y^* analyzers the procedure is similar except that both sides of the solenoid valve are connected to the analyzers: the normally closed side to the NO/NO2 analyzer and the normally open side to the NO_Y/NO_Y^* analyzer. When audit gas is added to one analyzer, the other analyzer is sampling ambient air alone.
16) As the audit progresses, read and record the responses of the analyzers as displayed on the site DAS after they have equilibrated (generally just before the next switch). Also record the time that the switch becomes apparent. Enter the concentrations and the switching times in the Excel Addition worksheet. Review the differences between the ambient readings to see if the background has large changes from one period to the next. Some modifications to the ambient readings may be necessary.
17) Compare the instrument response to the audit input by calculating the percent differences between the instrument response and the audit input.

4.2.2 Gas Replacement Audit (GRA)

The GRA of the CO and SO_2 analyzers are done at the same time since the analyzers use the same inlet and the diluted gas is a mixture of CO and SO_2. The GRA of the NO/NO_2 and NO_Y/NO_Y^* analyzers are done at the same time. In either case, enough zero air must be generated so as to supply excess flow to each analyzer. The dilution air flow rate must exceed 3 l/min for the CO and SO_2 analyzers and 5 l/min for the NO/NO_2 and NO_Y/NO_Y^* analyzers.

The recommended order of the GRA is (1) CO/SO_2 analyzer, (2) NO and NO_2 by gas phase titration (GPT) to the NO/NO_2 and NO_Y/NO_Y^* analyzers, (3) NO_2 to the NO/NO_2 analyzer, and (4) NPN to the NO_Y/NO_Y^* analyzer.

1) Prepare audit forms or audit notebook by entering site name and date of audit.
2) Prepare portable computer and Excel Gas Replacement audit worksheets.
3) Unpack the gas dilution system, zero air system, cylinders that will be used for the GRA, regulators, tubing, and fittings.
4) Place the gas dilution system on small table or box under tent with the zero air system nearby. Remove caps from fittings. Attach $1/4^{th}$ in Teflon tubing from outlet of zero air system to air inlet of dilution system.
5) For the gas that is to be introduced, attach regulator to its designated gas cylinder. Attach Teflon tubing to outlet of regulator. Purge each regulator of air using the following procedure: turn regulator valve counter-clockwise to close; open cylinder valve to pressurize high pressure side of regulator; close cylinder valve; open regulator valve by turning clockwise to release pressure; close regulator valve; repeat process at least 4 more times. Leave cylinder valve closed. Connect tubing from regulator to gas inlet fitting on gas dilution system.
6) For the CO/SO_2 analyzers, connect a Teflon “T” to the small piece of Teflon tubing attached to the inlet. Connect a ¼ in Teflon tube from the gas output fitting of the gas dilution system to one side of a Teflon “T”. Connect a small piece of Teflon tubing to the other side of the “T” to prevent back flow from the air into the analyzer. Turn on the pump for the zero air system and set the pressure regulator to approximately 30 psi. For the zero level, leave all gas switches in the off position. Check that there is excess flow at the analyzer inlet by connecting a small rotameter to the open tube. Connect a digital voltmeter to the MFC voltage output terminals and set thumbwheel to read the air flow voltage. Record the voltage and enter in the Excel GRA worksheet.
7) For the NO/NO_2 and NO_Y/NO_Y^* analyzers, the audit gas is introduced into two Teflon “T’s” that are in series with one “T” going to each analyzer. Again connect a small Teflon tube to the open side of the second “T”. Check for excess flow at that tube.
8) Allow the analyzers to equilibrate on zero air. Read and record 5 readings from the site DAS for the analyzers being audited. The Excel GRA worksheet will average the readings and copy that value to a location for comparison with the audit input concentration.
9) Introduce the highest gas concentration to the analyzers by setting the gas switch. Record the voltages for the air and gas MFC’s and enter into the Excel GRA worksheet. The worksheet will calculate the audit concentration from these voltages.

After the readings have equilibrated, read and record 5 readings from the site DAS and enter into the Excel GRA worksheet.

10) For the CO/SO_2,analyzers, introduce gas concentrations at up to 4 more lower values followed by a final zero level. In all cases, enter site instrument data into worksheet and compare to the audit input concentrations.
11) For the NO audit input to the NO/NO_2 and NO_Y/NO_Y^* analyzers, the first GPT point is done after the analyzers equilibrate at the highest audit concentration. Nitrogen dioxide is generated by adding ozone to the audit NO. Turn the ozone generator power on and allow the temperature to stabilize (denoted by a blinking light). Generate enough ozone to reduce the NO reading of the analyzer to about 20% of the value at the high concentration. Allow instruments to equilibrate. Record 5 readings from the DAS and enter in Excel GRA worksheet as the after values for NO and NO_X. After the first GPT point, turn the ozone generator off and introduce the next lower NO concentration. Perform GPT's after the third and fourth points. The second and fifth points only have NO introduced. After the fifth point, introduce zero air to obtain a final zero.
12) Generate the differences between the audit input and the site instrument response for each instrument including the GPT for the NO/NO_2 analyzer. Calculate the converter efficiency for the NO/NO_2 for the GPT. Generate linear regressions for the instrument response vs. audit input.

4.2.3 Return Site Analyzer to Sampling Mode

1) Disconnect Teflon tubing from sample inlets. Attach inlet funnels.
2) Raise gas tower and secure.
3) Enable gas instrument channels on DAS. Record time that the gas analyzers were returned to operational status.

4.2.4 Final Audit Procedures

1) Turn power to MFC systems and zero air system off. Disconnect tubing from MFC systems and zero air system. Pack tubing and containers in Gas Audit bag.
2) Generate a preliminary report of audit findings that includes the differences between the audit inputs and site analyzer responses. Problems should be identified

5.0 QUANTIFICATION

5.1 Calibration procedures

5.1.1 The Tylan mass flow controllers (MFC) in the audit dilution systems are calibrated with Brooks Vol-u-met mercury-sealed piston flow meters. The 30 and 50 cm^3/min MFCs are calibrated with Vol-u-met model 1053-A2A with a 100 cm^3 tube. The 5 and 10 l/min MFCs are calibrated with Vol-u-met model B-924!-007-WAA with a 1200 cm^3 tube. Both Vol-u-mets have been fitted with electronic sensors that measure the time required for the piston to move a fixed distance. The volumes associated with the movement of the pistons are determined with Hastings bubblemeters that are NIST-traceable.

The Tylan MFCs are calibrated to produce flow rates at standard conditions of 1 atm and 273.15 °K (0 °C). The resulting flows rates need to be adjusted by the Ideal Gas Law if flows are required at other conditions.

1) The 30 and 50 cm^3/min MFCs are calibrated with nitrogen. The 5 and 10 l/min MFCs are calibrated with clean air.
2) The MFCs are calibrated in place in their enclosure. Disconnect outlet tube from MFC to be audited. Leave electronic connector attached to the MFC. Connect air or nitrogen to inlet of audit enclosure and outlet side of MFC to inlet of Vo-u-met. Attach digital volt meter to terminals of enclosure. Turn on enclosure power. Record voltage from flow meter with no flow.
3) Turn air or nitrogen on and set MFC flow voltage to 4.5 volts. Measure and record actual flow voltage. Measure and record temperature and pressure. Press button on Vol-u-met to start flow. Timer will automatically time the movement of the piston as it covers the volume. Record the Vol-u-met chamber pressure as the piston is rising. Record the time when the piston reaches its upper limit. Repeat 4 more times at 4.5 volts. Enter pressure, temperature, Vol-u-met pressure, and time in Excel MFC Calibration worksheet. The worksheet calculates the Vol-u-met flow rate at calibration and standard conditions using the following:

$$Q_{Cal} = \frac{Vol}{Time}\left(\frac{p_{Cal} + p_{Vol}}{p_{Cal}}\right)$$

and

$$Q_{Std} = Q_{Cal}\left(\frac{p_{Cal}}{p_{Std}}\right)\left(\frac{T_{Std}}{T_{Cal}}\right)$$

where Q_{Cal} is flow rate at calibration conditions,

Vol is volume of Vol-u-met in cm^3,
Time is average time of 5 runs in min,
P_{Cal} is atmospheric pressure at calibration conditions in mb or mmHg,
P_{Vol} is Vol-u-met pressure in mb or mmHg,
Q_{Std} is flow rate at standard conditions,
p_{Std} is pressure at standard conditions (1 atm = 1013.25 mb = 760 mmHg),
T_{Std} is temperature at standard conditions (273.15 °K), and
T_{Cal} is temperature at calibration conditions in °K.

4) Repeat step 3) at MFC control voltages of 3.5, 2.5, 1.5, and 0.5 volts.
5) The Excel MFC Calibration worksheet computes the calibration curve using a linear least-squares regression with the Vol-u-met flow rate as the x variable and the MFC voltage as the y variable.

$$V_{MFC-Cal} = M\ Q_{Std} + B$$

where $V_{MFC-Cal}$ is the voltage of the MFC during the calibration and
M and B are the slope and intercept for the least squares fit.

The flow rate at standard conditions for the MFC during use is given by

$$Q_{Std} = \frac{(V_{MFC} - B)}{M}$$

5.1.2 Gilibrator bubble flow meter

The Gilibrator Bubble Flow Meter Model S cell is calibrated with a Hastings Bubble flow meter, model HBM-1A, 100 cm^3, S/N 1426, that is NIST-traceable.

1) Prepare Gilibrator for operations.
2) Connect outlet of Gilibrator to vacuum source (pump or laboratory vacuum) with valve between flow meter and vacuum.
3) Invert Hastings 100 cm^3 tube and secure chain clamp to ring stand. Connect tube from tapered end of Hastings tube to inlet of Gilibrator. Tubing of different sizes will be necessary with reducing unions between. Place bubble solution in a small dish that is wider than the inlet to the Hastings. Bubbles are generated in the Hastings by quickly touching the bubble solution to the inlet of the inverted Hastings tube to pull a bubble into the tube.
4) Turn vacuum on and wet inside of the Hastings tube and the Gilibrator.
5) Set valve so that flow rate is approximately 5 l/min on the Gilibrator. Record ambient temperature and pressure. Generate bubble in the Hastings tube and measure

time required to pass by several lines. Record time and volume. Repeat four times. Generate three sets of ten Gilibrator readings and record average values.

6) Repeat step 5) at flow rates near 4, 3, 2, 1, and 0.5 l/min.
7) Calculate Hastings flow rates using $Q_{Hast} = V_{Hast}t$, where V_{Hast} is volume of time bubbles in liters and t is time in minutes. The Hastings flow rates do not need correction for water vapor pressure because the air entering the tube is at ambient conditions. The air entering the Gilibrator does need to be corrected for the water vapor added by the Hastings. The Gilibrator flow rate is corrected for water vapor by

$$Q_{Gil-cvp} = Q_{Gil}\left(\frac{p + p_v}{p}\right)$$

where $Q_{Gil-cvp}$ is average Gilibrator flow rate in lpm corrected for vapor pressure,
Q_{Gil} is average Gilibrator flow rate in lpm,
p is ambient pressure in mb or mm Hg, and
p_v is saturation vapor pressure in same units as p.

The saturation vapor pressure is found from the following expression given by Buck (1981):

$$p_v = \left(1.0007 + 3.46x10^{-6}\,p\right)6.1121\,\mathbf{exp}\left(\frac{17.502\,T}{240.97 + T}\right)$$

where p_v is saturation vapor pressure in mb,
p is ambient pressure in mb, and
T is ambient temperature in °C.

8) Generate a linear least squares fit using the Hastings flow rates as the x variable and the Gilibrator flow rates as the y variable to obtain

$$Q_{Gil-cvp} = MQ_{Hast} + B$$

where M and B are the slope and intercept from the least squares fit.

The corrected Gilibrator flow rate relative to the Hastings bubble meter is given by

$$Q_{Gil-corr} = \frac{\left(Q_{Gil-cvp} - B\right)}{M}$$

5.1.3 Thommen altimeter

The Thommen altimeter is checked with a Princo Fortin-type mercury-in-glass barometer. The barometer reading is corrected for temperature and altitude using corrections provided by the Smithsonian Meteorological Tables.

1) Place altimeter near Princo barometer. Gently tap altimeter and record reading.
2) Turn cistern adjustment screw at bottom of Princo barometer until white zero pointer in cistern just touches top of mercury.
3) Raise vernier above top of mercury meniscus and lower slowly until the front and back bottom edges of the vernier just appear to touch the top of the meniscus.
4) Read the millibar scale indicated by the vernier. The 1's, 10's and 100's places are given by the first line on the scale below the bottom of the vernier. The tenth's digit is given by the line on the vernier that aligns most closely with a scale line.
5) Read and record the temperature on the mercury-in-glass thermometer attached to the front of the Princo barometer.
6) Repeat steps 1) – 5) three times.
7) In Excel spreadsheet, "BARRCORR.XLS", for the next calibration, enter the Princo barometer and temperature readings and the altimeter reading. Duplicate calculations from previous calibrations to determine corrected barometer reading and difference between altimeter and Princo barometer.
8) If the altimeter reading differs from the corrected Princo barometer by more than ±3 mb, the altimeter should be adjusted. There is an adjustment small screw on the back side of the altimeter behind a small slider. Adjust and recheck against Princo barometer.
9) The following corrections are applied to the Princo barometer readings to correct for temperature, latitude, and altitude:

Temperature correction:

$$C_T = p_T - p_R = p_R\left(\frac{1+L(T-T_S)}{1+M(T-T_M)}-1\right)$$

where C_T is temperature correction,
p_T is pressure in mb corrected for temperature,
p_R is barometer pressure reading in mb,
L is coefficient of expansion for brass scale = 0.0000184 m/m°C,
T_S is standard temperature for brass expansion = 0 °C,
M is coefficient of expansion for mercury volume = 0.0001818 m^3/m^3°C,
T_M is standard temperature for mercury expansion = 0°C.

Altitude correction for gravity:

$$\begin{aligned} g_a = g &- [3.085462x10^{-4} + 2.27x10^{-7}\cos(2\varphi)]\,Z \\ &+ [7.254x10^{-11} + 10x10^{-18}\cos(2\varphi)]\,Z^2 \\ &- [1.517x10^{-17} + 6x10^{-20}\cos(2\varphi)]\,Z^3 \end{aligned}$$

where g is gravity at a latitude of 45° and elevation of 0 meters (= 980.616 cm-s^{-2}),
φ is latitude, and
Z is altitude above sea level in meters.

Latitude correction for pressure:

$$C_G = p_L - p_T = p_T\left\{\frac{g_a}{980.665}\left[1 - 2.6373x10^{-3}\,\mathbf{cos(}2\varphi\mathbf{)} + 5.9x10^{-6}\,\mathbf{cos(}2\varphi\mathbf{)}\right] - 1\right\}$$

where C_G is correction for latitude,
p_L is pressure in mb corrected for latitude, altitude, and temperature,
p_T is pressure in mb corrected for temperature, and
980.665 is gravity for which correction tables were developed.

Final corrected barometer reading:

$$p_L = p_R + C_T + C_G$$

5.1.4 Fluke thermocouple

The Fluke thermocouple is calibrated at approximately 0 and 30 °C in a water bath using a Brooklyn Thermometer (29 – 31 °C) S/N 10772 NIST-traceable. The water bath can be in a small vacuum bottle for a single thermometer or in a temperature controlled bath if more thermometers are calibrated at the same time.

1) Fill bottle with cold water and chipped ice. Stir vigorously with a stirring rod – not with the Brooklyn thermometer. Check temperature of bath with the Fluke probe.
2) As the temperature approaches 0 °C, place Brooklyn thermometer in the bath. Continue stirring of the bath but at a reduced intensity. The height of the mercury in the Brooklyn will eventually decrease to the point that it be in the near zero scale of the thermometer. The thermometer should be at the 6 inch immersion depth during the stirring but needs to be lifted out of the water to read the near zero scale. Read and record the Brooklyn thermometer values to 0.01 °C and Fluke readings to 0.1 °C.
3) If the Fluke and Brooklyn thermometer readings differ by more than ±0.2 °C, turn the Fluke adjust screw to bring the readings into agreement. Both channels of the Fluke should be checked with either the same probe or with a second probes if available.
4) Fill the vacuum bottle with water that is near 31 °C. Place Brooklyn thermometer and Fluke probe into water.
5) Hold Brooklyn thermometer and Fluke probe side-by-side with the end of the Fluke probe near the end of the bulb of the Brooklyn thermometer.

6) Gently stir water so that it is well-mixed. Be careful not to hit the side of the vacuum bottle with the thermometer.
7) Raise thermometer until the 6 inch immersion line is at top of water and read and record thermometer value to 0.01 °C and read and record Fluke reading to 0.1 °C.
8) Repeat stirring and reading values for at least 3 sets of readings as the temperature of the water in the vacuum bottle gradually decreases.
9) Average the differences between the Fluke probe and Brooklyn thermometer readings near 0 °C and near 30 °C. Add differences to 0 and 30 °C, respectively, to obtain Fluke probe responses to temperatures at 0 and 30 °C. Generate a linear fit to the Fluke and Brooklyn readings to obtain the following expression for the corrected Fluke reading:

$$CorrFluke = \frac{30}{(30 + \Delta_{30} - \Delta_0)} \left(Fluke - \Delta_{30} \right)$$

where CorrFluke represents the corrected Fluke temperature reading in °C,
Fluke represents the Fluke temperature reading in °C,
Δ_{30} is the difference between the Fluke and Brooklyn readings near 30 °C,
Δ_0 is the difference between the Fluke and Brooklyn readings near 0 °C.

5.2 Calculations

5.2.1 Standard Flow Rate Calculations

The Tylan MFC measures flow rate at standard conditions for a pressure of 1 atm and a temperature of 273.15 °K (0 °C). The conversion of flow rate at standard conditions, Q_{Std}, to flow rate at different standard conditions, Q_{Std}, or to actual conditions follows the ideal gas law:

$$Q_{Std/Act} = Q_{MFC\text{-}Std} \left(\frac{p_{MFC\text{-}Std}}{p_{Std/Act}} \right) \left(\frac{T_{Std/Act}}{T_{MFC\text{-}Std}} \right)$$

where $Q_{Std/Act}$ is the flow rate at new standard or actual conditions,
$Q_{Std\text{-}MFC}$ is the standard flow rate references to 1 atm and 273.15 °K,
$P_{MFC\text{-}Std}$ is the standard pressure (1 atm),
$T_{MFC\text{-}Std}$ is the standard temperature (273.15 °K,
$p_{Std/Act}$ is the pressure at the new standard or actual conditions, and
$T_{Std/Act}$ is the temperature at the new standard or actual conditions.

5.2.2 Differences between Instrument and Audit Measurements

The results of the audit are quantified by comparing the displayed instrument values to the audit measurements for those quantities. The comparison includes the computation of the difference and the percent difference between the instrument values and the audit values. The difference and percent differences are computed from the following expressions:

$$Difference = Instrument - Audit$$

$$\%\ Difference = \left(\frac{Instrument - Audit}{Audit} \right) 100$$

where Instrument represents the value of the audited quantity displayed by the instrument or DAS and
Audit represents the measurement of the audited quantity with the audit equipment.

5.3 Data Acquisition

Data acquisition is done manually by entering audit and site concentrations, pressures, and temperatures on log sheets or in a notebook. The differences between the audit and site responses are calculated in an Excel worksheet and periodically checked by hand. The worksheet also calculates the linear regression between the audit and site concentrations. The regression is also checked by hand.

6.0 QUALITY CONTROL

Quality control is maintained by period recalibration of the Brooks Vol-u-met mercury-sealed piston flow meters with NIST-traceable Hastings bubbles meters. The audit MFCs are calibrated with the Brooks Vol-u-mets before each major audit trip. Calibrations may also be performed following an audit trip if major discrepancies arose between the audit inputs and the site instrument responses.

7.0 REFERENCES

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