Standard Operating Procedure for Analysis of Particulate Phase Mercury

Gerald J. Keeler and Matthew S. Landis
University of Michigan
Air Quality Laboratory
109 South Observatory Street
Ann Arbor, MI 48109-2029

June 1, 1994

Version 2.0

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1.0 Introduction/Overview

The objective of the Lake Michigan Loading Study is to assess the contribution of atmospheric deposition to the concentration of mercury and other toxic trace species found in Lake Michigan. The atmosphere has been implicated as one of the dominant sources of mercury and trace elements to bodies of water and it is clear from investigations in remote regions of the globe that long range transport of mercury and other toxics from source regions is occurring. By quantifying the wet deposition and ambient concentrations of mercury it will be possible to determine the relative importance of precipitation and dry deposition in accounting for the atmospheric loading of mercury to Lake Michigan. In addition, investigating other ambient trace species will aid in the identification of significant mercury sources.

Particle-phase mercury, Hg(p), generally represents a small but significant fraction of total atmospheric mercury. Recent advances in analytical chemistry have made quantification of the extremely low levels of Hg(p) possible, however, tremendous care must be exercised in all phases of sample handling and analysis. This protocol describes analysis of 'acid-extractable' total mercury from atmospheric particulate samples.

2.0 Sample Analysis

2.1 Summary

The technique described by this protocol is designed for use with glass-fiber or quartz fiber filter media. When used in conjunction with an open-faced filter pack, these media demonstrate a low pressure drop and have a very low background level of Hg with proper pretreatment. Sample filters are stored at -40°C before analysis to prevent volatilization of the collected Hg(p). Particulate mercury is extracted into a 1.6 M nitric acid solution utilizing a microwave digestion technique. The mercury forms are then oxidized with bromine monochloride, to Hg^{2+}. Oxidized mercury forms are subsequently reduced to Hg0 with stannous chloride ($SnCl_2$). In this volatile form, the metal is purged from solution using an Hg-free nitrogen stream and collected on a gold-coated bead trap. A mercury-free pretreated soda lime trap is utilized in the purge system to capture acid gases that may damage the gold-coated bead trap. Quantification is accomplished using a dual amalgamation technique followed by cold vapor atomic fluorescence spectroscopy (CVAFS).

All analytical procedures for determination of particulate phase mercury are carried out in a class 100 laminar flow exhaust hood inside a Class 100 Clean Room. Nitrogen utilized for purging is 99.998% pure and is stripped of any mercury using a gold coated trap before use in the purge system. Clean room gloves are worn at all times and all labware with which the samples and reagents comes into contact is cleaned weekly using the acid cleaning procedure described in *Standard Operating Procedure for Sampling of Particulate Phase Mercury*, Section 2.1.

2.2 Reagents and Materials

All reagent lot numbers, preparation dates and procedures are recorded for each new batch of reagent used. A reagent blank is obtained after each new batch of reagent has been prepared. Bromine monochloride (BrCl), stannous chloride ($SnCl_2$) and hydroxylamine hydrochloride ($NH_2OH•HCl$) are prepared fresh monthly.

Solid reagents (potassium bromide, potassium bromate, hydroxylamine hydrochloride and stannous chloride) are stored in the clean room in a desiccator containing silica gel and an open bed of activated charcoal. The caps of all reagent bottles are Teflon taped to reduce entry of vapor phase compounds. Even with these precautions, reagents will nevertheless absorb mercury over time and must be replaced. All reagents are made in the clean room, except the working standard solution.

2.2.1 Hydrochloric Acid

EM Science Suprapur hydrochloric acid is used to prepare BrCl and $SnCl_2$. This acid characteristically has a very low blank value (20 pg/mL).

2.2.2 Bromine Monochloride

Bromine monochloride is prepared in a class 100 laminar flow exhaust hood by adding 11.0 mg KBr per mL of HCl while the solution is stirred using an acid-cleaned Teflon-coated magnestir. When the KBr is dissolved, 15.0 mg $KBrO_3$ per mL of HCl is added slowly and the solution is allowed to continue stirring. This process produces chlorine and bromine gas and must be performed slowly in a functioning exhaust hood. After addition of the salts the solution is a deep yellow color. If there is no color (or very faint) then the BrCl has been substantially reduced and will not have enough oxidizing power for use. In this case, the solution is remade. Bromine monochloride is stored at room temperature in the clean room. Fresh bromine monochloride is be prepared monthly or as needed.

2.2.3 Hydroxylamine Hydrochloride

30 grams of $NH_2OH•HCl$ is dissolved in MQ-water to make 100 mL in an acid-cleaned 100 mL volumetric flask. This solution is purified by adding 0.5 mL of $SnCl_2$ and purging overnight with Hg-free N_2. The solution is stored in an acid-cleaned, dark Teflon bottle in the refrigerator. Fresh hydroxylamine solution is prepared every month or as needed.

2.2.4 Stannous Chloride

20.0 gm of $SnCl_2•H_2O$ is placed into an acid-cleaned 100 mL volumetric flask. Working in a fume hood, 10 mL of concentrated HCl is added and the solution is then brought to 100 mL with Milli-Q water. The solution is stored in an acid-cleaned, dark Teflon bottle in the refrigerator. Fresh stannous chloride is prepared every month or as needed.

2.2.5 Milli-Q Water

Deionized water, with a resistivity of 18.2 MÙ/cm, is prepared using a Milli-Q system from a pre-purified (reverse osmosis) water source. Milli-Q water is used for reagent preparation.

2.2.6 Soda Lime Traps

High purity grade soda lime (EM Science) is utilized in an acid-cleaned glass tube with glass wool endplugs and Teflon connectors. After packing, this trap is conditioned by purging a 0.5 M HCl solution through the trap for 30 minutes. The soda lime trap is changed after analysis of 30 samples.

2.2.7 Preparation of Working Standard Solution

100 µL of the stock Hg solution (1 mg/mL in nitric acid) is pipetted into a 1 L volumetric flask. 5 mL of concentrated BrCl is added and the flask is brought up to volume with MQ-water and thoroughly mixed. This is the Secondary Standard solution (100 ng Hg/mL). Replace this solution as needed (it is stable for at least one year).

The Working Standard (2 ng Hg/mL) is prepared from the Secondary Standard solution by placing 2 mL of Secondary Standard into a 100 mL volumetric flask, adding 1 mL of BrCl and bringing the solution to volume with MQ. The Working Standard is replaced monthly.

2.2.8 Nitric Acid Extraction Solution.

The extraction solution is a 10% dilution of concentrated nitric acid (1.6M). A 1000 mL volumetric flask is filled with about 800 mL of Milli-Q water. *In a hood*, 100 mL of suprapur HNO_3 (EM Science) is measured using a graduated cylinder and poured into the flask. The solution is mixed completely and allowed to cool in the hood with a glass stopper closing the top. When cool, the flask is brought up to volume with Milli-Q water. After the extraction solution is thoroughly mixed it is poured into an acid-cleaned re-pipetting dispenser.

2.3 Sample Handling and Preparation

2.3.1 Sample Handling

If samples are not analyzed immediately, they are stored triple bagged in a dark freezer (-40°C) to avoid exposure to laboratory air. Particle free gloves are worn whenever vials, filters or dishes are handled or transferred.

2.3.2 Sample Preparation

Eighteen samples, five standards and one vessel check are prepared for each day of particulate mercury analysis. Eighteen acid-cleaned Teflon vessel liners are inserted into outer vessel bodies and are placed in a laminar flow work station. The vessel bodies are then labeled with complete sample identifications. The petri dishes containing the samples

to be analyzed are taken out of their polyethylene bags and the Teflon sealing tape is removed. Each sample filter is carefully folded into quarters and placed in its corresponding vessel using Teflon-coated forceps. The forceps are rinsed in a beaker of HNO_3 extraction solution followed by a beaker of Milli-Q water and are dried using a particle-free wipe before handling the next filter. After each filter has been placed in a vessel it is capped and is moved into a laminar flow exhaust hood.

2.4 Sample Filter Extraction

The HNO_3 extraction solution is made on the same day that it is used and is dispensed using a calibrated Repipet II dispenser. 20 mL of extraction solution is dispensed into each of the Teflon vessels containing the sample filters. The Teflon vessel liners are then weighted and inserted back into their digestion vessel body and tightly capped. An acid-cleaned rupture disc membrane is placed into an acid-cleaned vent stem which is attached to the top of each microwave vessel cap. Each capped vessel is swirled lightly.

Note: Vigorous shaking of the vessel will cause the filter to disperse in solution which will make it very difficult to pipette solution for analysis.

Only twelve samples and/or standards can be microwave digested at a time. One vessel from each of the two digestion runs is outfitted with a Teflon thermowell cap into which a Teflon-coated Pyrex thermowell is inserted. Eleven regular vessels and one thermocouple vessel are loaded in the carousel tray. The carousel tray is then removed from the clean room and is placed in the microwave digester. The fiber optic temperature probe is carefully inserted into the vessel with the thermowell. A pressure monitoring and control probe is also attached to the same vessel. The digestion program for the particulate mercury filters is then initiated. The program heats the samples to 160°C (approximately 70 psi) for 20 minutes.

After the samples are heated, the microwave digester fan will remain on to help cool the Teflon vessels. The vessels are allowed to cool until the pressure inside the control vessel is 1-2 psi (approximately 60 minutes). The fiber optic probe and pressure probe are carefully removed and the carousel is transferred back into the clean room. The vessels are then reweighed to confirm no loss during digestion. 0.5 mL of BrCl is added to each vessel. The vessels are then gently swirled to collect liquid droplets from the side of the liner. The vessels are allowed to react for one hour prior to analysis.

2.5 Sample Analysis and Data Acquisition

2.5.1 Volatilization/Recapture

Volatilization of mercury from solution is accomplished using a glass impinger assembly manufactured at the University of Michigan. A 25 mL graduated bubbler attaches to an impinger via a ground glass fitting. N_2 flow is regulated using a Teflon stopcock. A soda lime trap is incorporated into the system to prevent damage of the gold-coated bead traps by capturing acid gases liberated during the purging procedure.

Total mercury is quantified by oxidizing all mercury forms using bromine monochloride. Bromine monochloride is a strong oxidizing agent, capable of breaking organic bonds with

mercury, thus liberating the divalent form of mercury (Hg^{2+}). A 5 mL aliquot of the oxidized filter sample solution is carefully pipetted into a graduated glass bubbler containing 20 mL of a previously purged sample and 100 µL of hydroxylamine hydrochloride is added. A stopper is then inserted into the bubbler, its swirled briefly and allowed to react for 5 minutes to reduce the excess bromine monochloride from solution. Bromine monochloride is reduced from solution since halogens liberated from solution will quickly damage the gold-coated bead traps onto which the purged elemental mercury is amalgamated.

A blanked gold-coated bead sample trap is affixed to the end of the soda lime trap. The bubbler is opened, 500 µL of stannous chloride is added, and the bubbler is quickly attached to the impinger. The N_2 flow is adjusted to 450 cc/min using a calibrated rotameter and the solution is purged for 7 minutes. The stannous chloride reduces the divalent mercury to Hg^o which is quantitatively captured on the gold-coated bead trap.

2.5.2 Analysis of Total Mercury

The CVAFS analyzer used for particulate mercury analysis is kept on at all times, since this has been shown to stabilize the UV lamp and maintain consistency from one day to the next. The power supplied to the CVAFS analyzer is modulated by a line tamer (Shape Magnetronics) to prevent power fluctuations. It is imperative that the mercury lamp not experience wide temperature fluctuations or power surges since both of these drastically affect the sensitivity of the instrument. During operation of the instrument the helium carrier gas flow rate is regulated upstream of the analyzer using a mass flow controller (Tylan) which is set to maintain a 35 cc/min flow rate. This flow rate has been determined by UMAQL to yield the optimal peak characteristics for mercury standards. The regulator on the helium cylinder is set at 50 Kilopascals. The helium stream is prefiltered using a gold-coated trap before entering the analytical train in order to remove any mercury. In the analytical train, mercury is thermally desorbed from the sample trap, and amalgamated onto the analytical trap which is subsequently thermally desorbed into the CVAFS analyzer where the mercury atoms are detected. Traps are desorbed by heating a nichrome coil which is wrapped around the trap covering the gold-coated beads. Application of 12 volts of current to the coil is sufficient to achieve a temperature of 500°C inside the gold bead trap (voltage may vary due to variations in length and thickness of nichrome wire). Two fans supply cool air to the sample and analytical traps separately in order to speed analysis time.

The gain on the particulate phase mercury CVAFS analyzer is set to yield approximately 2000 mV of net response for a 1 ng mercury standard. The background on the CVAFS analyzer is set at 5.0 and maintained in that position in order to track the drift in the baseline of the analyzer. A Hewlett Packard Integrator is connected to the analyzer to convert output signal into an integrated area of the detected response. Area units are used for all sample calculations since area is much more reliable than peak height.

To analyze a sample trap, the trap is placed snugly into the analytical train using friction fit Teflon connectors and Teflon sleeves. The nichrome coil used specifically for the sample trap is slid over the trap and moved to completely cover the quartz wool plugs and the gold-coated beads contained between the plugs. Helium is allowed to flow through the

sample trap for 2 minutes before analysis begins in order to purge air and water vapor from the analytical train. A circuit controller (ChonTrol) is employed which is programmed to turn on the variable transformers and fans in a precise and reproducible manner. First, the sample coil is heated for 2 minutes, then it is cooled while the analytical trap is heated for 2 minutes. The analytical trap is then cooled for 2.5 minutes and the fan to the sample trap is turned off. While the analytical trap is cooling, a new sample trap is installed in the analytical train and helium is passed through this trap until the analytical trap is cool and ready for another sample. When the analytical trap begins heating, the integrator is turned on and the ambient temperature, time and base mV are recorded in a log book and the LCD display on the analyzer is set to record the peak mV (by depressing the Peak button on the face of the analyzer). After the sample is analyzed and the peak height and area reported by the CVAFS and integrator respectively, these values are recorded in the log book.

A standard curve is analyzed at the beginning of each day of analysis and a control standard which yields a response in the range of the samples being analyzed is run every six samples. Criteria for the standard curves and control standards are described below in Section 2.5.4. All sample analysis is recorded in a log book specific to the analyzer with which samples are being quantified and also in a lab notebook specific to the study for which the samples were collected. At the end of the day of analysis all results from the log sheet are entered into a computer spreadsheet file for subsequent checking and processing by a statistical software program, SAS (Cary, NC).

2.5.3 System Purge and Blanks

At the start of each day of analysis, each impinger system is purged after the soda lime trap is conditioned. First 20 mL of Milli-Q water is added to an acid-cleaned bubbler, then 1.0 mL of $SnCl_2$ is added and the solution is purged at 450 cc/min for 15 minutes. After each system is purged a System Blank is generated to ensure the impinger assembly is free of contamination.

System Blank (Bubbler Blank): This blank is generated by adding 500 µL of $SnCl_2$ to the system purge solution and purging the solution onto a blanked gold-coated bead trap at 450 cc/min for 5 minutes. After the System Blanks have been completed, one of the purged bubblers is dedicated for generation of standards.

Total Reagent Blank: This blank is synonymous with the 0 pg filter standard (Section 2.5.4), which is generated on each day of analysis. The Total Reagent Blank is used to calculate the method detection limit (presently 1.0 pg/m^3) and to calculate sample concentration (Section 2.5.5).

2.5.4 Standard Curve and Control Standards

A standard curve, generated by bubbling five different filter standard solutions, is analyzed before each day of analysis. The concentration of the 5 mL filter standard solution aliquots for the calibration curve are tailored to the expected value of the samples to be analyzed. At UMAQL, a typical calibration curve consists of five filter standards: 0 pg, 100 pg, 200 pg, 500 pg and 1000 pg. Because of the BrCl dilution factor imparted onto the filter standards, the nominal pg of mercury delivered by each 5 mL aliquot is slightly less than standard name indicates. The volumes of standard working solution added to each filter standard vessel to achieve the five standard concentrations in each 5 mL aliquot are shown in Table 1.

Table 1. Calibration Curve for Bubbled Hg Standards

Hg in 5 mL of Filter Standard Solution	Volume of Standard Working Solution
0 pg	0 µL
96.6 pg	200 µL
191.4 pg	400 µL
465.1 pg	1000 µL
888.9 pg	2000 µL

The filter standard solutions are prepared at the same time that the field samples are extracted. Baked glass fiber filters are folded and placed into acid-cleaned Teflon vessel liners and the appropriate volume of standard working solution is pipetted directly onto the filter. The filters are then extracted in the same manner as the sample filters (described in Section 2.4)

Standards for the calibration curve are generated starting with the zero point and continued in ascending order to the highest, usually 1000 pg. First, a blanked gold-coated bead trap is attached to the end of the soda lime trap. Then 5.0 mL of filter standard solution is pipetted into the standard bubbler followed by 100 µL of NH_2OH•HCl. After the solution has reacted for 5 minutes 500 µL of $SnCl_2$ is added. The standard bubbler is quickly attached to the impinger and the solution is purged at 450 cc/min for 5 minutes. The gold-coated bead trap is analyzed immediately after purging.

After each of the standards for the calibration curve has been analyzed, a linear regression is calculated to establish the coefficient of determination (r^2), the slope of the line and how well the slope of the curve predicts each of the points in the calibration curve. The 0 pg standard area is subtracted from each of the other points which are then regressed against the expected values using no intercept (line is forced through zero). The r^2 must be >0.995 and each of the points on the curve must be predicted by the slope within 10% of their true value (Table 2). If these criteria are not met, specific points which are errant are repeated and the linear regression recalculated.

Table 2. Example Calibration Curve and Calculation of Slope

Standard (pg Hg)	Response (AU)	Response (AU)-Zero Point (AU)	Predicted Value (pg Hg)
0	141,510	0	0
96.6	2,156,000	2,010,490	92.4
191.4	4,126,400	3,984,890	183.2
465.1	10,214,000	10,072,490	463.0
888.9	19,548,000	19,406,490	892.1

Slope = 4.5969E-5 ng/AU
Slope^{-1} = 21,754 AU/ng
r^2 = 0.9998

This curve is accepted and sample analysis commences.

Control standards are analyzed every sixth sample. The control standards are generated in the same manner as described above and are chosen to be representative of the samples being analyzed. The integrated area from each of the control standards must be within 10% of the slope of the calibration curve in order to continue analyzing. If this is not the case, a second control is analyzed immediately. If the second control indicates that analyzer sensitivity has changed a second calibration curve is generated and sample analysis is continued.

2.5.5 Calculation of Particulate Phase Mercury Concentration

The particulate phase mercury concentration from a glass fiber or quartz fiber filter is calculated in pg/m^3. The total reagent blank response is subtracted from the analytical aliquot response and the difference is multiplied by the slope of the calibration curve which is in pg/AU. The mass of Hg for the entire sample is then calculated by dividing the analytical aliquot Hg mass by the analytical aliquot volume and multiplying the result by the total volume of sample. The calculated value, in picograms of mercury is converted to pg Hg/m^3 by calculating the total volume of air drawn through the filter and dividing the pg of mercury by the cubic meters of air sampled (Table 3).

Table 3. Calculation of pg Hg/m^3 in a Particle Phase Sample.

1. Calculation of pg of mercury recovered from the analytical aliquot *pg Hg = (sample response (AU)-total reagent blank (AU)) * slope of calibration curve (pg/AU)* *(5,944,100 - 141,510) * 4.5969E-5 = 266.7 pg Hg*
2. Calculation of ng of mercury in entire sample volume *pg Hg = (pg Hg from analytical aliquot * total volume of sample)/ volume of analytical aliquot* *(266.7 pg Hg * 20.5 mL) / 5.0 mL = 1093.4 pg Hg*
3. Calculation of m^3 sampled at a flow rate of 30 lpm and a sample duration of 24 hours: *Volume of Air Sampled = (DTM Reading Off - DTM Reading On) * DTM Calibration Curve* *(1982.597 - 1937.864) * 0.97886 -0.00024 = 43.787 m^3*
4. Calculation of Particle Phase Mercury Concentration in Sample = pg Hg/m^3 *1093.4 pg Hg / 43.787 m^3 = 25 pg Hg/m^3*

2.5.6 Trouble-Shooting

A source of irreproducible results may be due to faulty gold-coated bead traps. These traps are numbered with discrete identifiers. Contact with halogen fumes, organic fumes or overheating of the trap during analysis can damage the trap, rendering it unusable. If performance of a gold trap is suspect, at least two consecutive standards are analyzed from this trap to determine its ability to amalgamate and release mercury.

If a low response is observed, the impinger assembly is checked for leaks. Teflon compression fittings on the soda lime trap and the Teflon nut on the Teflon stopcock are the most common location of leaks.

If peak-broadening is observed or no peak is detected in a sample, the analytical train is checked for leaks. Peak broadening is often the result of low gas flow, water vapor on the gold-coated bead trap, inadequate heating of analytical trap or an analytical trap damaged by exposure to halogen fumes or overheating. The analytical trap is not replaced unless it begins to demonstrate poor recovery or release of amalgamated mercury.

If the baseline drifts more than 10% the UV lamp is replaced. After replacement, the analyzer is allowed to equilibrate for 24 hours. If the problem persists, sources of power fluctuation, drafts or air currents that may be changing the temperature of the UV lamp are investigated.

Room temperature in which the CVAFS is located is maintained between 20-22°C, however, if the temperature exceeds 26°C analysis is stopped, since instrumental noise

increases significantly.

3.0 Performance Criteria, Quality Assurance and Quality Control

3.1 Field operators are carefully instructed in the techniques of contaminant-free particulate phase mercury sample collection. All of the operators are currently operating sampling equipment for either the National Dry Deposition Network, the National Atmospheric Deposition Program, the Integrated Atmospheric Deposition Network or the Great Lakes Acid Deposition Network.

3.2 Every 6 months UMAQL personnel inspect each of the sampling sites to audit the performance of the equipment and to make all necessary repairs or adjustments.

3.3 Co-located samples are collected from one sampling site during the study to quantify method precision. Reported concentrations for co-located samples are based on the mean of the two samples.

3.4 Precision and accuracy levels will be set and maintained for each type of analysis. A relative precision for total mercury of less than 15% is maintained for samples with values at least 3 standard deviations greater than the detection limit. Analysis of standards and controls is within 10% of the stated value.

A minimum of 25% of all samples are analyzed in duplicate. Reported concentrations are based on the mean of the replicates. Analytical precision averages better than 6%.

3.5 Every 3 months maintenance on the CVAFS analyzer is conducted, including replacement of the UV lamp, the Teflon tubing, and the detection cell.

4.0 Clean Room Procedures

4.1 Entering the Clean Room

Shoes are taken off outside the clean room by all UMAQL personnel. Personnel then enter the outer vestibule (changing room). Once inside, the hood is put on followed by the clean room suit and clean room boots. The boots are snapped to the suit at the back of the leg (to hold up the boots) and are buckled in the front. Personnel then step over a dividing bench where they put on clean room gloves and snap the clean room suit at the wrist. Now fully clothed they enter the clean room making sure to securely close the door behind.

4.2 Taking Supplies into the Clean Room

All supplies to be taken into the clean room are double bagged in polyethylene. The supplies to be taken into the clean room are placed in the outer dressing room. Upon entering the clean room, the outer bag is removed and left in the entry room. All supplies that enter the clean room that have not been bagged are rinsed with MQ-water and wiped off with particle-free wipes.

Appendix A: Facilities, Equipment and Reagents

Following is a list of the required facilities, equipment, supplies and reagents for sample preparation, sample collection and sample analysis that are outlined in this document. The make and model of the following items are those used at The University of Michigan Air Quality Laboratory. Many of these items are available from a variety of sources.

1. Preparation of Field Supplies

- Class 100 Clean Room, Work Stations
- Clean Room Gloves
- Particle-free Wipes
- Clean Room Cap, Gown and Boots
- Milli-Q Water (18.2 MÙ/cm)
- Exhaust Hood
- Acetone
- Alconox
- Polyethylene Tubs
- EM Science Tracepur and Suprapur Hydrochloric Acid
- Polytherm Water Bath (Science/Electronics)
- Baker Instra-Analyzed or EM Science Suprapur Nitric Acid
- New Polyethylene Bags
- 20 Liter Polyethylene Carboys

2. Sample Collection

- Vacuum Pump (URG, Model 3000-02M)
- Calibrated Dry Test Meter (DTM)
- Calibrated 30 lpm Rotameter (Matheson)
- HDPE Tubing with quick connects
- Black Latex Tubing
- Mercury Sampling Box (UMAQL, See Appendix B)
- Acid-Cleaned 47 mm Teflon Filter Holders (Savillex, PFA Labware)
- 47 mm Preheated Glass Fiber Filters (Gelman Sciences A/E)
- Acid-Cleaned Teflon Jars (Savillex, PFA Labware)
- Teflon-Coated Forceps
- Particle-Free Gloves
- Teflon Tape
- Sample Labels
- Field Operator Log Book
- Sample Tracking Forms
- Shipping Boxes

3. Sample Analysis

- Cold Vapor Atomic Florescence Detector (Brooks Rand, LTD.)
- Line Tamer/Conditioner (Shape Magnetronics Model PCLT 150)
- Integrator (Hewlett-Packard Model 3390A)

- Helium, Ultra High Purity Grade (99.999%)
- Mass Flow Controller (Tylan)
- Nichrome Coils (UMAQL)
- Electric Leads
- Variable Transformers (Staco Energy Products Co. Type 3PN1010)
- Cooling Fans
- Gold-Coated Glass Bead Traps (UMAQL)
- Pre-purified (99.998%), Analyzed Nitrogen
- Glass Impingers
- Resin-coated Ring Stand
- 25 mL Graduated Glass Bubblers
- 12.7 cm lengths of 1.27 cm OD Glass Tubing (Soda Lime Trap)
- Automatic Pipettes
- Repipet II Dispenser (Labindustries)
- Reagents (Section 4.2)
- Magnetic Stir Plate
- Class A Volumetric Flasks
- Teflon Reagent Bottles (Clear and Opaque)
- Teflon Reagent Vials
- Resin-coated Wire Rack (Support Bubblers)
- Refrigerator
- Freezer (-40°C)
- Microwave Digester (CEM)
- Microwave accessories:
- 24 Teflon Lined Vessels
- Rupture Disks
- Thermowell
- Fiber Optic Temperature Probe
- Pressure Tubing
- Carousel