

DRI STANDARD OPERATING PROCEDURE

**Performance Audit of Continuous Particulate Sulfate,
Nitrate, and Ammonium Samplers**

DRI SOP #4-116.1

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Title: Performance Audit of Continuous Particulate Sulfate, Nitrate, and Ammonium Samplers

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 system that continuously measures particulate sulfate, nitrate, and ammonium 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

Ambient air passes through a series of denuders to remove gaseous sulfur dioxide (SO₂), oxides of nitrogen (NO_x), and ammonia (NH₃) so that only particulate sulfate (SO₄), nitrate (NO₃), and ammonium (NH₄) are sampled. A part of the sample flow is diverted through a SO₄ to SO₂ converter and then to a pulsed fluorescence SO₂ analyzer. The other part of the flow is switched between a NO₃ to NO converter and a NH₄ to NO converter and then to a chemiluminescence NO analyzer. The flows are controlled by mass flow controllers. The inlet has cyclone to limit the sampled particles to aerodynamic diameters of 2.5 μm and less. One minute averages are collected by the site computer data acquisition system. The ambient sample is collected at a level above the round of approximately 2 meters above the top of the shelter at about the same level as the inlets of the other particle samplers.

The performance audit consists of several steps. A total particle filter is attached to the inlet to remove particulate matter to measure the zero level. Known quantities of SO₂, NO, and NH₃ are introduced to the inlet to test denuder efficiency. Gas Addition Audits are conducted by introducing known concentrations of SO₂, NO, and NH₃ at known rates to the sample stream at a point downstream of the denuders where the trace gases are diluted by the sample flows. The responses of the instruments to air with and without the audit gases are compared to the concentrations of gases that are introduced.

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

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Ammonia gas can be removed by the audit delivery system. The system for the ammonia gas has to be conditioned so that the gas is not removed from the audit gas stream.

1.4 Ranges and Typical Values of Measurements

The ambient concentration of particulate SO₄ and NO₃ are usually in the range of 0 to 50 µg/m³, often in the form of (NH₄)₂SO₄ and NH₄NO₃. The audit concentrations of the Gas Addition Audits are in the 50 to 60 ppb for gaseous SO₂, NO, and NH₃.

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 60 ppb.

1.6 Audit Criteria

The following set of flags is used to 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

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.

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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

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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 cm³/min
Scott-Marrin gas cylinders with SO₂, NO, and NH₃ in N₂ at approximate concentrations of
10 ppm
Whatman HEPA-CAP disposable filter
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.

2.1.3 Spare Parts and Supplies

Whatman HEPA-CAP disposable inline filter, Fisher Scientific, 750 Laurelwood Rd.,
Santa Clara, CA 95054

2.2 Forms and Paperwork

Audit forms for Gas Addition 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.

Figure 2-1: Blank Worksheet for SO₄ Addition Audit Input

Figure 2.2: Blank Worksheet for NO₃ Addition Audit Record

Figure 2.3: Blank Worksheet for NH₃ Addition Audit Record

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Figure 2-1: Blank Worksheet for SO₄ Addition Audit Input

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Figure 2.2: Blank Worksheet for NO₃ Addition Audit Record

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Figure 2.3: Blank Worksheet for NH₄ Addition Audit Record

3.0 CALIBRATION STANDARDS

3.1 Preparation, Ranges, and Traceability of Standards

The Tylan mass flow controllers (MFC) in the audit addition system are calibrated with a Brooks Vol-u-met mercury-sealed piston flow meter. The 30 and 50 cm³/min MFCs are calibrated with Vol-u-met model 1053-A2A with a 100 cm³ tube. The Vol-u-met has been fitted with an electronic sensor that measures the time required for the piston to move a fixed distance. The volume associated with the movement of the piston is 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 cm³ 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

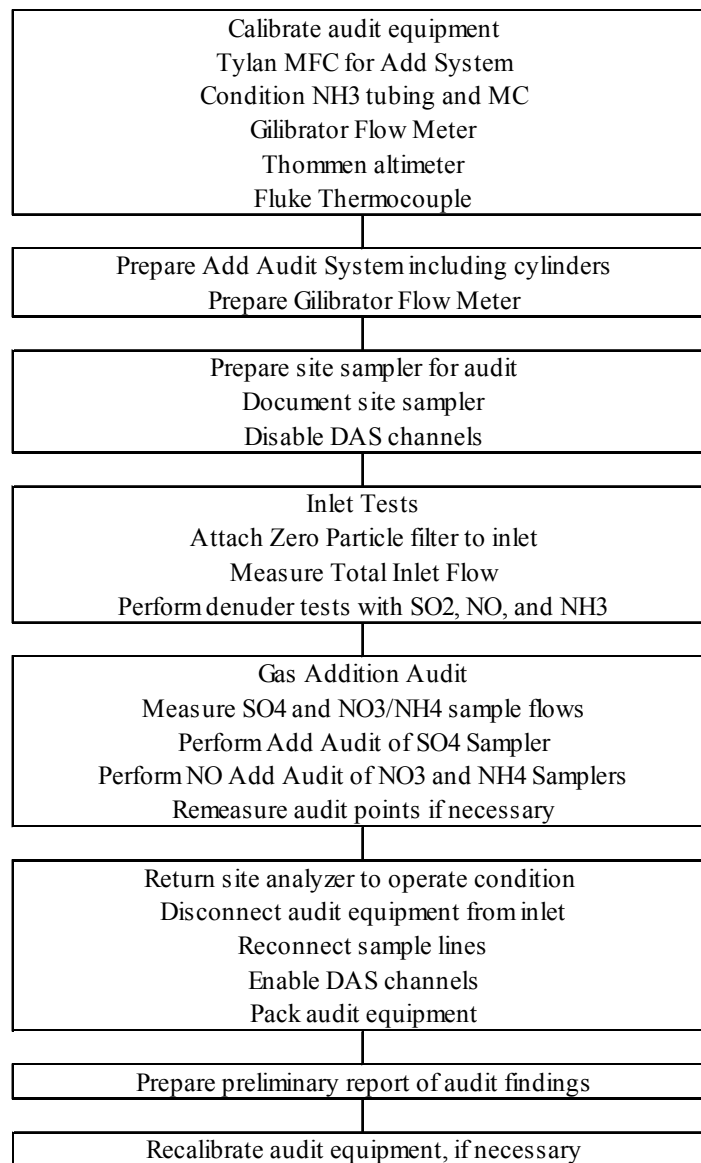
The accuracy of the Brooks Vol-u-met is ±1%. The accuracy of the pressure standard is ±1 mb. The accuracy of the temperature standard is ±0.01 °C.

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4.0 PROCEDURES

4.1 General Flow Diagram

The typical flow of the audit procedures for the continuous particulate SO₄, NO₃, and NH₄ samplers is depicted in the following figure.



4.2 Audit Procedures

The following sections describe in detail the audit procedures for the continuous particulate SO₄, NO₃, and NH₄ samplers. It should be reviewed before each audit so that all necessary tasks will be accomplished.

During the audit of the continuous particulate SO₄, NO₃, and NH₄ samplers, audit gases are introduced to the instrument at a point in the sample stream after the gas denuders. The Gas Addition Audit system is operated at the sampler and is placed under a tarp to protect it from direct sunlight and rain.

4.2.1 Prepare Audit Equipment

- 1) Prepare audit forms or audit notebook by entering site name and date of audit.
- 2) Prepare portable computer and Excel Addition audit worksheets for SO₄, NO₃, and NH₃.
- 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 near sample inlet. Remove caps from fittings. Attach 1/8th in Teflon tubing from outlet of 30 cm³/min MFC to common side of gas addition switching valve
- 7) For the each gas 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 continuous particulate channels on data acquisition system (DAS). Record time that channels were disabled.

4.2.2 Zero Particle Filter and Denuder Tests

- 1) Remove inlet cyclone and attach Whatman HEPA-CAP filter to inlet. Record the last 5 one-minute average readings before the filter was installed. Allow the filter to remain on the inlet for 5 minutes and record the one-minute averages. Remove filter for 5 minutes and record the one-minute averages. Repeat switching of filter on and off one more time. Determine differences in readings with filter on and filter off.
- 2) Measure inlet flow with Gilibrator. 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 sum of the MFC flow rates displayed on the site DAS.
- 3) Attach GAA system with SO₂ cylinder to inlet of sampler and introduce gas in the range of 50 ppb. Set switching to 300 sec. Collect 4 sets of switches between ambient sample and ambient sample plus SO₂. Subtract the adjacent sets of readings to determine the denuder efficiency.
- 4) Repeat step 3) with NO gas and NH₃ gas as input to test NO₃ and NH₄ denuders, respectively.

4.2.3 Gas Addition Audits

- 1) Disconnect SO₄ sample line from sample line below denuders. Measure SO₄ sample flow with Gilibrator and convert to standard conditions of 1 atm and 298.15 °K. Compare to value displayed on site DAS.
- 2) Disconnect NO₃/NH₄ sample line and measure total NO₃/NH₄ sample flow with Gilibrator. Convert flow rate to standard conditions of 1 atm and 298.15 °K and compare to value displayed on site DAS.
- 3) Enter the audit flow rates in the Excel Gas Addition worksheets for SO₄, NO₃, and NH₃. 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)
- 4) The Excel Addition worksheets calculate 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 rates of the Add MFCs to obtain concentrations in the 50 to 60 ppb range for the each sampler.

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- 5) Start with the SO₄ sampler. Connect the SO₂ cylinder to the Add input. 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 cm³/min MFC.
 - 6) 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 SO₄ sample line. 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.
 - 7) Repeat switching for up to 8 complete periods. 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.
 - 8) Repeat steps 5)-7) for the NO₃ and NH₄ samplers. For the NO₃ sampler use the 30 cm³/min MFC. For the NH₄ sampler, use the 50 cm³/min MFC, which has been seasoned with NH₃. The gas is introduced at a point before the converters and switches. The MFC flow rate will have to be changed for these samplers because the flow rate differs from the SO₄ flow rate.
 - 9) Compare the instrument responses to the audit inputs by calculating the percent differences.

4.2.4 Return Site Analyzer to Sampling Mode

- 1) Disconnect Teflon tubing from sample inlets. Reconnect sample lines. Replace inlet cyclone.
- 2) Enable SO₄, NO₃, and NH₄ instrument channels on DAS. Record time that the continuous particulate samplers were returned to operational status.

4.2.5 Final Audit Procedures

- 1) Turn power to Add-MFC system off. Disconnect tubing from Add-MFC 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

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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 cm³/min MFCs are calibrated with Vol-u-met model 1053-A2A with a 100 cm³ tube. The Vol-u-met has 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 piston is determined with a Hastings bubblemeter 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 cm³/min MFCs are calibrated with nitrogen.
- 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 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 cm³,
 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 cm³, S/N 1426, that is NIST-traceable.

- 6) Prepare Gilibrator for operations.
- 7) Connect outlet of Gilibrator to vacuum source (pump or laboratory vacuum) with valve between flow meter and vacuum.
- 8) Invert Hastings 100 cm³ 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.
- 9) Turn vacuum on and wet inside of the Hastings tube and the Gilibrator.
- 10) 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.

- 11) Repeat step 5) at flow rates near 4, 3, 2, 1, and 0.5 l/min.
- 12) 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):

$$p_v = (1.0007 + 3.46 \times 10^{-6} p) 6.1121 \exp \left(\frac{17.502 T}{240.97 + T} \right)$$

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

- 13) 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

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

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

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

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 = $0.0000184 \text{ m/m}^\circ\text{C}$,
 T_S is standard temperature for brass expansion = 0°C ,
 M is coefficient of expansion for mercury volume = $0.0001818 \text{ m}^3/\text{m}^3^\circ\text{C}$,
 T_M is standard temperature for mercury expansion = 0°C .

Altitude correction for gravity:

$$g_a = g - [3.085462 \times 10^{-4} + 2.27 \times 10^{-7} \cos(2\phi)] Z \\ + [7.254 \times 10^{-11} + 10 \times 10^{-18} \cos(2\phi)] Z^2 \\ - [1.517 \times 10^{-17} + 6 \times 10^{-20} \cos(2\phi)] Z^3$$

- where g is gravity at a latitude of 45° and elevation of 0 meters (= $980.616 \text{ cm-s}^{-2}$),
 ϕ is latitude, and

Z is altitude above sea level in meters.

Latitude correction for pressure:

$$C_G = p_L - p_T = p_T \left\{ \frac{g_a}{980.665} [1 - 2.6373 \times 10^{-3} \cos(2\phi) + 5.9 \times 10^{-6} \cos(2\phi)] - 1 \right\}$$

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:

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

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

$$\begin{aligned} \text{Difference} &= \text{Instrument} - \text{Audit} \\ \% \text{ Difference} &= \left(\frac{\text{Instrument} - \text{Audit}}{\text{Audit}} \right) 100 \end{aligned}$$

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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