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Bangladesh Air Pollution Studies (BAPS): Task 5 (Industrial Emission Estimate)

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Executive Summary

As part of the Bangladesh Air Pollution Studies (BAPS) under Clean Air & Sustainable Environment Project (CASE), stack emission measurements were made on several days at a steel mill and a ceramic industry, both located in the outskirts of Dhaka city. The measurements were made by ChE-BUET Team of the Bangladesh University of Engineering & Technology (BUET), Dhaka. The team has access to all the sophisticated equipment and expertise for emission measurements at industrial stacks. All equipment used were calibrated as per manufacturers' instructions. USEPA/ASTM approved methods were followed for all measurements. Stack emission index for steel mill and ceramic industry are shown below.

Parameters	Stack emission index for steel mill (Electric induction furnace)	Stack emission index for ceramic industry (Natural gas fired tunnel kilns)
	Stack emission index (g/ton steel)	Stack emission index (g/ton ceramic ware)
Carbon Dioxide (CO_2)	40,970.59	1,797,317.35
Carbon Monoxide (CO)	1,191.24	1,658.99
Nitric Oxide (NO)	7.42	1,520.77
Nitrogen Dioxide (NO_2)	26.18	238.03
Sulfur Dioxide (SO_2)	52.22	0.00
Total Particulate	2,297.49	1,378.25

However, these stack emission index values are purely related to the main production process. If these values are added with the respective emission factor due to use of electric energy in the production process, certainly the combined stack emission index will be of higher value. Both industries use electric energy from their own captive power plant. Data analysis of electric energy utilization shows that steel mill requires 800 kWh to produce 1 ton finished steel product, whereas ceramic industry requires 1200 kWh per ton of finished tableware. In steel mill the captive power plant consumes around 0.45 Nm^3 natural gas to produce 1 kWh energy, whereas, in ceramic industry this value stands around 0.43 Nm^3/kWh.

Besides, fugitive emissions index of different gaseous and particulates were also calculated from the measured and quantified data at both the industries. Fugitive emission index values for steel mill and ceramic industry are shown below.

Parameters	Fugitive emission index for steel mill	Fugitive emission index for ceramic industry
	Fugitive emission index (g/ton steel)	Fugitive emission index (g/ton ceramic ware)
Carbon Dioxide (CO_2)	105,041.17	165,812.31
Carbon Monoxide (CO)	2,700.90	5,715.71
Nitric Oxide (NO)	353.74	5,654.25
Nitrogen Dioxide (NO_2)	209.13	2,888.58
Sulfur Dioxide (SO_2)	0.00	0.00
Total Particulate	400.02	165.17

Dispersion modelling for both the Steel Mill and the Ceramics Factory, including a Brick Kill, have also been performed for NO_2, SO_2, and particulates using both the TAPM and CONCX models. Results from this modelling gives a good indication of the location of the maximum concentrations and the level of these concentrations.

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Bangladesh Air Pollution Studies (BAPS): Task 5 (Industrial Emission Estimate)

Introduction

Government of Bangladesh (GOB) initiated Clean Air and Sustainable Environment (CASE) project with assistance from International Development Association (IDA) / World Bank (WB). For some of the components (S-13) Norwegian Institute for Air research (NILU) was selected jointly by GOB and WB. Out of these, two components – Industrial Emission Estimate (Task-5) and Cost-effectiveness Assessment for Dust Control Measures (Task-4) were sub-contracted to a group in the Chemical Engineering Department of the Bangladesh University of Engineering & Technology (BUET), Dhaka (ChE-BUET Team). The core group of this team consists of Mr. Md. Mominur Rahman, Assistant Professor; Dr. Dil Afroza Begum, Professor and Dr. Nooruddin Ahmed, Retired Professor / UGC Professor of ChE Dept. Other teachers and technicians are also involved in the field work/measurements. This team has access to appropriate equipment and know-how for this type of work.

The current report deals with stack emission measurements of two local industries. Initially, the project aimed to make one day measurements at 4 or 5 different industries viz. steel making, ceramics, cement, urea fertilizer, etc. Later, on the advice of the international consultant for the CASE Project, it was decided that instead of single day measurements at many industries, it would be more worthwhile to have emission measurements at two different industries on multiple days. Accordingly, it was settled that steel making and ceramic were to be target industries. Ministry of Environment & Forests (MOEF) and the Department of Environment (DOE) sent out request letters to many steel and ceramic industries. Only a few responded. These were then visited by ChE-BUET team for their suitability for stack measurements. Finally, Rahim steel Mills (RSM) a private company located outside Dhaka on the Dhaka Narayanganj highway was selected for steel making industry. RSM is the second largest steel mill in the country. On the ceramic side, Shinepukur Ceramics (SPC) located at Savar, an industrial hub near Dhaka was selected. This is owned by the Beximco Group, one of the large private industrial conglomerates. SPC is the largest exporter of ceramic tableware in the country.

ChE-BUET Team had to visit these industrial units several times before actual measurements could be made. The management had to be convinced about the usefulness and harmless nature of the project and plans to make measurements at appropriate stack locations were negotiated and agreed upon. Temporary working platform had to be built with their permission.

ChE-BUET Team is grateful to the management of these two industries for their help and cooperation during these difficult and arduous tasks. Because of the novelty of the work in this region, problems of transportation of field staff and equipment proved rather difficult and the work proved hazardous specially at the steel mill. Some of the photographs in the report amply illustrate this. The task took long hours from morning till late evening and some members of the team got sick because of the heat and dust/soot.

At the steel complex stack measurements were made on four different days. At the ceramic factory, stack measurements were made for six days. Air quality measurements were also made inside and outside factory shed in both industries to quantify fugitive emission rate. It is obvious that working environment at ceramic factory was lot better than that at the steel complex.

Methodology, description of equipment used and results for both steel and ceramic industries have been included in this report. USEPA/ASTM methods were followed which were earlier okayed by

CASE/WB/NILU as per Inception Report (IR) for Task 5. This report consists of two parts. Part-I is related to steel mills and part-II is related to ceramic industry.
All measuring equipment used were calibrated as per normal procedure.

Part I

Rahim Steel Mills Co. Ltd.

S1.0 Introduction

Rahim Steel Mills Co. (Pvt.) Ltd. (RSM) is the second largest steel mill in Bangladesh and located at Sonargaon, Narayangonj beside the Dhaka-Chittagong highway which is about 22 km away from Dhaka city center. (Figures S1.1 and S1.2).
This Steel making facility produces Mild Steel (MS) billet and slabs using scrap iron (basically MS scrap) which are then used as the raw materials for re-rolling mills producing MS bar/rods and MS sheet for construction of buildings and ships respectively. Besides, this mill complex has other production facilities viz, re-rolling mills, coke production facility, ferro-alloy production facility, oxygen and liquid nitrogen production facility.

Figure S1.1. Roadway driving directions to RSM (B) from BUET (A)

Figure S1.2. Google satellite picture of RSM Complex.

RSM has a daily production capacity of 441 ton finished product (MS billet or slab). There are three pairs of Crucible Type Electric Induction Furnaces (EIF) of different capacity in the melt shop of the steel mill. A brief description of the EIF is given in Appendix-A.

Each EIF of pair 1, pair 2 and pair 3 has a production capacity of 18 ton billet or slab/Batch (running production 16 ton/batch), 20 ton billet or slab/Batch (running production 18 ton/batch) and 25 ton billet or slab/Batch (running production 23 ton/batch) respectively. Three EIFs from each pair operate for 24 hours while the rest three EIFs remain as standby. Unit EIF of each pair can operate up to seven batches a day considering loading and unloading activities of raw materials and molten metal. Each EIF takes about 3 hours to complete each batch for preparing finished MS molten metal. Presently the mill produces 400 ton billet or slab/day. Each of EIFs requires 1.28 tons of MS scrap and 800 kWh energy to produce 1 ton of final product-billet or slab. Presently, RSM uses self generated electrical energy.

The mill premise has its own captive power plant consists of 8 natural gas fired generators each having a rated production capacity of 4MW, whereas each generator actually produces 3.5 MW. There is also a gas fired steam turbine power plant having rated capacity of 15 MW that actually produces 14 MW. This captive power plant (gas fired generators and steam turbine) requires 0.45 Nm^3 of natural gas to produce 1kWh energy. The whole steel production facility requires 320,000 kWh energy/day which means natural gas consumption around 144,000 Nm^3/day.

The mill authority sells excess electric energy to Bangladesh Rural Electrification Board (REB). This steel mill produces basically two types of final products: 1. MS Billet (120 × 120 mm with a length of 4000-6000 mm) and 2. MS Slab (115 × 900 mm with a length of 3657.6 mm). Carbon content of each of the final product varies between 0.20 to 0.30%. The factory shed, wherein steel making takes place, is about 160 m long, 16 m wide and 21 m high. All three pairs of EIF, tandish and continuous casting unit are inside this shed. Each pair of EIF has a single swing type hood connected with a metallic chimney of 36.5 m height from ground level. An induced draft fan (IDF) is used to create high draft inside the chimney to suck and emit the gases and particulates produced during EIF's operations.

S2.0 Process Description of Existing Steel Production Facility in RSM

S2.1 Scrap collection and segregation

Scrap metals are collected and bought through the country wide network and brought to the scrap yard in the factory premise. Some scrap metals are also imported. Scrap metals are then segregated based on their grade (cast iron, MS etc.), size, shape and uses. Oversize metals are resized through hydraulic cutting and shearing. Oil and gas cylinders are first emptied through drilling and the empty cylinders are then resized through cutting. Segregated and resized scrap metals are then stored in separate piles and are ready to feed the EIF. Figures S2.1.1 to S2.1.4 show different scrap yard of the steel mill.

Figure S2.1.1. Unprocessed scrap yard

Figure 2.1.2. Processed scrap yard

Figure S2.1.3. Low grade metal dust

Figure S2.1.4. Sponge/pig/cast iron yard

S2.2 Scrap Charging and Melting Process

Charging of the scrap metals are performed using charging car and hoisted electric magnet. Scraps are brought to the furnace floor from the scrap yard with the help of hoisted large electric magnet. This scrap is then charged into the EIF using charging car and hoisted electric magnet inside factory shed (Figures S2.2.1 and S2.2.2).

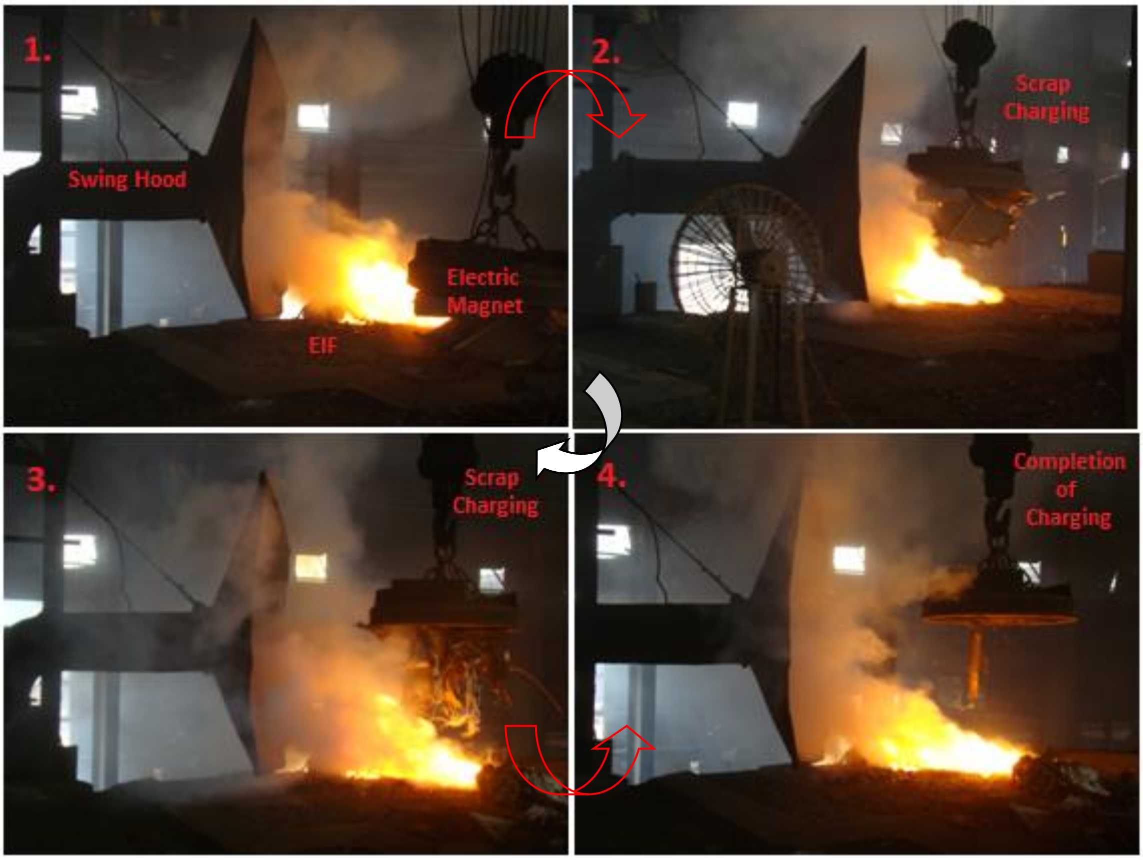


Figure S2.2.1. Scrap charging into EIF with hoisted electric magnet

Figure S2.2.2. Scrap charging into EIF with charging car

During EIF charging, coke is added to the furnace at a ratio 4-5 kg coke/ton of MS scrap considering effective performance level of coke as 50%. MS scrap usually contains about 0.15-0.3% carbon. During melting process this carbon drastically reduces in the furnace due to reduction reaction which may cause damage to the furnace lining. To avoid damages coke is charged along with the scrap to maintain carbon percentage at a reasonable level. Alternatively cast iron, pig iron and coke are charged with MS scrap to maintain the carbon content during melting process since cast iron contains about 2.1-4% carbon and pig iron contains about 3.5-4.5% carbon. The carbon present in the cast iron or pig iron or coke primarily provides reduction of iron oxides in MS scrap into iron.

Initially the EIF is fully charged with the scrap. The scrap starts melting at 1450°C through magnetic field flushing inside the EIF. The bulk volume of the scrap reduces as it melts. The EIF is then charged slowly and continuously in a manner that charged scrap gets lead time to melt between consecutive charging. It takes an hour to melt 50% of the total estimated scrap for a batch based on EIF capacity. After that EIF is hydraulically tilted to drain top layer slag through the pouring spout. Then EIF is charged with scarp up to 80% of the EIF's capacity within next 45 minutes. Then again slag is drained out of the EIF through the spout. At this point molten metal sample is taken out to characterize its property. If carbon content in the molten metal is found higher (> 0.3%), excess carbon is oxidized by charging sponge iron and hot briquette iron (HBI) as desired carbon content in the molten metal at this stage ranges from 0.15 to 0.3%. If carbon content is found lower than this range, excess cast/pig/sponge iron is added to the molten metal. Si and Mn in final product should be in the ranges 0.15-0.5% and 0.6-1.6% respectively. If Si and Mn contents in molten metal are found lower compared to the required values, furnace temperature is raised to 1550°C from 1450°C and Ferro-Si alloy, Ferro-Mn alloy are added to the furnace. Si alloy is added to kill residual oxides and as a composition filler; whereas, Mn-alloy is added to enhance the strength of final product and also as a composition filler. If Mn and Si contents are found higher then re-oxidization of the molten metal is carried out. The process of adjusting the composition of the elements is known as ladle refining which may be carried out in a ladle refining furnace separately or can be carried out in the same EIF. RSM performs the ladle refining in the EIF. This refining process takes additional one hour to be completed. Melting and refining processes inside EIF are shown in Figure S2.2.3.

Figure S2.2.3. Melting and refining of scrap inside EIF

After refining, the temperature of the molten metal is raised to 1680°C and taped into ladle where lime is added at a ratio 10-15 kg lime/ton of molten metal to remove sulfur as a top layer slag. It takes around three hours to complete a batch from initial charging to taping molten metal into ladle. Desired level of sulfur content in the final product is less than 0.04%. Taping of molten metal into ladle is shown in Figure S2.2.4.

Figure S2.2.4. Taping of molten metal into ladle from furnace

The ladle filled with molten metal is then taken to the tandish and molten metal is allowed to flow into tandish through bottom taping of the ladle (Figure S2.2.5).

Figure S2.2.5. Transferring Ladle with molten metal towards tandish

Tandish actually serves as a molten metal storage wherefrom liquid metal flows through the continuous casting machines that produce the final desired product-billet/slab with definite shape and size. Tandish is a metallic and internally insulated dish. Rice husk is also used externally as an insulation material. If the temperature inside the tandish falls down, gaseous oxygen is bubbled through the molten metal to raise its temperature. The process of billet/slab making in continuous casting machine is shown in Figure S2.2.6.

Figure S2.2.6. Billet production through continuous casting machines

The finished product (billet/slab) is then piled up in the rack (Figure S2.2.7) to process further or to sell to customers.

Figure S2.2.7. Finished product (Billet) yard

EIF undergoes routine maintenance work after the shelf life of its lining. Maintenance of the EIF is shown in Figure S2.2.8.

Figure S2.2.8. Regular basis furnace maintenance work

S3.0 Environmental Aspects of RSM

RSM presently has three pairs of EIF with different production capacity as mentioned earlier. Each pair of EIF is furnished with a single swing hood through which a strong IDF sucks the gases and particulates and takes them out through the chimney. This chimney is built with mild steel sheet of 3 mm thickness. Each of the chimneys has an internal diameter of 0.82 m and a height of 36.5 m from ground level. Expert guess says that only a fraction (one third) of the produced gas and particulates during melting process of the EIF enters into the swing hood and goes out through the chimney.

Rest of the emission mixes with air inside the shed and goes out through the corrugated sheet made cascade type exit surrounding the factory shed. There are also some uncontrolled emission points inside the shed. During de-slagging and transferring molten metal into ladle huge emission occurs which mixes with air inside the shed and eventually goes out of the shed and is carried by the ambient air. Emission also takes place in continuous casting process area also.
However, during routine maintenance of EIF lining, inner zones of factory seems densely laden with dust particles due to use of high pressure air jet for cleaning purpose. There may be particulate emission from scrap yard outside factory shed and particulate emission from transferring scrap from outside to furnace floor inside the shed. Visually this emission was not manifested with bare eyes. Probable emission source-points along the steel production line are shown schematically in Figure S3.0. Presently the factory has no pollution mitigation facility in operation except sucking and dispersing a fraction of the emission through the 36.5 m tall chimney. Though there are air pollution mitigation facilities (cyclone separator followed by a water scrubber) installed outside the shed, they are not in operation.

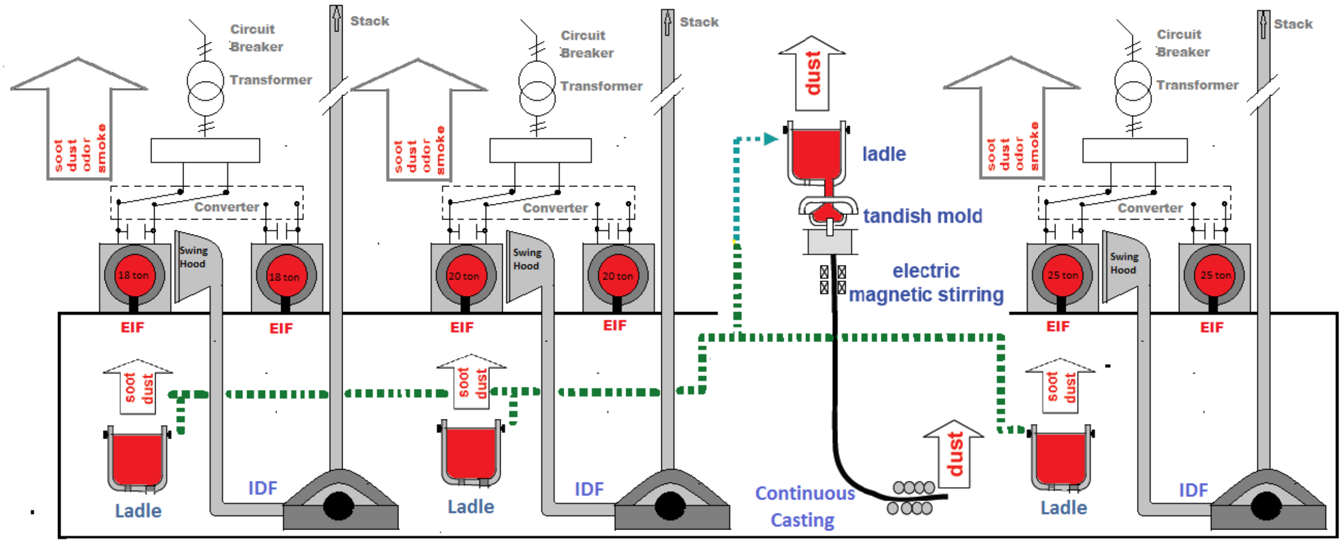


Figure S3.0. Schematic of steel production line from scrap metals and associated emission sources

S3.1 Stack Emission and Fugitive Emission Measurement

For stack emission measurement, EIF of pair 1 with a production capacity of 18 ton billet or slab/Batch/EIF was selected. Both gaseous (CO_2, CO, SO_2, NO, NO_2) and total particulate pollutants of the stack were measured on four separate days (March 14, 15, 17 & 22, 2013). Gaseous emissions were measured for three hours since it takes 3 hours time to complete a batch of production whereas stack particulates were sampled for variable time depending on stack conditions to satisfy the isokinetic sampling procedure.

For fugitive emission measurement, both gaseous (CO_2, CO, SO_2, NO, NO_2) and particulate (PM_{10}) pollutants of ambient air just adjacent to the factory shed and inside the factory shed were measured. Gaseous pollutants were measured for three hours whereas particulate pollutants (PM_{10}) were measured for eight hours. Fugitive emissions were measured on two consecutive days (March 14 & 15, 2013).

S3.1.1 Stack Emission (gaseous and particulate) Measuring Protocols

Steps involved in stack emissions measurement were: selecting appropriate sampling location and traverse points of the stack, measuring the gaseous pollutants' concentrations, determining average molecular weight of the stack gas (both in wet and dry basis) and isokinetic sampling conditions for measuring particulate concentration in stack gas, calculating and determining average stack gas velocity and actual volumetric flow rate at stack conditions on wet basis from the measured values and converting the actual volumetric flow rate into dry volumetric flow rate at standard conditions.

S3.1.1.1 Sampling Location and Traverse Point

Stack selected for measuring the emission was connected to the swing hood dedicated for the EIF of capacity 18 ton/batch. The stack was 36.5 m high (Figure S3.1.2) from the ground level and with a strong IDF at the ground. The stack was made of mild steel sheet having a thickness of 3 mm and internal diameter of the stack was 0.82 m. The blower exit was 1.85 m high from the ground level (Figure S3.1.1). Selection of appropriate sampling location and traverse points of the stack were determined following USEPA Reference Method 1 (40CFR60 App. A.)/ASTM D 3154-91.

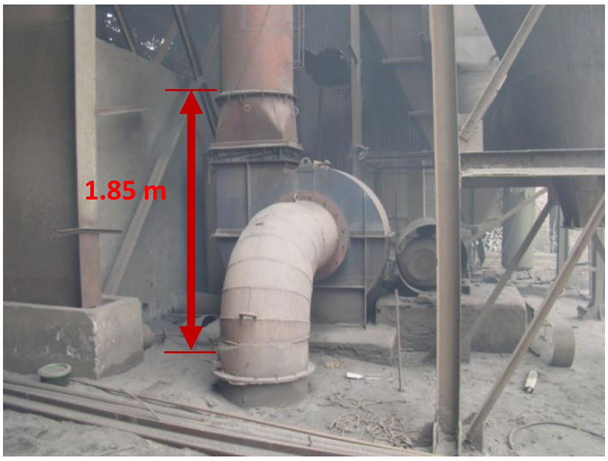
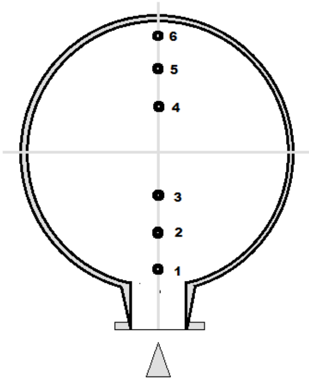


Figure S3.1.1. Blower exit height of the stack

Minimum sampling height for this case is around 6.56 m from the exit of the IDF (i.e., 8.41 m from ground level). However, in this case a sampling location at 8.5 m height of the chimney from ground level was chosen. At this position of the chimney, a hole of internal diameter (ID) 0.0762 m was bored and an extension pipe (0.3048 m long) of similar ID was welded for better workability. At this sampling location of the chimney a metallic scaffold with ladder was built for working platform.

Figure S3.1.2. Stack height and working platform height from ground level

For a circular stack of ID > 0.61 m, 6.65 m downstream distance from the IDF exit and 28 m upstream distance from stack exit, minimum number of traverse points required for non-particulate and particulate sampling was calculated to be 12, six in each of two directions 90° apart. Though, it is customary to measure the emission at six traverse points on each of two diameters apart to each other by 90°, measurement was carried out only at six traverse points on a single diameter due to reluctance of the factory authority to allow boring of two holes 90° apart on the same plane of the stack. Number of traverse points and their positions along the diameter of the stack are shown in Figure S3.1.3.



Traverse Point	Distance (% of diameter)
1	4.4
2	14.6
3	29.6
4	70.4
5	85.4
6	95.6

Figure S3.1.3. Traverse points along the stack diameter

S3.1.1.2 Stack Gas Compositions

Concentrations of different gaseous components of the stack gas were measured from diluted or non-diluted stack gas sample based on the concentration levels of gaseous components and measuring range of the equipments (Figure S3.1.4). Dilution of stack gas was prepared with pressurized regulated zero air at a known dilution ratio by means of a stack gas single dilution probe and a dilution controller (Model 200L, Thermo Environmental Instruments Inc., USA). The dilution method meets the requirements pertained in the USEPA 40CFR60. All the equipment were calibrated in the laboratory following calibration procedures given in the respective manuals (Appendix-C) before field sampling.

CO_2 concentration of the stack gas was measured using Infrared Absorption Principle with a High Level Gas Filter Correlation CO_2 analyzer (Model 41C, Thermo Environmental Instruments Inc., USA).

CO and NOx (NO and NO_2) concentrations of the stack gas were measured simultaneously using a portable analyzer having Electrochemical Sensor (Model 600-2-4-5, NOVA Analytical Systems Inc., Canada).

SO_2 concentration of the stack gas was measured using a portable analyzer having Electrochemical Sensor (Model 600-8, NOVA Analytical Systems Inc., Canada).

O_2 of the stack gas was measured using direct sensing WDG-INSITU Flue Gas Analyzer coupled with Thermox Flue Gas Monitor (2000 Series), AMETEK Inc., USA.

Moisture content of the flue gases was measured following USEPA Reference Method 4 and using Isokinetic Source Sampler XC 500 Series, Apex Instruments Inc., USA.

Balance of the stack gas (excluding CO_2, CO, O_2 and Moisture) was assumed as N_2.

Stack Gas Molecular Weight on wet/dry basis was calculated from the measured concentrations of CO_2, CO, O_2, moisture and N_2 content of the stack gas using the formula mentioned in section 12 of ASTM D 3154-91 and USEPA Reference method 2 and 4.

Average stack gas velocity and actual volumetric flow rate at stack conditions on wet basis were determined following USEPA Reference Method 2 (40CFR60 App. A.)/ASTM D 3154-91 and using Isokinetic Source Sampler XC 500 Series, Apex Instruments Inc., USA.

Total Particulate Concentration in Stack Gases was determined following USEPA Reference Method 5 (40CFR60 App. A.)/ASTM D 3685/D 3685M-98 and using Isokinetic Source Sampler (XC 500 Series), Apex Instruments Inc., USA (Figure S3.1.5).

Figure S3.1.4. Measuring of gaseous concentrations of stack gas at RSM

Figure S3.1.5. Lifting of particulate sampler on working platform and sampling of stack particulates

Gaseous (CO_2, CO, NOx and SO_2) and total particulate emission rate of the stack were determined from the concentration levels of gaseous and particulate pollutants and volumetric flow rate data of the stack gases obtained through the measurement. For stack particulate measurement, 82.6 mm diameter glass microfiber filter papers were used. Pre and post conditioning of the filters were carried out at 20°C and 50% RH for 24 hours. The procedure and working principle of each method is given in **Appendix-B.**

S3.1.2 Fugitive Emission (gaseous and particulate) Measuring Protocols

For fugitive emissions from steel manufacturing process, gaseous and particulate pollutant concentrations of ambient air-gas mixture were measured both inside and outside of the factory shed. For gaseous concentrations of the ambient air, ambient air sampling probe of Environmental Monitoring Unit (EMU) was placed at a height of 4.5 m from ground level (Figure S3.1.6). The analyzers measured ambient CO_2, CO, NO, NO_2 and SO_2 concentrations of non-diluted indoor air inside factory shed. Measuring procedures of ambient gaseous pollutants were same as those followed during the measurement of stack gaseous pollutants except the dilution of gas sample. The procedure and working principle of each method is given in **Appendix-B.**

For respirable particulate (PM_{10}) concentration of the ambient air, USEPA certified Graseby Andersen High Volume PM_{10} Sampler (GMW PM10/VFC), USA was used. The inlet of the sampler was also placed at a height of 4.5 m from ground level outside the shed (Figure S3.1.7) as the height of the working floor inside the factory was 3 m above the ground level. For ambient PM_{10} measurement, 20.3 cm X 25.4 cm glass microfiber filters were used. Pre and post conditioning of the filters were carried out at 20°C and 50% RH for 24 hours. All the equipment were calibrated in the laboratory following calibration procedures given in the respective manuals (Appendix-C) before sampling.

Figure S3.1.6. Measurement of ambient gaseous components adjacent to the factory shed

Figure S3.1.7. Lifting of Andersen high volume PM_{10} sampler on the roof and ambient PM_{10} sampling

S4.0 Results

Concentration data of CO_2, CO, NO, NO_2 and SO_2 and total particulate of stack gas were analyzed, calculated and reported as average values along with actual stack gas conditions. Reported concentration, emission rate and emission index values of gaseous and particulate pollutants of stack gas are based on dry basis at 25°C and 760 mm Hg.

Concentration of ambient CO_2, CO, NO, NO_2 and SO_2 and PM_{10} were analyzed, calculated and reported as average values along with dry bulb and wet bulb temperatures and percentage of relative humidity. Reported concentration values of ambient air are based on dry basis at 25°C and 760 mm Hg.

S4.1 Stack Emission

Gaseous (CO_2, CO, SO_2, NO, NO_2) and total particulate pollutants of the stack were measured on four separate days (March 14, 15, 17 and 22, 2013). Concentrations of gaseous pollutants were measured for three (3) hours since it takes 3 hours time to complete a batch of production whereas stack particulates were sampled for variable time depending on stack conditions to satisfy the isokinetic sampling procedure. Day to day average compositions of the stack gas, stack gas molecular weight and stack gas volumetric flow rate on dry basis are given in Tables S4.1.1-S4.1.4 along with the actual average stack conditions below each table.

Table S4.1.1. Dry basis average stack gas compositions (gaseous and total particulates), stack gas molecular weight and stack gas volumetric flow rate at 25°C and 760 mm Hg measured on March 14, 2013

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	3,155.63	28.85	572.32
Carbon Monoxide (CO)	141.25		
Nitric Oxide (NO)	1.12		
Nitrogen Dioxide (NO_2)	4.84		
Sulfur Dioxide (SO_2)	6.73		
Total Particulate	168.00		

***Note:** Stack conditions on March 14, 2013*

Average stack temperature: 52.5°C, Absolute stack pressure: 752.38 mm Hg, Stack ID: 0.82 m, Stack height from ground: 36.5 m
Stack sampling height from ground: 8.5 m, Stack flow area: 0.528103 m^2, Average stack gas velocity (wet basis) at stack conditions: 20.578 m/s, Average stack moisture content: 3.3473 vol. or mol%, Wet gas molecular weight: 28.48876 g/g-mol, Wet gas volumetric flow rate at stack condition: 652.0382 m^3/min

Table S4.1.2. Dry basis average stack gas compositions (gaseous and total particulates), stack gas molecular weight and stack gas volumetric flow rate at 25°C and 760 mm Hg measured on March 15, 2013

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	3,754.85	28.88	578.80
Carbon Monoxide (CO)	135.01		
Nitric Oxide (NO)	1.099		
Nitrogen Dioxide (NO_2)	3.37		
Sulfur Dioxide (SO_2)	11.72		
Total Particulate	365.64		

***Note:** Stack conditions on March 15, 2013*

Average stack temperature: 59.5°C, Absolute stack pressure: 752.015 mm Hg, Stack ID: 0.82 m, Stack height from ground: 36.5 m, Stack sampling height from ground: 8.5 m, Stack flow area: 0.528103 m^2, Average stack gas velocity (wet basis) at stack conditions: 21.348 m/s, Average stack moisture content: 3.7221 vol. or mol%, Wet gas molecular weight: 28.4480 g/g-mol, Wet gas volumetric flow rate at stack condition: 676.4366 m^3/min

Table S4.1.3. Dry basis average stack gas compositions (gaseous and total particulates), stack gas molecular weight and stack gas volumetric flow rate at 25°C and 760 mm Hg measured on March 17, 2013

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	6,100.10	28.89	591.99
Carbon Monoxide (CO)	127.18		
Nitric Oxide (NO)	1.11		
Nitrogen Dioxide (NO_2)	2.83		
Sulfur Dioxide (SO_2)	6.60		
Total Particulate	444.97		

***Note:** Stack conditions on March 17, 2013*

Average stack temperature: 55.3°C, Absolute stack pressure: 751.647 mm Hg, Stack ID: 0.82 m, Stack height from ground: 36.5 m, Stack sampling height from ground: 8.5 m, Stack flow area: 0.528103 m^2, Average stack gas velocity (wet basis) at stack conditions: 21.446 m/s, Average stack moisture content: 2.9032 vol. or mol%, Wet gas molecular weight: 28.5370 g/g-mol, Wet gas volumetric flow rate at stack condition: 679.5418 m^3/min

Table S4.1.4. Dry basis average stack gas compositions (gaseous and total particulates), stack gas molecular weight and stack gas volumetric flow rate at 25°C and 760 mm Hg measured on March 22, 2013

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	11,594.30	28.92	625.10
Carbon Monoxide (CO)	311.96		
Nitric Oxide (NO)	1.12		
Nitrogen Dioxide (NO_2)	4.71		
Sulfur Dioxide (SO_2)	6.31		
Total Particulate	401.16		

Note: *Stack conditions on March 22, 2013*

Average stack temperature: 52.8°C, Absolute stack pressure: 751.074 mm Hg, Stack ID: 0.82 m, Stack height from ground: 36.5 m, Stack sampling height from ground: 8.5 m, Stack flow area: 0.528103 m^2, Average stack gas velocity (wet basis) at stack conditions: 22.664 m/s, Average stack moisture content: 3.6464 vol. or mol%, Wet gas molecular weight: 28.4563 g/g-mol, Wet gas volumetric flow rate at stack condition: 718.1356 m^3/min

weight, volumetric flow rate, emission rate and emission index during four day sampling for *a single stack connected with 18 ton capacity/batch EIF pair* are given in Table S4.1.5. These reported values are based on 25°C and 760 mm Hg. Also average values of different parameters of the stack and stack gas during four day sampling are given below the table. RSM has a daily average production of 400 ton finished product (MS billet or slab). There are three pairs of Crucible type Electric Induction Furnaces (EIF) of different capacity in the melt shop of the steel mill. Each EIF of pair 1, pair 2 and pair 3 has a current production of 16 ton billet or slab/Batch, 18 ton billet or slab/Batch and 23 ton billet or slab/Batch respectively. Three EIFs from each pair operate for 21 hours a day while the rest three EIFs remain as standby. Unit EIF of each pair can operate up to seven batches a day considering loading and unloading activities of raw materials and molten metal. Each EIF takes about 3 hours to complete each batch for preparing finished MS molten metal. Stack emission index was calculated on the basis of *a single stack connected with 18 ton capacity/batch EIF pair (whose actual field production is 16 ton/batch/EIF).* This EIF produces 112 tons of molten finished metal in 7 batches during 21 hours a day.

Table S4.1.5. Dry basis average stack gas compositions (gaseous and total particulates), stack gas molecular weight and stack gas volumetric flow rate and stack emission index at 25°C and 760 mm Hg during four day sampling.

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)	Stack Emission index^{Ø} (g/ton steel)
	Avg. value			
Carbon Dioxide (CO_2)	6,151.22	28.89	592.05	40,970.59
Carbon Monoxide (CO)	178.85			1,191.24
Nitric Oxide (NO)	1.1142			7.42
Nitrogen Dioxide (NO_2)	3.93			26.18
Sulfur Dioxide (SO_2)	7.84			52.22
Total Particulate	344.94			2,297.49

Note: *Average stack conditions during four day sampling*

Average stack temperature: 55.04°C, Absolute stack pressure: 751.78 mm Hg, Stack ID: 0.82 m, Stack height from ground: 36.5 m, Stack sampling height from ground: 8.5 m, Stack flow area: 0.528103 m^2, Average stack gas velocity (wet basis) at stack conditions: 21.5091 m/s, Average stack moisture content: 3.404 vol. or mol%, Wet gas molecular weight: 28.4825 g/g-mol, Wet gas volumetric flow rate at stack condition: 681.5380 m^3/min

^{Ø} Emission from captive power plant is not included in these stack emission index values

The smelting and refining process of scrap metals is very unsteady. It was observed that when the scrap metals were charged into the furnace, smoke evolution rate was high and with time smoke evolution rate decreased. Within first two hours of three hours batch, more than 80% of scrap charging is finished and corresponding smoke evolution rate is high during this two hour period. The last one hour is left for refining of molten metal to adjust the desired property of the finished product and corresponding smoke evolution rate at this stage is rather low. During the first day sampling on March 14, 2013, particulate sampling was started at the refining stage and the corresponding concentration of particulate matter on that day (Table S4.1.1) was found to be the lowest. However, particulate sampling on other days were carried out during the first two hours of a three hours batch time. Therefore, particulate concentrations on those days (Tables S4.1.2 to S4.1.4) were found to be higher compared to that of first day sampling.

S4.2 Fugitive Emissions

Gaseous (CO_2, CO, SO_2, NO, NO_2) and PM_{10} pollutants of the ambient air inside and outside factory shed were measured on two consecutive days (March 14 and 15, 2013). Concentrations of gaseous pollutants were measured for three (3) hours since it takes 3 hours time to complete a batch of production whereas PM_{10} was sampled for eight (8) hours each day.

Day to day average ambient concentrations of gaseous pollutants and PM_{10} and volumetric flow rate at 25°C and 760 mm Hg are given in Tables S4.2.1-S4.2.2 along with the actual ambient conditions below each table. Several pedestal fans run continuously on the EIF floor to remove smoke from the working place towards the stack of the factory shed.

To calculate fugitive emission, it was assumed that ambient air-gas mixture from factory shed flows through a rectangular window with a length of 160 m and a height of 12.5 m. Air-gas mixture flow area was assumed to be 50% of this rectangular window. Wind speed was also measured at various points and different times at the exit of this rectangular window to find out the air-gas mixture volumetric flow rate.

Table S4.2.1. Average ambient concentrations of gaseous pollutants and PM_{10}, and volumetric flow rate at 25°C and 760 mm Hg outside the shed on March 14, 2013.

Parameters	Concentrations (mg/m^3)	Volumetric flow rate of gas and air mixture (m^3/min)
Carbon Dioxide (CO_2)	899.31	31,800
Carbon Monoxide (CO)	17.79	
Nitric Oxide (NO)	2.21	
Nitrogen Dioxide (NO_2)	1.88	
Sulfur Dioxide (SO_2)	0	
PM_{10}	3.26	

Note: *Ambient conditions on March 14, 2013*

Average dry bulb temperature: 33.93°C, Average wet bulb temperature: 27.5°C,
Average percentage of relative humidity (RH%): 60, Average wind speed: 0.53 m/s

Table S4.2.2. Average ambient concentrations of gaseous pollutants and PM_{10}, and volumetric flow rate at 25°C and 760 mm Hg inside the shed on March 15, 2013.

Parameters	Concentrations (mg/m^3)	Volumetric flow rate of gas and air mixture (m^3/min)
Carbon Dioxide (CO_2)	989.24	30,000
Carbon Monoxide (CO)	30.77	
Nitric Oxide (NO)	4.15	
Nitrogen Dioxide (NO_2)	1.88	
Sulfur Dioxide (SO_2)	0	
PM_{10}	3.94	

Note: *Ambient conditions on March 15, 2013*
Average dry bulb temperature: 33.17°C, Average wet bulb temperature: 24.05°C,
Average percentage of relative humidity (RH%): 47, Average wind speed: 0.50 m/s

However, dry basis average ambient compositions (gaseous and PM_{10}), volumetric flow rate of dry gas and air mixture and emission index during two day sampling are given in Table S4.2.3. These reported values are based on 25°C and 760 mm Hg. Also average values of different parameters of the ambient air and gas mixture during two day sampling are given below the table. To calculate fugitive emission index it was considered that 3 EIFs of different production capacity produce 400 ton of finished product during 24 hours a day.

Table S4.2.3. Dry basis average ambient compositions (gaseous and PM_{10}), volumetric dry gas and air mixture flow rate, fugitive emission rate and emission index at 25°C and 760 mm Hg during two day sampling.

Parameters	Concentrations (mg/m^3)	Volumetric flow rate of gas and air mixture (m^3/min)	Fugitive emission rate (g/min)	Fugitive emission index (g/ton steel)
Carbon Dioxide (CO_2)	944.28	30,900	29178.10	105,041.17
Carbon Monoxide (CO)	24.28		750.25	2700.90
Nitric Oxide (NO)	3.18		98.26	353.74
Nitrogen Dioxide (NO_2)	1.88		58.09	209.13
Sulfur Dioxide (SO_2)	0.00		0.00	0.00
PM_{10}	3.596		111.12	400.02

Note: *Average ambient conditions during two day sampling*
Average dry bulb temperature: 33.55°C, Average wet bulb temperature: 25.775°C,
Average percentage of relative humidity (RH%): 53.5, Average wind speed: 0.515 m/s

S5.0 Conclusions based on emission measurements

The melting operation in the steel mill is an unsteady process. During a 3 hour batch operation, emission reduces gradually from the beginning to the ending of melting process. During first one hour of the melting process, about 50% of the metal scraps are charged into the EIF and by the next two third of the time more than 80% metal scrap charging is finished and the last hour of a batch is the purification time.

This last one hour is left for refining of molten metal to adjust the desired property of the finished product. Various additives are added during this stage. Therefore, emission is more during first one hour as the scrap charging rate is higher compared to the charging rate in subsequent hours of a batch preparation and it decreases gradually as the melting process progresses.

The least emission was observed visually as well as experimentally during the last hour of a batch time. Therefore, in this work all the segments of a batch time were covered during sampling to get a representative average emission index for the industry.

S6.0 Ground level concentrations based on dispersion modelling

The models CONCX and TAPM have been utilized to generate ground level concentrations of particles, SO2, and NO2. CONCX is a NILU developed stationary Gaussian dispersion model for calculating the dispersion of emissions from single point sources. TAPM is a numerical meteorological and air quality prediction model. It predicts three-dimensional meteorology and air pollution concentrations.

The results presented below are based on a 25x25km grid (.3km resolution), with the industry source as the grid center point, over the period of one year (using virtual metrological data from 2012 retrieved at each industrial point).

Input data used for CONCX and TAPM dispersion calculations for the steel mill can be seen in Table S6.0.1 and S6.0.2 below.

Table S6.0.1: Emission rates for measured components at the steel mill

Component	Concentration mg/m3	Dry gas Flowrate m3/min	Emission Rate (g/s)
Carbon Dioxide (CO_2)	6,151.22	592.05	60.70
Carbon Monoxide (CO)	178.85		1.76
Nitric Oxide (NO)	1.1142		0.01
Nitrogen Dioxide (NO_2) TR4	3.93		0.04
Sulfur Dioxide (SO_2) TR3	7.84		0.08
Total Particulate (TSP) TR1	344.94		3.40

Table S6.0.2: Standard stack and emission variables for the steel mill

Stack Height (m)	36.5
Stack flow area (m2)	0.528103
Stack diameter (m)	0.82
Volumetric flowrate of wet gas (m3/min)	681.538
stack gas velocity	21.51
Exit gas temperature (K)	328.04
Ambient temperature(K)	306
X coordinate	23 deg 42 min
Y coordinate	90 deg 32 min

The results from CONCX for NO_2, SO_2, and TSP can be seen in Figures S6.0.1, S6.0.2, and S6.0.3 below. During unstable wind conditions (1m/s), concentration will appear inside 500m from the stack (NO_2: 1.2 µg/m^3, SO_2: 2.0 µg/m^3, and TSP: 88 µg/m^3).

However during light stable meteorological conditions with wind speeds around 1m/s the highest concentrations at ground level may be found at distances around 2.5 km downwind from the stack. In this case the concentrations are: NO_2: 0.6 µg/m^3, SO2: 1.3 µg/m^3, and TSP: 55 µg/m^3,

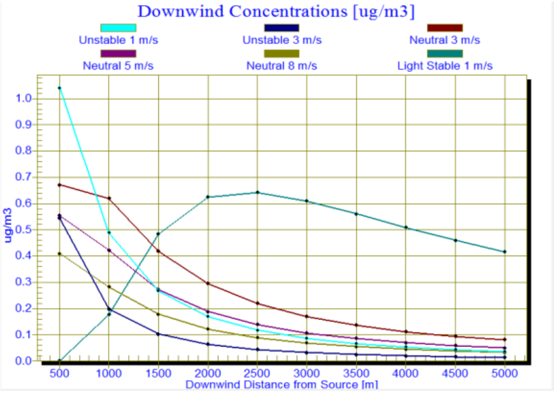


Figure S6.0.1: Estimated maximum ground level concentrations of NO2 for different meteorological conditions from stack emission of RSM Ltd

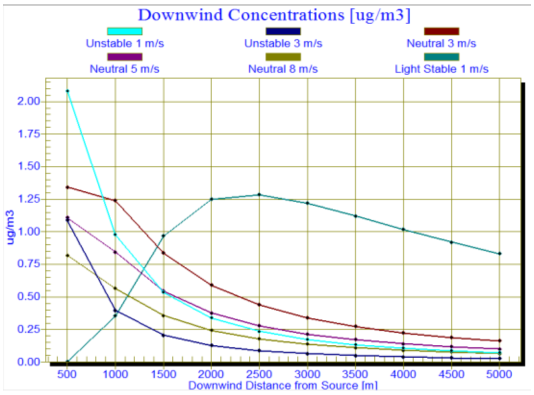


Figure S6.0.2: Estimated maximum ground level concentrations of SO2 for different meteorological conditions from stack emission of RSM Ltd.

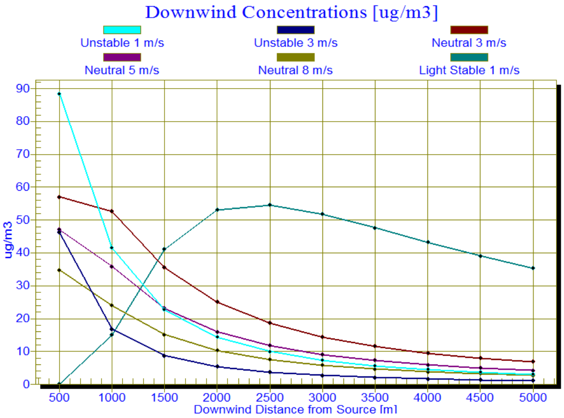


Figure S6.0.3: Estimated maximum ground level concentrations of TSP for different meteorological conditions from stack emission of RSM Ltd.

Dispersion patterns from TAPM for all pollutants can be visualized in Figures S6.0.4 and S6.0.5, as grid cell maximums for the year. The figures represents maximum hourly concentrations the other on maximum 24-hour average concentrations.

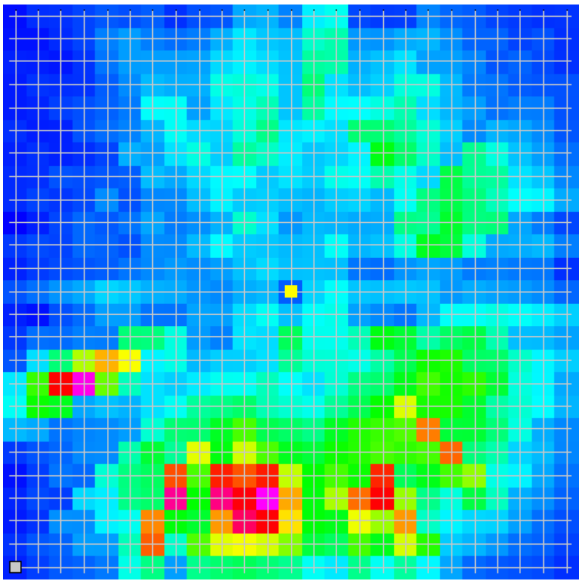


Figure S6.0.4: The one hour average cell maximum concentrations based on met data for one year at the Steel Mill. (.3x.3km grid cell resolution)

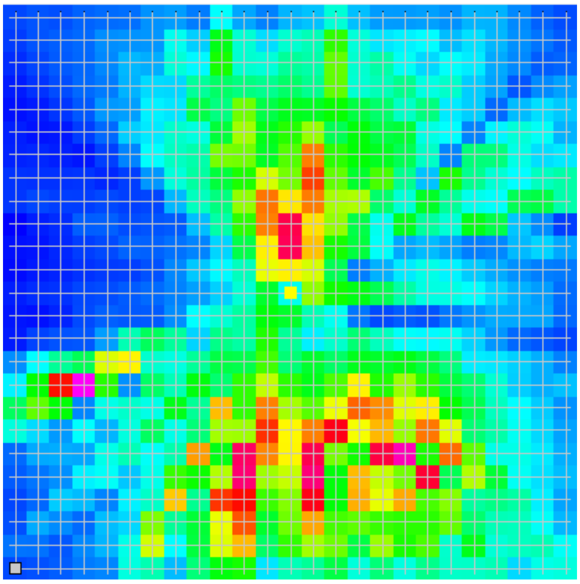


Figure S6.0.5: The 24-hour maximum cell concentration based on data for one year at the Steel Mill. (.3x.3km grid cell resolution)

The concentration values for the dispersion results visualized above can be seen in Table S6.0.3. SO_2 and NO_2 concentrations are low, while TSP concentrations are of particular notice. The highest hourly maximum concentrations can be found approximately 3 km south of the factory. The highest 24-hour average concentrations can be found north as well as south and south-east of the factory.

Table S6.0.3: Concentration results over entire grid for SO2, NO2, and TSP for the Steel Mill (based on TAPM).

	SO_2 (µg/m^3)	**NO_2 (µg/m^3)**	**TSP (µg/m^3)**
Highest one hour average grid cell concentrations based on met data for one year	3.67	0.64	75.9
Highest 24-hour average grid cell concentrations based on met data for one year	.63	0.13	17. 5
Highest annual average concentrations	.05	0.07	9.3

The highest one-hour average concentrations were estimated at 3.6 µg/m3 for SO_2, 0.6 µg/m3 for NO_2 67 µg/m3 for TSP.

Receptor points were chosen at the two largest communities in the near vicinity to the Steel Mill (see Figure S6.0.7 below):

1. Kanchpur is 1.2km NW from steel mill (23°42'28.06"N, 90°31'23.44"E; TAPM grid cell 10,17).
2. Shiddhirganj 2.0 km SW from steel mill (23°41'38.09"N, 90°30'52.82"E, TAPM grid cell 7,11).

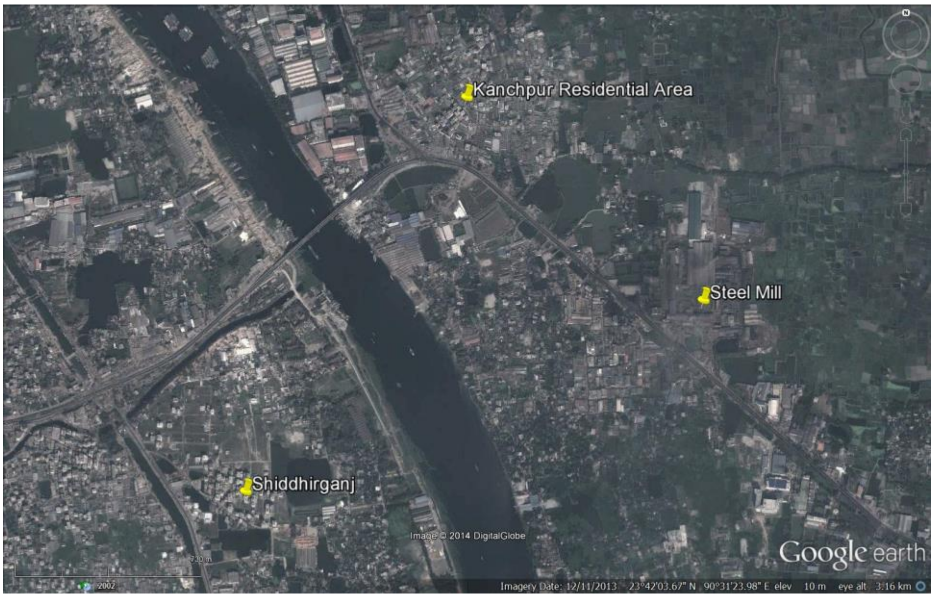


Figure S6.0.7: Receptor Point Locations

Concentrations found at these 2 receptor points are presented in Table S6.0.4.

Table S6.0.4: Concentration results at receptor points for SO2, NO2, and TSP for the Steel Mill (based on TAPM).

	SO_2 (µg/m^3)		**NO_2 (µg/m^3)**		**TSP (µg/m^3)**	
	Kanchpur	Shiddhirganj	Kanchpur	Shiddhirganj	Kanchpur	Shiddhirganj
Highest grid cell max for the year (based on 1-hour avg):	.90	1.31	0.09	0.1	45.	65.
Highest grid cell max for the year (based on 24-hour avg)	.16	.18	0.02	0.02	8	9.

PART II

Shinepukur Ceramics Ltd.

C1.0 Introduction

Shinepukur ceramics (SPC) is one of the largest ceramic industries in Bangladesh. It manufactures all kinds of tableware both porcelain and bone china types with a yearly production capacity of 1,600 ton Bone China and 5,250 ton Porcelain tableware. They are also the biggest exporter of ceramic tableware in the country. The factory produces 5,475 ton of ceramic products every year. SPC owned by the BEXIMCO Group is located within the Beximco Industrial Park at Savar near the Dhaka Export Processing Zone (DEPZ) which is about 40 km away from Capital Dhaka City (Figure C1.1 and C1.2).

There are other industries in the industrial park including Composite Textile Mills and a Denim Plant. SPC produces World Class Bone China using the raw materials and ingredients sourced from abroad. It uses Lead and Cadmium free glaze materials. Besides Bone China, SPC also produces Porcelain, Ivory China and High Aluminum tableware for different market segments. SPC is equipped with machineries and technology from Germany and TAKASAGO, MINO, SKK and NIKKO of Japan. Presently, it is the largest Bone China manufacturing industry in the South Asia region. The factory has its own captive power generation facility based on natural gas which is supplied by Titas gas transmission and distribution company limited. This natural gas is about 96% methane (CH_4) and sulfur free i.e. sweet gas. In Bone China production section, there are one tunnel kiln for biscuit firing, one tunnel kiln for glost firing and two roller hearth kilns for decoration firing which produce an average of 3 ton Bone China tableware/day, whereas in porcelain production section there are two biscuit firing, two glost firing tunnel kilns and three decoration firing roller hearth kilns that collectively produce an average of 12 ton Porcelain tableware/day.

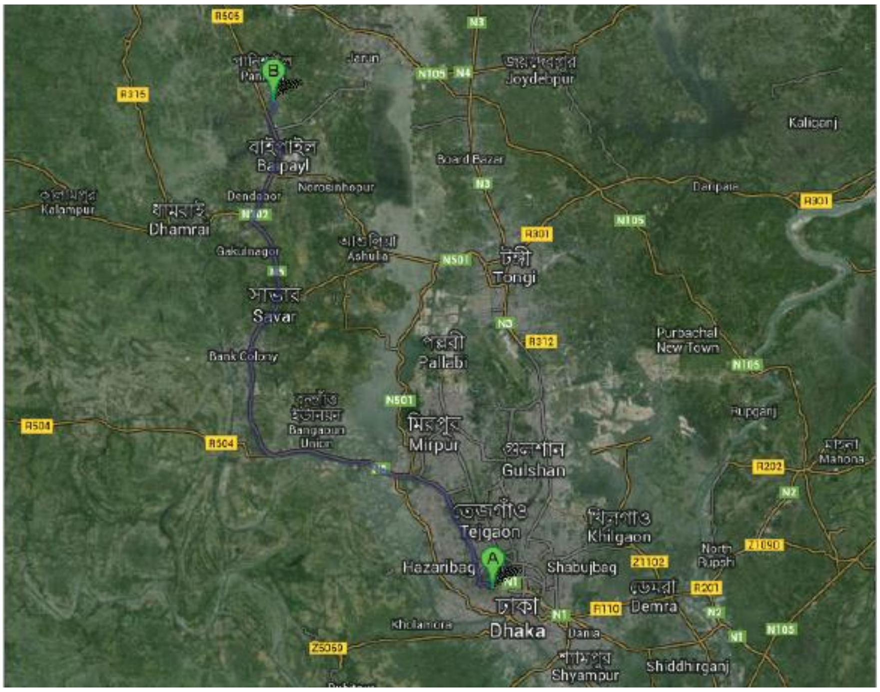


Figure C1.1. Roadway driving directions to SPC (B) from BUET (A)

Figure C1.2. Closer view and the location of SPC (A)

C2.0 Existing Process Description of Bone China and Porcelain Ceramics Production in SPC

C2.1 Bone China tableware production process

To produce bone china tableware it uses bone ash 50%, clay (Al_2O_3) 25%, quartz (SiO_2) 25% to prepare the body of different shape and sized tableware. Each batch of these raw materials is mixed in the ball mill for 24 hours for fine grinding. This ball mill has a wet grinding capacity of one ton dry raw materials per batch. The slurry from the ball mill is then passed though a magnetic filtration unit to remove residual iron metals and after that the slurry is filtered in a filter press to produce filter cake, the mixed final raw material, to produce the body of Bone China tableware. The filter cake when passes through the auger mill it becomes cylindrical in shape, known as clay roll, is actually the final raw materials for preparing the body of the wares in forming/casting and jiggering section (Figures C2.1.1 - C2.1.2). The final wet product is then dried in a natural gas fired drying chamber. After drying the green wares are ready for subsequent treatments (biscuit firing, glazing, glost firing, decoration and decoration firing) to produce final product.

Figure C2.1.1. Clay rolls preparation for manufacturing the body of green tableware

Figure C2.1.2. Body preparation sections of the green tableware

The dried green wares are arranged by layers on the cars and the cars are automatically pushed into the biscuit firing kiln one after another at a regular interval (Figures C2.1.3. to C2.1.5). The retention time of the wares in this kiln is around 13 hours. During this time span each of the cars crosses different temperature zones inside the kiln. The maximum temperature inside the biscuit kiln is around 1210°C. There are 3 temperature zones of a biscuit kiln: preheating zone, firing zone and cooling zone in which temperature varies from 220°C to 770°C, 970°C to 1210°C and 920°C to 500°C respectively. These three distinct zones are sequenced along the car moving direction inside the kiln i.e. from kiln inlet to outlet. This biscuit firing kiln has a production capacity of 4.5 ton/day but this kiln runs below the design capacity which actually produces 3 ton bone china/day.

Figure C2.1.3. Kiln cars with Green table wares

Figure C2.1.4. Loading of green wares inside the kiln

Figure C2.1.5. Unloading of fired wares from the kiln

The initially fired wares are then glazed with liquid mixture of glazing materials composed of bone ash, frit, $CaCO_3$ etc. initially ground wet in a ball mill of 1 ton capacity/batch. Glazing of initially fired product is carried out in an automated glaze spray chamber (Figures C2.1.6 and C2.1.7).

Figure C2.1.6. Glaze preparation

Figure C2.1.7. Automated glaze application on fired wares

Milling process of glaze materials takes 1 hour to complete a batch. Presently it requires 0.5 ton of dry glaze material for glazing 3 tons of products fired in biscuit kiln. The glaze materials are Lead and Cadmium free. After initial drying of the applied glaze materials, products are arranged again on the cars to pass it through the glost firing kiln. The retention time of the glazed wares in this kiln is around 10.4 hours. During this retention time the wares pass through different temperature zones like that of biscuit firing kiln. The maximum temperature inside this kiln is around 1109°C and corresponding temperature ranges of preheating, firing and cooling zones are 475°C to 894°C, 959°C to 1109°C and 401°C to 875°C respectively. The glost kiln operates at its design capacity of 3 ton/day.

Products from glost firing kiln are then polished with very smooth stones in water medium. The polished and fired glazed products are then inspected, further polished if required and ready for decoration purpose (Figures C2.1.8 to C2.1.10). Liquid gold (11%), platinum (10%) and other chemicals are used for the border lining of the wares. Various designs as per buyer’s requirements are generally developed and applied on the wares in the decal section. The imprints of these various designs on wares are applied with various kinds of pigments. After ambient initial drying the wares are again charged on the cars and

Figure C2.1.8. Polishing of the fired wares from glost kiln

Figure C2.1.9. Visual inspection

Figure C2.1.10. Fine grinding

pushed into the decoration firing kiln. The retention time of these decorated wares inside the kiln is around 3.5 hours during which they pass different temperature zones of the kiln. The maximum temperature of this kiln is around 890°C and corresponding temperature ranges of preheating, firing and cooling zones are 72°C to 775°C, 775°C to 890°C and 115°C to 685°C respectively. The decoration kiln also operates at its design capacity of 3 ton/day.

Fired products from decoration kiln are considered as final products and are ready for packing after checking and quality control. The minor defective wares are sold in local market. Raw material processing and green ware making steps are carried out under wet condition. Chances of fugitive emissions from these steps are essentially insignificant in this ceramic industry.

The block diagram of the whole production process of making bone china ceramic tableware is shown in Figure C2.1.11.

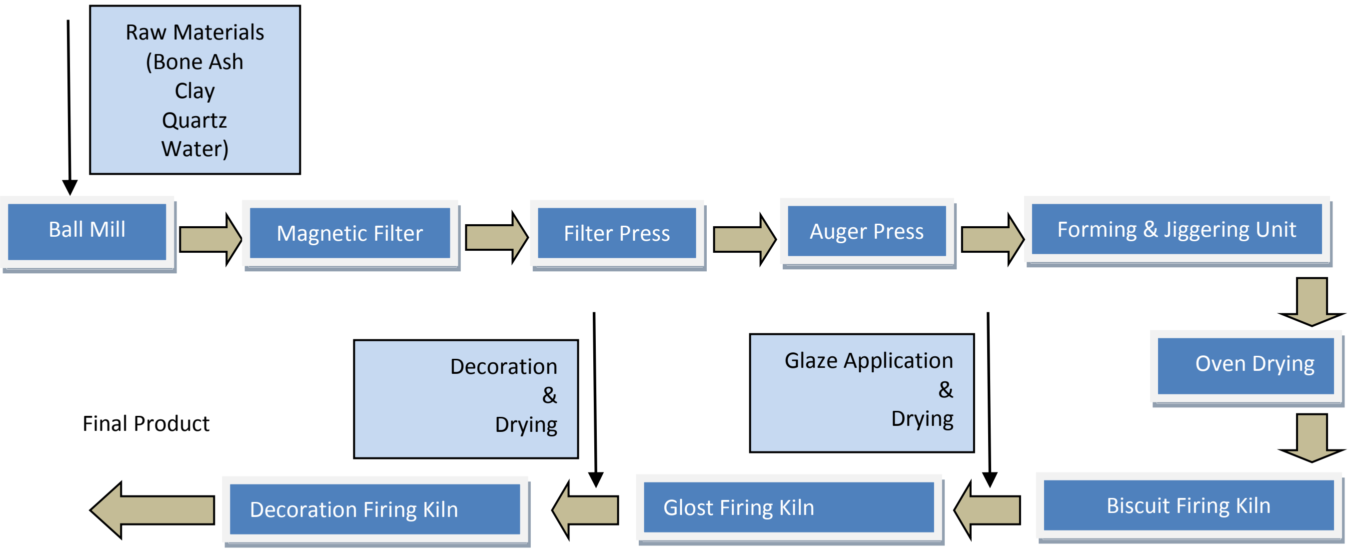


Figure C2.1.11. Block diagram of Bone China tableware production process at SPC.

C2.2 Porcelain tableware production process

Production process of porcelain tableware is similar to bone china tableware production as shown in Figure C2.1.11. The only difference is in raw materials. In porcelain tableware production Feldspar

(30%), Quartz (30%) and Clay (40%) raw materials are used. There are two biscuit firing kilns, two glost firing kilns and three decoration firing roller hearth kilns under a different shade at SPC which produces an average of 12 ton finished porcelain tableware/day. Each of the biscuit or glost firing kilns has a production capacity of 7.5 ton/day but actually they operate below the rated capacity and produces 6 ton/day. Among all the kilns, decoration kilns operate at their rated capacity of 4 ton/day/kiln.

C2.3 Tunnel kiln operations (preheating, firing and cooling)

Operations of all the tunnel kilns in SPC are very similar to each other. There are four different temperature zones of each of the kilns: (i) preheating zone, (ii) firing zone, (iii) stabilization zone and (iv) cooling zone (Figure C2.3.1). Natural gas is fired at several positions with 30% excess air along the length of firing zone inside the kiln. Combustion air is supplied by a blower (capacity 7.5 kw) to a common header, wherefrom side pipelines distribute controlled amount of combustion air to the burners at different locations of the firing zone.

The combustion gases produced are then conveyed in the opposite direction to that of cars transport direction i.e., towards the kiln entrance (preheating zone) under a strong induced draft fan (capacity 7.5 kw) to preheat the green wares. The outlet of this induced draft fan is connected with a stack outside the factory shed which eventually emits flue gas in the atmosphere. Combustion air blower sucks the ambient air through a filter at its inlet to remove any ambient dust particles. In preheating zone, combustion gas has every possibility to be diluted with the incoming floor air through the kiln entrance.

After passing the firing zone, fired wares require temperature stabilization which is carried out in the stabilization zone. Then thermally stabilized wares are slowly cooled down in cooling zone by blowing ambient air underneath the cars along the transport direction. A blower of capacity 3.7 kw is used to blow the cooling air at this zone. The hot air from this zone is transported away by an induced draft fan (capacity 3.7 kw) whose outlet is connected to chimney/stack outside the factory shed that emits the hot air in the atmosphere.

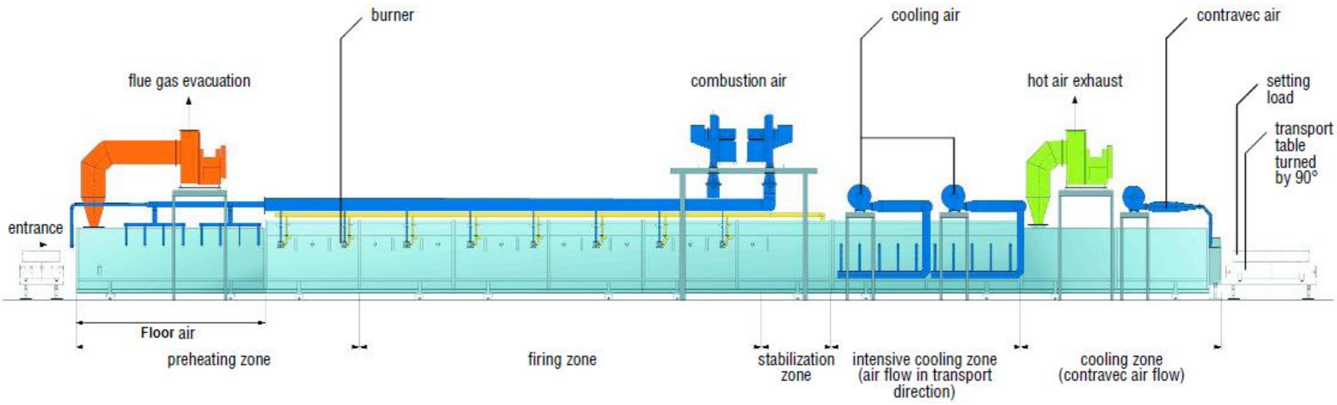


Figure C2.3.1. Different temperature zones of a gas fired tunnel kiln

C2.4 Fuel consumption for kiln firing and drying of green wares, molds etc.

In bone china production section biscuit firing kiln, glost firing kiln and decoration firing kiln require 2,900±50 Nm^3, 1,800±50 Nm^3 and 550±50 Nm^3 natural gas/day respectively to produce 3 ton of bone china product per day. To dry green wares, molds and glaze materials inside the dryer in forming section of bone china unit it requires around 240 Nm^3 natural gas/day.

In porcelain unit biscuit firing kiln, glost firing kiln and decoration firing kiln require 11,600±100 Nm^3, 7,200±100 Nm^3 and 2,200±100 Nm^3 natural gas/day respectively to produce 12 ton of porcelain product per day. To dry green wares and glaze materials inside the dryer in forming section of porcelain unit it requires around 1000 m^3 natural gas/day.

C2.5 Fuel consumption for captive power generation

There is captive power plant in the factory premise consisting of 4 natural gas fired generators. Total capacity of the power plant is 3,025 kW. Among them, 3 generators have equal power generation capacity of 675 kW. The rest one has a power generation capacity of 1000 kW. Presently these 4 generators produce around 2,500 kW that suffices the requirement of the ceramic industry. Specific natural gas consumption of this power plant is around 0.43 Nm^3/kWh. Specific electric energy consumption to produce finished ceramic tableware is 1200 kWh/ton, which means daily electric energy consumption in SPC is 18,000 kWh and the power plant requires 7740 Nm^3 natural gas to supply this electric energy. Excess electric energy is shared with other neighboring industries of BEXIMCO Ltd. in the industrial park.

C3.0 Environmental Aspects of SPC

Presently SPC has two types of production line: bone china and porcelain tableware. These production lines are under different sheds. In these two production lines there are several unit operations (wet grinding of raw materials in ball mill, magnetic filtration, glaze preparation, filtering through plate & frame filter press, clay roll preparation using auger mill, green ware and mould preparation in jiggering unit, drying and firing of green wares in different kilns). All the mixing, filtration, molding and shaping of green wares are carried out in wet process on wet clay.

In bone china production section there are four kilns: one tunnel kiln for biscuit firing, one tunnel kiln for glaze firing and another two roller hearth kilns (variant of tunnel kiln) for decoration firing, whereas in porcelain production section there are seven kilns: two tunnel kilns for biscuit firing, two tunnel kilns for glaze firing and three roller hearth kilns for decoration firing. Each of the kilns is attached with two chimneys: one is attached with the preheating section and second one is attached with the cooling section of the kiln as shown in Figure C2.3.1.

All the chimneys are of similar dimensions. Each chimney has a height of 9.75 m from ground level with a wall thickness of 1.5 mm and internal diameter of 0.48 m. All chimneys are made of mild steel sheet. These chimneys carry the combustion gases out of the kilns and dryers to the atmosphere. In bone china and porcelain production units there is natural ventilation provision at the top of the roof to take out inside air of the factory shed to the ambient atmosphere. Several high speed pedestal fans usually run inside the shed during production to keep the inside environment soothing to the workers.

C3.1 Stack Emission and Fugitive Emission Measurement

For stack emission measurement, biscuit firing kiln of bone china production unit with a production capacity of 4.5 tons bone china tableware/day (actual field production is 3 ton/day) was selected. Both gaseous (CO_2, CO, SO_2, NO, NO_2) and total particulate pollutants of the two stacks (stacks for preheating and cooling zone) were measured. Stack emissions from cooling zone and preheating zone were measured on two separate days (May 30 & 31, 2013) and four separate days (June 13, 14, 20 & 21, 2013) respectively. Gaseous emissions were measured for three hours, whereas stack particulates were sampled for variable time depending on stack conditions to satisfy the isokinetic sampling procedure.

For fugitive emission measurement, both gaseous (CO_2, CO, SO_2, NO, NO_2) and particulate (PM_{10}) pollutants inside the factory shed were measured. Gaseous pollutants were measured for three hours whereas particulate pollutants (PM_{10}) were measured for eight hours per sampling day. Fugitive emissions were measured on two different days (June 13 and 14, 2013).

C3.1.1 Stack Emission (gaseous and particulate) Measuring Protocols

Steps involved in stack emissions measurement were: selecting appropriate sampling location and traverse points of the stack, measuring the gaseous pollutants’ concentrations, determining average molecular weight of the stack gas (both in wet and dry basis) and isokinetic sampling conditions for measuring particulate concentration in stack gas, calculating and determining average stack gas velocity and actual volumetric flow rate at stack conditions on wet basis from the measured values and converting the actual volumetric flow rate into dry volumetric flow rate at a particular temperature and pressure.

C3.1.1.1 Sampling Location and Traverse Point

Stacks selected for measuring the emission were connected to the cooling and preheating zones of biscuit firing kiln of bone china production unit having a production capacity 4.5 ton/day (actual production 3 ton/day). Both the stacks were 9.75 m high (Figure C3.1.1) from the ground level and with a strong IDF at kiln top. The stacks were made of mild steel sheet having a thickness of 1.5 mm and internal diameter of 0.48 m. Selection of appropriate sampling location and traverse points of the stacks were determined following USEPA Reference Method 1 (40CFR60 App. A.)/ASTM D 3154-91.

For the cooling zone stack of the biscuit firing kiln a 4.88 m straight vertical section of the stack was available outside the shed. Sampling location for this stack was chosen in a way to simplify the sampling procedure and to build the working platform at a suitable location. The sampling location was 9 m high from the ground level. For this case, sampling location on the stack was chosen at a distance of 9.3 times the duct diameter downstream from a bend and 1.49 times the duct diameter upstream from the stack exit (Figure C3.1.1). This location corresponds to a minimum 20 traverse points for sampling. However, for better accuracy 24 traverse points were chosen for sampling.

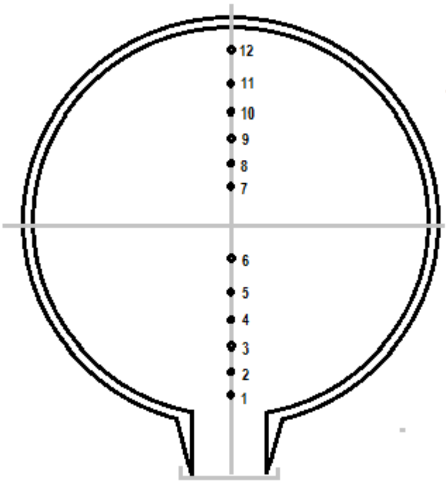
Figure C3.1.1. Stack height of biscuit firing kiln (for both cooling and preheating sections) and sampling port location for cooling zone stack sampling

For the preheating zone stack of the biscuit firing kiln a 2.2 m straight horizontal section of the stack (at the exit of the induced draft fan) was selected inside the shed. Sampling location for this stack was chosen due to simplify the sampling procedure and to build the working platform at a suitable location. The sampling location was 4.5 m high from the ground level. For this case, sampling location on the stack was chosen at a distance of 3.39 times the duct diameter downstream from a bend and 1.5 times the duct diameter upstream from another bend (Figure C3.1.2). This location corresponds to a minimum 24 traverse points for sampling.

Figure C3.1.2. Preheating zone stack section for sampling with sampling port location

At the above mentioned positions of the chimneys, a hole of internal diameter (ID) 0.0762 m was bored and an extension pipe (0.3048 m long) of similar ID was welded for better workability. At these sampling locations of the chimneys a metallic scaffold with ladder was built for working platform.

Though, the number of traverse points required for non-particulate and particulate sampling was calculated to be 24, twelve in each of two directions 90° apart for each case, measurement was carried out only at twelve traverse points on a single diameter due to reluctance of the factory authority to allow boring of two holes 90° apart on the same plane of the stack. Number of traverse points and their positions along the diameter of the stack are shown in Figure C3.1.3.



Traverse Point	Distance (% of diameter)
1	2.1
2	6.7
3	11.8
4	17.7
5	25.0
6	35.6
7	64.4
8	75.0
9	82.3
10	88.2
11	93.3
12	97.9

Figure C3.1.3. Traverse points along the stack diameter

C3.1.1.2 Stack Gas Compositions

Concentrations of different gaseous components of the cooling zone stack were measured from non-diluted stack gas and for preheating zone stack different gaseous components were measured from diluted or non-diluted stack gas depending of the stack gas concentrations and measuring range of the equipments (Figures C3.1.4 and C3.1.5). Dilution of stack gas was done with pressurized regulated zero air at a known dilution ratio by means of a stack gas single dilution probe and a dilution controller (Model 200L, Thermo Environmental Instruments Inc., USA). The dilution method meets the requirements pertained in the USEPA 40CFR60.

CO_2 concentration of the preheating zone and cooling zone stack gases was measured using Infrared Absorption Principle with a High Level Gas Filter Correlation CO_2 analyzer (Model 41C, Thermo Environmental Instruments Inc., USA).

CO and NOx (NO and NO_2) concentrations of the preheating zone and cooling zone stack gases were measured simultaneously using a portable analyzer having Electrochemical Sensor (Model 600-2-4-5, NOVA Analytical Systems Inc., Canada).

SO_2 concentration of the preheating zone and cooling zone stack gases was measured using a portable analyzer having Electrochemical Sensor (Model 600-8, NOVA Analytical Systems Inc., Canada).

O_2 of the preheating zone and cooling zone stack gases was measured using direct sensing WDG-INSITU Flue Gas Analyzer coupled with Thermox Flue Gas Monitor (2000 Series), AMETEK Inc., USA.

Moisture content of original flue gases was measured following USEPA Reference Method 4 and using Isokinetic Source Sampler XC 500 Series, Apex Instruments Inc., USA.

Balance of the stack gas (excluding CO_2, CO, O_2 and Moisture) was assumed as N_2.

Stack Gas Molecular Weight on wet/dry basis was calculated from the measured concentrations of CO_2, CO, O_2, moisture and N_2 content of the stack gas using the formula mentioned in section 12 of ASTM D 3154-91 and USEPA Reference method 2 and 4.

Average stack gas velocity and actual volumetric flow rate at stack conditions on wet basis were determined following USEPA Reference Method 2 (40CFR60 App. A.)/ASTM D 3154-91 and using Isokinetic Source Sampler XC 500 Series, Apex Instruments Inc., USA.

Total Particulate Concentration in Stack Gases was determined following USEPA Reference Method 5 (40CFR60 App. A.)/ASTM D 3685/D 3685M-98 and using Isokinetic Source Sampler (XC 500 Series), Apex Instruments Inc., USA (Figures 3.1.6 and C3.1.7)).

Figure C3.1.4. Measuring of cooling zone stack gas composition (gaseous)

Figure C3.1.5. Measuring of preheating zone stack gas composition (gaseous)

Figure C3.1.6. Measuring of cooling zone stack particulates (total)

Figure C3.1.7. Measuring of preheating zone stack particulates (total)

Gaseous (CO_2, CO, NOx and SO_2) and total particulate emission rate of the stack were determined from the concentration levels of gaseous and particulate pollutants and volumetric flow rate data of the stack gases obtained through the measurement. For stack particulate measurement, 82.6 mm diameter glass microfiber filter papers were used. Pre and post conditioning of the filters were carried out at 20^{o}C and 50% RH for 24 hours. The procedure and working principle of each method is given in **Appendix-B.**

C3.1.2 Fugitive Emission (gaseous and particulate) Measuring Protocols

For fugitive emissions from ceramic manufacturing process, gaseous and particulate pollutant concentrations of indoor air were measured inside the factory shed. For gaseous concentrations of the shed air, air sampling probe of Environmental Monitoring Unit (EMU) was placed at a height of 2 m from ground level inside the shed. The analyzers measured ambient CO_2, CO, NO, NO_2 and SO_2 concentrations of non-diluted indoor air. Measuring procedures of ambient gaseous pollutants were same as those followed during the measurement of stack gaseous pollutants. The procedure and working principle of each method is given in **Appendix-B.**

For respirable particulate (PM_{10}) concentration of the shed air, USEPA certified Graseby Andersen High Volume PM_{10} Sampler (GMW PM10/VFC), USA was used. The inlet of the sampler was placed at a height of 1.5 m from ground level inside the factory shed (Figure C3.1.8). For ambient PM_{10} measurement, 20.3 cm X 25.4 cm glass microfiber filters were used. Pre and post conditioning of the filters were carried out at 20°C and 50% RH for 24 hours.

Figure C3.1.8. PM_{10} high volume sampler placed inside the factory shed of ceramic industry

C4.0 Results

Concentrations data of CO_2, CO, NO, NO_2 and SO_2 and total particulate of stack gas were analyzed, calculated and reported as average values along with actual stack gas conditions. Reported concentration, emission rate and emission index values of gaseous and particulate pollutants of stack gas are based on dry basis at 25°C and 760 mm Hg.

Concentrations of ambient CO_2, CO, NO, NO_2 and SO_2 and PM_{10} inside the shed were analyzed, calculated and reported as average values along with dry bulb and wet bulb temperatures and percentage of relative humidity. Reported concentration values of ambient air are based on dry basis at 25°C and 760 mm Hg.

C4.1 Stack Emission

For stack emission measurement, biscuit firing kiln of bone china production unit with a production capacity of 4.5 tons bone china tableware/day was selected. The field production of this kiln is around 3 tons bone china tableware/day. Both gaseous (CO_2, CO, SO_2, NO, NO_2) and total particulate pollutants were measured from the stacks connected with preheating and cooling zones of the said kiln. Emissions from cooling zone stack were measured on two separate days (May 30 and 31, 2013) and that of preheating zone stack on four separate days (June 13, 14, 20 & 21, 2013). Gaseous emissions were measured for three hours, whereas stack particulates were sampled for variable time depending on stack conditions to satisfy the isokinetic sampling procedure. Day to day average compositions of the stack gas, particulate matter, stack gas molecular weight, stack gas volumetric flow rate on dry basis are given in Tables C4.1.1-C4.1.4 along with the actual average stack conditions below each table.

Table C4.1.1. Dry basis average stack gas compositions (gaseous and total particulates), molecular weight and volumetric flow rate of *cooling zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *May 30, 2013*

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	1,126.43	28.85	80.89
Carbon Monoxide (CO)	9.31		
Nitric Oxide (NO)	4.99		
Nitrogen Dioxide (NO_2)	2.35		
Sulfur Dioxide (SO_2)	0.00		
Total Particulate	1.977		

***Note:** Stack conditions on May 30, 2013*

Average stack temperature 202.92°C, Absolute stack pressure: 753.84 mm Hg, Stack ID: 0.48 m, Stack height from ground: 9.75 m, Stack sampling height from ground: 9.0 m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 12.39 m/s, Average stack moisture content: 3.13 vol. or mol%, Wet gas molecular weight: 28.51 g/g-mol, Wet gas volumetric flow rate at stack condition: 134.44 m^3/min

Table C4.1.2. Dry basis average stack gas compositions (gaseous and total particulates), molecular weight and volumetric flow rate of *cooling zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *May 31, 2013*

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	1,013.96	28.85	80.28
Carbon Monoxide (CO)	7.88		
Nitric Oxide (NO)	5.76		
Nitrogen Dioxide (NO_2)	2.35		
Sulfur Dioxide (SO_2)	0.00		
Total Particulate	1.802		

***Note:** Stack conditions on May 31, 2013*

Average stack temperature: 202.83 °C, Absolute stack pressure: 753.794 mm Hg, Stack ID: 0.48 m, Stack height from ground: 9.75 m, Stack sampling height from ground: 9.0 m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 12.26 m/s, Average stack moisture content: 2.91 vol. or mol%, Wet gas molecular weight: 28.53 g/g-mol, Wet gas volumetric flow rate at stack condition: 133.12 m^3/min

Table C4.1.3. Dry basis average stack gas compositions (gaseous and total particulates), molecular weight and volumetric flow rate of *preheating zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *June 13, 2013*

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	31,213.88	29.09	61.41
Carbon Monoxide (CO)	18.90		
Nitric Oxide (NO)	21.59		
Nitrogen Dioxide (NO_2)	1.2		
Sulfur Dioxide (SO_2)	0.00		
Total Particulate	18.51		

***Note:** Stack conditions on June 13, 2013*

Average stack temperature: 192.5 °C, Absolute stack pressure: 753.375 mm Hg, Stack ID: 0.48 m, Stack height from ground: m, Stack sampling height from ground: m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 9.75 m/s, Average stack moisture content: 8.59 vol. or mol%, Wet gas molecular weight: 28.133 g/g-mol, Wet gas volumetric flow rate at stack condition: 105.86 m^3/min

Table C4.1.4. Dry basis average stack gas compositions (gaseous and total particulates), molecular weight and volumetric flow rate of *preheating zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *June 14, 2013*

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	31,267.67	29.08	62.42
Carbon Monoxide (CO)	18.67		
Nitric Oxide (NO)	20.01		
Nitrogen Dioxide (NO_2)	1.20		
Sulfur Dioxide (SO_2)	0.00		
Total Particulate	23.68		

Note: *Stack conditions on June14, 2013*

Average stack temperature: 192.92 °C, Absolute stack pressure: 753.375 mm Hg, Stack ID: 0.48 m, Stack height from ground: m, Stack sampling height from ground: m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 9.84 m/s, Average stack moisture content: 7.77 vol. or mol%, Wet gas molecular weight: 28.224 g/g-mol, Wet gas volumetric flow rate at stack condition: 106.75 m^3/min

Table C4.1.5. Dry basis average stack gas compositions (gaseous and total particulates), molecular weight and volumetric flow rate of *preheating zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *June 20, 2013*

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	31,005.44	29.08	57.65
Carbon Monoxide (CO)	17.86		
Nitric Oxide (NO)	20.67		
Nitrogen Dioxide (NO_2)	1.17		
Sulfur Dioxide (SO_2)	0.00		
Total Particulate	23.70		

Note: *Stack conditions on Jun 20, 2013*

Average stack temperature: 204.42 °C, Absolute stack pressure: 753.375 mm Hg, Stack ID: 0.48 m, Stack height from ground: m, Stack sampling height from ground: m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 9.55 m/s, Average stack moisture content: 10.21 vol. or mol%, Wet gas molecular weight: 27.953 g/g-mol, Wet gas volumetric flow rate at stack condition: 103.77 m^3/min

Table C4.1.6. Dry basis average stack gas compositions (gaseous and total particulates), molecular weight and volumetric flow rate of *preheating zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *June 21, 2013*

Parameters	Concentrations (mg/m^3)	Dry gas molecular weight (g/g-mol)	Dry gas volumetric flow rate (m^3/min)
Carbon Dioxide (CO_2)	30,564.67	29.09	62.54
Carbon Monoxide (CO)	18.86		
Nitric Oxide (NO)	19.04		
Nitrogen Dioxide (NO_2)	1.19		
Sulfur Dioxide (SO_2)	0.00		
Total Particulate	23.60		

Note: *Stack conditions on Jun 21, 2013*

Average stack temperature: 197.25 °C, Absolute stack pressure: 753.353 mm Hg, Stack ID: 0.48 m, Stack height from ground: m, Stack sampling height from ground: m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 10.19 m/s, Average stack moisture content: 9.99 vol. or mol%, Wet gas molecular weight: 27.982 g/g-mol, Wet gas volumetric flow rate at stack condition: 110.60 m^3/min

However, dry basis average stack gas compositions (gaseous and total particulates), molecular weight, volumetric flow rate and average emission rate of each component during two day sampling for cooling zone stack and four day sampling for preheating zone stack of biscuit firing kiln are given in Table C4.1.7. These reported values are based on 25°C and 760 mm Hg. Also average values of different parameters of the stack and stack gas during two and four day sampling are given below the table.

Table C4.1.7. Dry basis two day and four day average stack gas compositions (gaseous and total particulates), molecular weight, volumetric flow rate and corresponding emission rate of each component for *cooling zone stack and preheating zone stack (biscuit firing kiln)* at 25°C and 760 mm Hg measured on *May 30 and 31, 2013*

Parameters	**Concentrations** **(mg/m^3)**		**Dry gas molecular weight** **(g/g-mol)**		**Dry gas volumetric flow rate** **(m^3/min)**		**Emission rate** **(g/day)**	
	2-day avg. (cooling zone)	4-day avg. (preheating zone)	2-day avg. (cooling zone)	4-day avg. (preheating zone)	2-day avg. (cooling zone)	4-day avg. (preheating zone)	2-day avg. (cooling zone)	4-day avg. (preheating zone)
Carbon Dioxide (CO_2)	1,070.20	31012.92	28.85	29.085	80.585	61	124,188.58	2,724,174.89
Carbon Monoxide (CO)	8.60	18.57					997.96	1631.19
Nitric Oxide (NO)	5.38	20.33					624.31	1785.79
Nitrogen Dioxide (NO_2)	2.35	1.19					272.70	104.53
Sulfur Dioxide (SO_2)	0.00	0.00					0.00	0.00
Total Particulate	1.8895	22.37					219.26	1964.98

Note: *Average cooling zone stack conditions for biscuit firing kiln*

Average stack temperature: 202.875 °C, Absolute stack pressure: 753.817 mm Hg, Stack ID: 0.48 m, Stack height from ground: 9.75 m, Stack sampling height from ground: 9.0 m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 12.325 m/s, Average stack moisture content: 3.02 vol. or mol%, Wet gas molecular weight: 28.52 g/g-mol, Wet gas volumetric flow rate at stack condition: 133.78 m^3/min.

Average preheating zone stack conditions for biscuit firing kiln

Average stack temperature: 196.77 °C, Absolute stack pressure: 753.37 mm Hg, Stack ID: 0.48 m, Stack height from ground: m, Stack sampling height from ground: m, Stack flow area: 0.180956 m^2, Average stack gas velocity (wet basis) at stack conditions: 9.83 m/s, Average stack moisture content: 9.14 vol. or mol%, Wet gas molecular weight: 28.073 g/g-mol, Wet gas volumetric flow rate at stack condition: 106.745 m^3/min

In bone china production unit of SPC, stack emission from biscuit firing kiln was measured as the factory authority gave the permission to measure emission from this kiln only. There are other three kilns of which one is glost kiln and another two are decoration kilns. Each of these three kilns has two stacks: one is for preheating zone and another is for cooling zone of the kiln. Again there is a natural gas fired dryer in the bone china production unit to dry green wares, molds and glaze materials. Therefore, to find the emission index for ceramic industry, judicious assumptions were made to calculate the emission rate from two other types of kilns: glost tunnel kiln and roller hearth kiln and dryer. In this case fuel consumption ratio was taken as the basis for calculating emission rate.

In bone china production unit biscuit firing kiln, glost firing kiln, decoration firing kiln and the dryer require 2,900±50, 1,800±50, 550±50 and 240 Nm^3 natural gas/day respectively to produce 3 ton of bone china tableware per day. The fuel consumption ratios used to calculate the emission rate for other kilns and dryer in bone china unit were as follows: 0.62 for glost firing kiln, 0.19 for decoration kiln and 0.083 for dryer. The stack emission rate and emission index of different pollutants from bone china production unit of SPC are shown in Table C4.1.8.

Table C4.1.8. Emission rate of different kilns and dryer, total emission rate and emission index of bone china manufacturing unit, SPC.

Parameters	Emission rate (g/day)				Total emission rate (g/day)	Emission index (g/ton)
	Biscuit firing kiln (measured)	Glost kiln (calculated)	Decoration kiln (calculated)	Dryer (calculated)		
Carbon Dioxide (CO_2)	2,848,363.47	1,765,985.35	541,189.06	236,414.17	5,391,952.05	1,797,317.35
Carbon Monoxide (CO)	2,629.15	1,630.07	499.54	218.22	4,976.98	1,658.99
Nitric Oxide (NO)	2,410.10	1,494.26	457.92	200.04	4,562.32	1,520.77
Nitrogen Dioxide (NO_2)	377.23	233.88	71.67	31.31	714.09	238.03
Sulfur Dioxide (SO_2)	0.00	0.00	0.00	0.00	0.00	0.00
Total Particulate	2,184.24	1,354.23	415	181.29	4,134.76	1,378.25

Note: Emission from captive power plant is not included in these stack emission rate and emission index values

C4.2 Fugitive Emission

Several pedestal fans run continuously on the working floor to keep the area cool. To calculate fugitive emission, it was assumed that ambient air from factory shed flows through two rectangular windows at the top of the roof each having a length of 110 m and a height of 1 m (Figure C4.2.1). Air flow area was assumed to be 50% open of these rectangular windows, i.e., flow area was about 110 m^2. Air speed was also measured at various points and different times at the exit of these rectangular windows to find out the air volumetric flow rate.

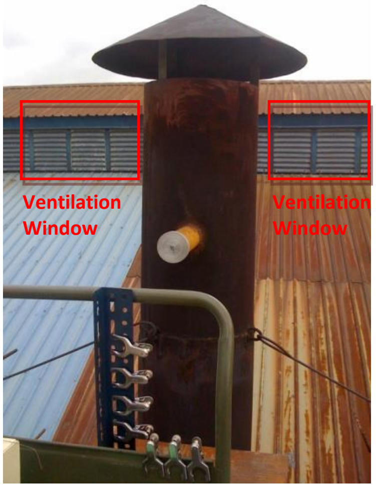


Figure C4.2.1. Ventilation window

Gaseous (CO_2, CO, SO_2, NO, NO_2) and PM_{10} pollutants of indoor air inside factory shed were measured on two consecutive days (June 13 and 14, 2013). Concentrations of gaseous pollutants of non-diluted indoor air were measured for three (3) hours whereas PM_{10} was sampled for eight (8) hours each sampling day. Day to day average ambient concentrations of gaseous pollutants and PM_{10} inside factory shed and ambient air volumetric flow rate at 25°C and 760 mm Hg are given in Tables C4.2.1-C4.2.2 along with the actual ambient conditions inside shed below each table.

Table C4.2.1. Average ambient concentrations of gaseous pollutants and PM_{10} (inside shed), exit air flow rate at 25°C and 760 mm Hg on June 13, 2013.

Parameters	Concentrations (mg/m³)	Volumetric flow rate of dry gas and air mixture (m³/min)
Carbon Dioxide (CO_2)	989.24	3,300
Carbon Monoxide (CO)	2.29	
Nitric Oxide (NO)	3.07	
Nitrogen Dioxide (NO_2)	1.88	
Sulfur Dioxide (SO_2)	0.00	
PM_{10}	0.089	

***Note:** Ambient conditions on June 13, 2013*

Average dry bulb temperature: 34.08°C, Average wet bulb temperature: 29.38°C,
Average percentage of relative humidity (RH%): 70, Average wind speed: 0.50 m/s

Table C4.2.2. Average ambient concentrations of gaseous pollutants and PM_{10} (inside shed), exit air flow rate at 25°C and 760 mm Hg on June 14, 2013.

Parameters	Concentrations (mg/m³)	Volumetric flow rate of dry gas and air mixture (m³/min)
Carbon Dioxide (CO_2)	1,169.10	3,102
Carbon Monoxide (CO)	5.15	
Nitric Oxide (NO)	4.29	
Nitrogen Dioxide (NO_2)	1.88	
Sulfur Dioxide (SO_2)	0.00	
PM_{10}	0.126	

***Note:** Ambient conditions on March 14, 2013*

Average dry bulb temperature: 34.18°C, Average wet bulb temperature: 29.82°C,
Average percentage of relative humidity (RH%): 72, Average wind speed: 0.47 m/s

However, dry basis average compositions of indoor air inside factory shed (gaseous and PM_{10}), exit air volumetric flow rate, fugitive emission rate and emission index during two day sampling are given in Table C4.2.3. These reported values are based on 25°C and 760 mm Hg. Also average values of different parameters of the ambient air inside shed during two day sampling are given below the table.

Table C4.2.3. Dry basis average ambient concentrations of gaseous pollutants and PM_{10} (inside shed), exit air volumetric flow rate, fugitive emission rate and emission index at 25°C and 760 mm Hg during two day sampling.

Parameters	Concentrations (mg/m³)	Volumetric flow rate of exit air (m³/min)	Fugitive emission rate (g/day)	Fugitive emission index (g/ton)
Carbon Dioxide (CO_2)	1079.17	3201	497,436.94	165,812.31
Carbon Monoxide (CO)	3.72		17,147.12	5,715.71
Nitric Oxide (NO)	3.68		16,962.74	5,654.25
Nitrogen Dioxide (NO_2)	1.88		8,665.75	2,888.58
Sulfur Dioxide (SO_2)	0.00		0.00	0.00
PM_{10}	0.1075		495.51	165.17

***Note:** Average ambient conditions during two day sampling*

Average dry bulb temperature: 34.13°C, Average wet bulb temperature: 29.6°C,
Average percentage of relative humidity (RH%): 71, Average wind speed: 0.485 m/s

C5.0 Conclusions based on emission measurements

Ceramic production operation is a steady state process especially the firing steps inside the kilns. The air-fuel ratio, burning rate and temperatures inside the kilns are controlled with a distributed Control System (DCS).

Though there are three different kilns (Biscuit firing kiln, Glost firing kiln and Decoration firing kiln) in the ceramic ware production facility, they all belong to tunnel kiln type. Each kiln has two chimneys: one is connected to the preheating zone and another is connected to the cooling zone of the kiln. In this work emission from these two types of chimneys of biscuit firing kiln was measured and the emission values of other kilns (Glost firing kiln and Decoration firing kiln) were calculated from the fuel consumption ratios of these kilns with respect to biscuit firing kiln.

The indoor pollutants level inside the factory shed was also analyzed to find out the fugitive emission index. Results on different days were found to be almost consistent as the process is a steady one.

C6.0 Estimated ground level concentrations around Shinepukur Ceramics ltd.

The models CONCX and TAPM have been utilized to generate ground level concentrations of particles, SO_2, and NO_2 in the surroundings of the Shinepukur Ceramics ltd. CONCX is a NILU developed stationary Gaussian dispersion model for calculating the maximum ground level concentrations from single point sources. TAPM is a numerical meteorological and air quality prediction model, which predicts three-dimensional meteorology and air pollution concentrations. The results presented below are based on a 25x25km grid (.3km resolution), with the industry source as the grid center point, over the period of one year (using virtual metrological data from 2012 retrieved at each industrial point).

Input data used for CONCX and TAPM dispersion calculations for the ceramics factory can be seen in Table C6.0.1 and C6.0.2 below.

Table C6.0.1: Emission rates for measured components at the ceramics factory

Component	Pre-heating (Zone Emission rate (g/s)	Cooling Zone Emission rate (g/s)	Fugitive Emission rate (g/s)	TOTAL Emission rate (g/s)
Carbon Dioxide (CO_2)	31.53	1.4374	35.20	68.164
Carbon Monoxide (CO)	0.02	0.0116	0.23	0.256
Nitric Oxide (NO)	0.02	0.0072	0.22	0.249
Nitrogen Dioxide (NO_2)	0.001	0.0032	0.10	0.109
Sulfur Dioxide (SO_2)	0.00	0.0000	0.00	0.000
Total Particulate (TSP)	0.02	0.0025	0.03	0.054

Table C6.0.2: Standard stack and emission variables for the ceramics factory

Stack Height(m)	9.75
Stack flow area(m2)	0.180956
Stack diamiter(m)	0.48
Volumetric flowrate of wet gas (m3/min)	106.745
Lucstack gas velocity (m/s)	9.83
Exit gas temperature (K)	469.77
Ambient temperature(K)	307
X coordinate	23 deg 58 min
Y coordinate	90 deg 16 min

The results from CONCX for NO_X (NO+NO2) and TSP can be seen in Figures C6.0.1 and C6.0.2 below using all the emission rates for all processes (not including fugitive emissions). During unstable and neutral meteorological conditions the highest concentrations are to be found inside 500 m from the stack. The ground level concentrations at this distance was estimated at 4.4 µg/m^3 for NOx and 3.4 µg/m^3 for TSP. During light stable conditions and wind speeds of around 1m/s concentrations of 2-2,5 µg/m^3 can be found around 1500 m from the stack.

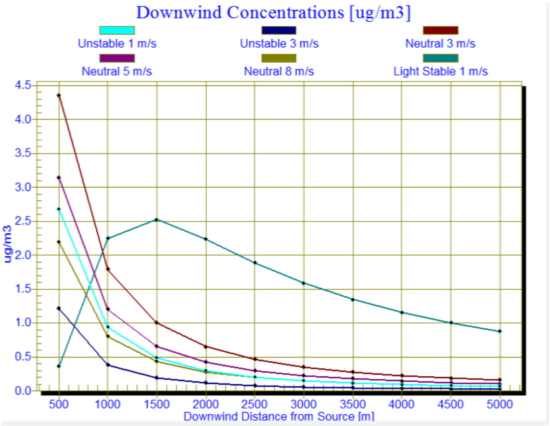


Figure C6.0.1: Estimated maximum ground level concentrations of NO_X for different meteorological conditions from stack emissions (all processes, not fugitive) of Shinepukur Ceramic Ltd.

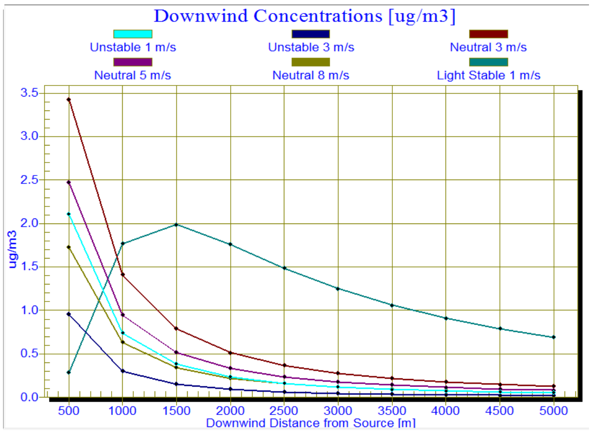


Figure C6.0.2: Estimated maximum ground level concentrations of TSP for different meteorological conditions from stack emissions (all processes, not fugitive) of Shinepukur Ceramic Ltd.

The spatial distribution of the highest 1-hour average concentrations of NOx are shown in Figures C6.0.3.

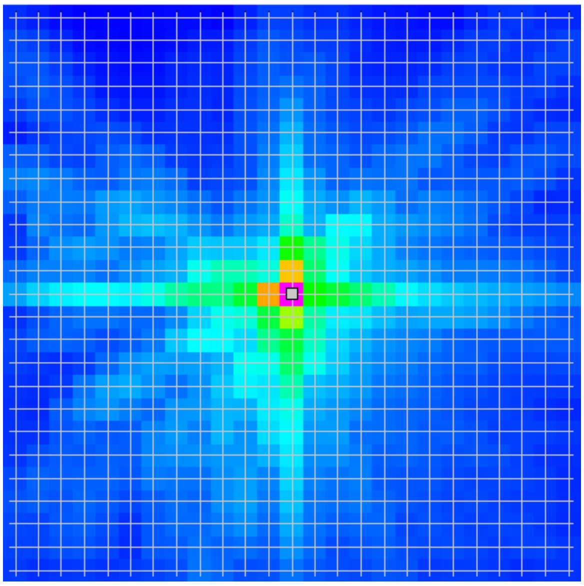


Figure C6.0.3: Estimated hourly grid cell maximum concentrations for NOx in the areas around the Ceramics Factory. Based on one year of met data.

The highest concentration can be found inside the 300 m square close to the stack. Relative elevated concentration values (more than 4 µg/m3) can be seen in the closest grid cells west and north of the plant.

One specific receptor point was selected in the near vicinity to the Ceramics Factory (see Figure S6.0.4 below. The community of Chakrobarti is located about 300m NW from the ceramics factory (23°58'43.71"N, 90°16'1.38"E; TAPM grid cell 12,14).

Figure C6.0.4: Receptor Point Locations

The hourly ground level maximum concentrations estimated in this community was about 5 to 8 µg/m3 for NOx, and 2-4 µg/m3 for TSP.

PART III

Yusuf Brick Kiln

One of the many brick kilns in Bangladesh was selected in order to estimate typical ground level concentrations downwind from this factory. For further studies of brick kiln impacts see Randall et. al (2014a and b). The Yusuf brick kiln is located 3-4 km west of Dhaka city, in a typical area with several brick factories. This Yusuf brick kiln is located 2.3 km NNE of the community Mograkanda located at 23°

B1.0 Dispersion Modelling

The models CONCX and TAPM have been utilized to generate ground level concentrations of particles, SO_2, and NO_2. CONCX is a NILU developed stationary Gaussian dispersion model for calculating the dispersion of emissions from single point sources. TAPM is a numerical weather and air quality prediction model, which predicts three-dimensional meteorology and air pollution concentrations. The results presented below are based on a 25x25km grid (.3km resolution), with the industry source as the grid center point, over the period of one year (using virtual metrological data from 2012 retrieved at each industrial point.

Input data used for CONCX and TAPM dispersion calculations for the brick kiln can be seen in Table B1.0.1 and B1.0.2 below.

Table B1.0.1: Emission rates for measured components at the brick kiln

Component	Emission rate (g/s)
Nitrogen Dioxide (NOx)	0.214
Sulfur Dioxide (SO_2)	22.88
Total Particulate	6.652

Table B1.0.2: Standard stack and emission variables for the brick kiln

Stack Height(m)	40
Stack flow area(m2)	1.1304
Stack diameter(m)	1.2
stack gas velocity (m/s), dry basis	7.4
Exit gas temperature (K)	315
Ambient temperature(K)	303
X coordinate	23°47.5'
Y coordinate	90°19'

The results from CONCX for NO_X , SO_2, and TSP can be seen in Figures B1.0.1, B1.0.2, and B1.0.3 below. During unstable wind conditions (1m/s), concentration are highest just 200-400m from the stack (NO_x: 9.6 µg/m^3, SO_2: 1200 µg/m^3, and TSP: 300 µg/m^3). However during light stable wind conditions (1m/s) concentrations are highest at 2000m downwind from the stack (NO_x: 4.2 µg/m^3, SO2: 460 µg/m^3, and TSP: 140 µg/m^3), and concentrations only reduce by 45% by the distance of 5000m.

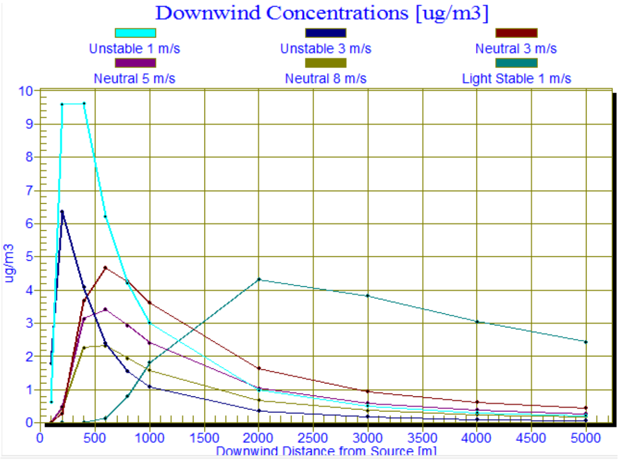


Figure B1.0.1: Estimated maximum ground level concentrations of NOx for different meteorological conditions from stack emission of Yusef Brick Kiln

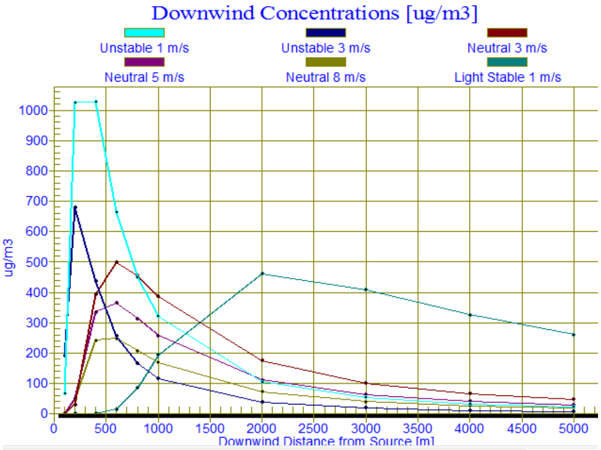


Figure B1.0.2: Estimated maximum ground level concentrations of SO_2 for different meteorological conditions from stack emission of Yusef Brick Kiln

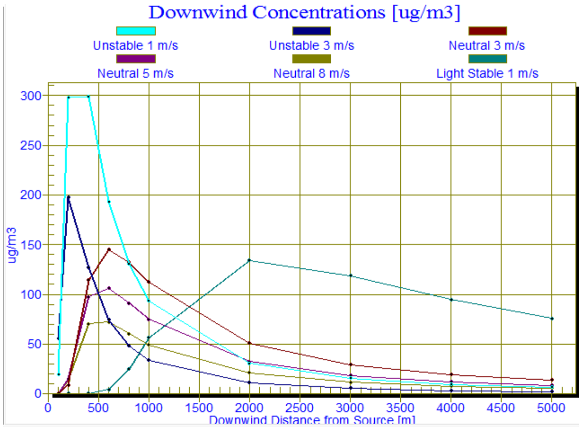


Figure B1.0.3: Estimated maximum ground level concentrations of TSP for different meteorological conditions from stack emission of Yusef Brick Kiln

The highest estimated one hour average ground level concentrations of NOx are found during unstable meteorological conditions. At very short distances the NOx concentration might reach 10 µg/m3. However, NOx is not the problem emissions from the brick kiln.
SO2 concentrations might exceed 4 to 500 µg/m3 on distances up till 2 km from the stack. Very close to the stack unstable low wind conditions may lead to short term ground level concentrations of SO2 as high as 1000 µg/m3.
The typical TSP concentrations at ground level are about 30 % of the SO2 concentrations.

The spatial 24 hour average SO2 concentration distribution at ground level is shown as an example in Figure B. 1.0.4 below.

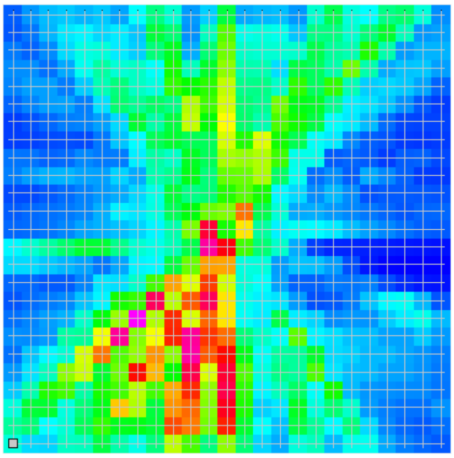


Figure B1.0.4: The maximum 24 hr average ground level concentration of SO_2. Based on dispersion for the 5-month dry season at the Brick Kiln. (.3x.3km grid cell resolution)

The highest maximum daily concentrations can be found south-south-west from the factory at distances of 300m to 3km. Typical maximum one-hour average ground level concentrations of SO_2 are between 200 and 700 µg/m3 at distances less than 1 km from the factory. Daily average concentrations are about 50 to 90 µg/m3 at 2-3 km from the brick factory stack.

Table B1.0.3 Estimated maximum ground level concentrations of, SO_2, $NO_2$and TSP downwind from the Yosuf Brick kiln

	SO_2 (µg/m^3)	**NO_2 (µg/m^3)**	**TSP (µg/m^3)**
Highest grid cell max for the 5 month period (based on 1-hour avg):	731.9	4.4	215.0
Highest grid cell max for the 5 month period (based on 24-hour avg)	89.5	.6	33.6
Highest grid cell avg for the 5 month period	22.6	.2	9.4

One receptor area located in one of the largest communities in the near vicinity to the Brick Kiln was selected. Mograkanda is located 2.3 km SSW from the brick kiln (23°46'22.20"N, 90°18'33.24"E, TAPM grid cell 10,6).

Figure B1.0.5: The location of the receptor points at Mograkanda

Typical 24 hour average and annual average concentrations estimated in the Mograkanda area are presented in the Table B 1.0.3 below.

Table B1.0.4 Estimated concentrations of NO_2, SO_2 and TSP in the area of Mograkanda, located south-south west of the Yosuf Brick kiln.

	Mograkanda (µg/m3)		
	NO2	SO2	TSP
Max 24 hour ground level concentration (1 year of data)	0.3	46.5	16.6
The highest grid cell annual average gr.l concentration	0.04	6.2	4.6

The highest daily SO_2 concentration at ground level caused by emissions from the brick factory has been estimated for the Mograkanda community to be 46.5 µg/m3. The highest daily concentrations of NO_2 was estimated at 0.3 µg/m3, while TSP concentrations were estimated at about 17 µg/m3. These are all daily maxima caused by emissions from the Yusuf brick kiln only.

Emission Mitigation Options for Steel and Ceramic Industries

The following points may be considered for reducing gaseous and particulate emissions from polluting industries:

1. Amendment/Revision of the emission standards for all major industries in the country in line with or close to US EPA Standards.
2. Asking the concerned industries to reduce gaseous/particulate emissions by adopting modern technologies available:
    a. Most of the ceramic industries use tunnel kiln for firing, glazing and decoration purposes. Though tunnel kilns are considered energy efficient with proper thermal insulation, effective use of waste heat from the kiln can save additional fuel requirement for drying green wares within the factory which in turn will reduce emissions. Additionally baghouse can be installed to separate particles from flue gases.
    b. Though EIF is considered energy efficient compared to blast/open hearth furnace, proper hood arrangement (for sucking emissions), water scrubber/baghouse can reduce the particulate emissions significantly. There is every possibility to recycle the recovered material from emission stream.
3. Provide incentives to them to adopt modern technology; e.g. bank loans on easy terms/tax holiday for a few years, etc.
4. Provide appropriate/modern emission measuring equipment for DOE.
5. Adequate/well trained manpower with proper educational background for DOE.
6. There is no denying the fact that DOE is hugely understaffed. DOE recruitment policy may ensure that manpower with proper scientific/engineering background is employed.
7. Knowledgeable/well trained personnel with adequate background should be given proper financial incentives including housing, so that they do not leave DOE in frustration. Liberal promotion policy may be adopted. Public Universities in the country, especially those in Dhaka retain teachers by providing decent housing and liberal promotion policies.
8. Lastly, DOE may be relieved of its multiple responsibilities viz. regulatory, monitoring .and enforcement.

References

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2. ASTM D 3685/D 3685M-98: Standard Test Methods for Sampling and Determination of Particulate Matter in Stack Gases. West Conshohocken, PA, ASTM International.
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4. USEPA Reference Method 2 (40CFR60 App. A.): Determining Stack Gas Velocity and Volumetric Flow Rate, Isokinetic Source Sampler XC 500 Series Instruction Manual. Apex Instruments Inc., USA.
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16. Randall, S., Nasiruddin, Md., Rana, M., Sivertsen, B., Dela Cruz, N. (2014a) Contribution of Brick Kilns to Air Quality in Dhaka City. Kjeller, NILU (NILU OR, 12/2014).
17. Randall, S., Sivertsen, B., Dam, V.T. Ahammad S., Cruz N.D. (2014b) Bangladesh Air Pollution Studies (BAPS): Task 1. Emissions Inventory for Dhaka and Chittagong of pollutants PM_{10}, $PM_{2.5}$, NOx, SOx and CO. Kjeller, NILU (NILU OR 45/2011).

Appendix-A

Basic features of EIF

The various features of crucible type EIF are shown in Figure A1.

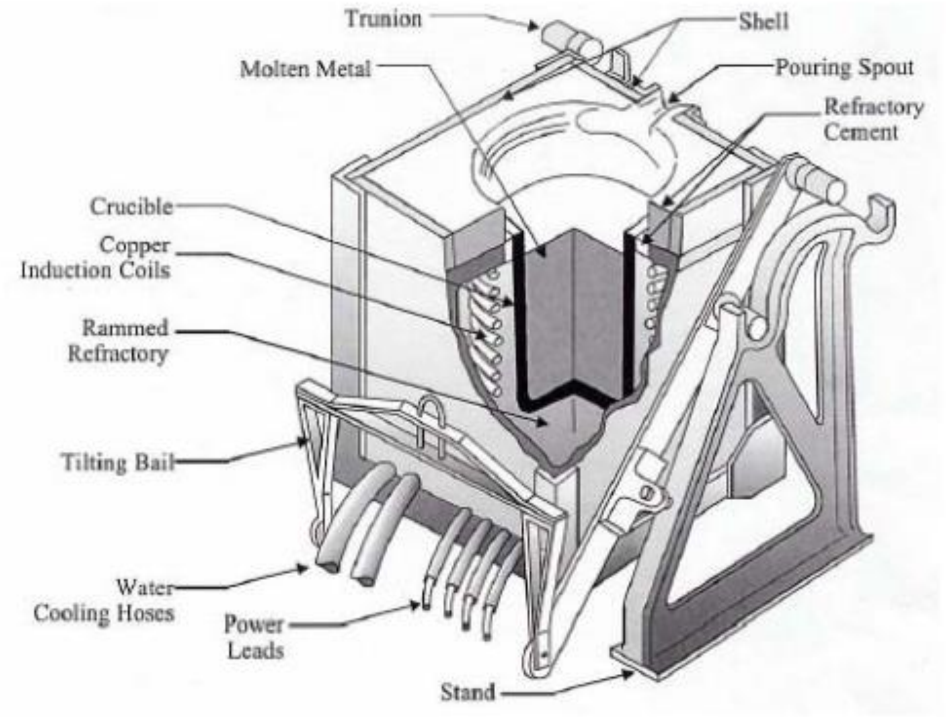


Figure A1. Schematic of Crucible Type Electric Induction Furnace (EIF)

Induction Electrical System Configurations:
EIFs require two separate electrical systems: one for the cooling system, furnace tilting and instrumentation, and the other for the induction coil power. A line to the plant's power distribution panel typically furnishes power for the pumps in the induction coil cooling system, the hydraulic furnace tilting mechanism, and instrumentation and control systems. Electricity for the induction coils is furnished from a three-phase, high voltage, high amperage utility line. An A.C. current from the transformer is fed to the rectifier of the furnace's electronic circuit. This converts A.C. to D.C, voltage is smoothed out by a D.C. choke, and then fed to the inverted section of the furnace. Here the D.C is converted to a high frequency A.C. current and this is fed to the Copper Induction Coils.

Refractory Lining:
Spinel-forming dry masses on MgO and Al_2O_3 basis are the lining materials that can withstand temperature over 1750^{o}C.

Cooling System:

The cooling system is a through-one-way- flow system with the tubular copper coils connected to water source through flexible rubber hoses. The inlet is from the top while the outlet is at the bottom. The cooling process is important because the circuit of the furnace appears resistive, and the real power is not only consumed in the charged material but also in the resistance of the coil. This coil loss as well as the loss of heat conducted from the charge through the refractory crucible requires the coil to be cooled with water as the cooling medium to prevent undue temperature rise of the copper coils.

Working principle:

Induction furnaces produce their heat cleanly, without combustion. Alternating electric current from an induction power unit flows into a furnace and through a coil made of hollow copper tubing. This creates an electromagnetic field that passes through the refractory material (furnace lining) and couples with conductive metal charge inside the furnace. This induces electric current to flow inside the metal charge itself, producing heat that rapidly causes the metal to melt. The melting principle is shown in Figure A2.

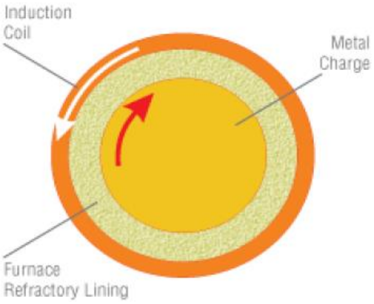
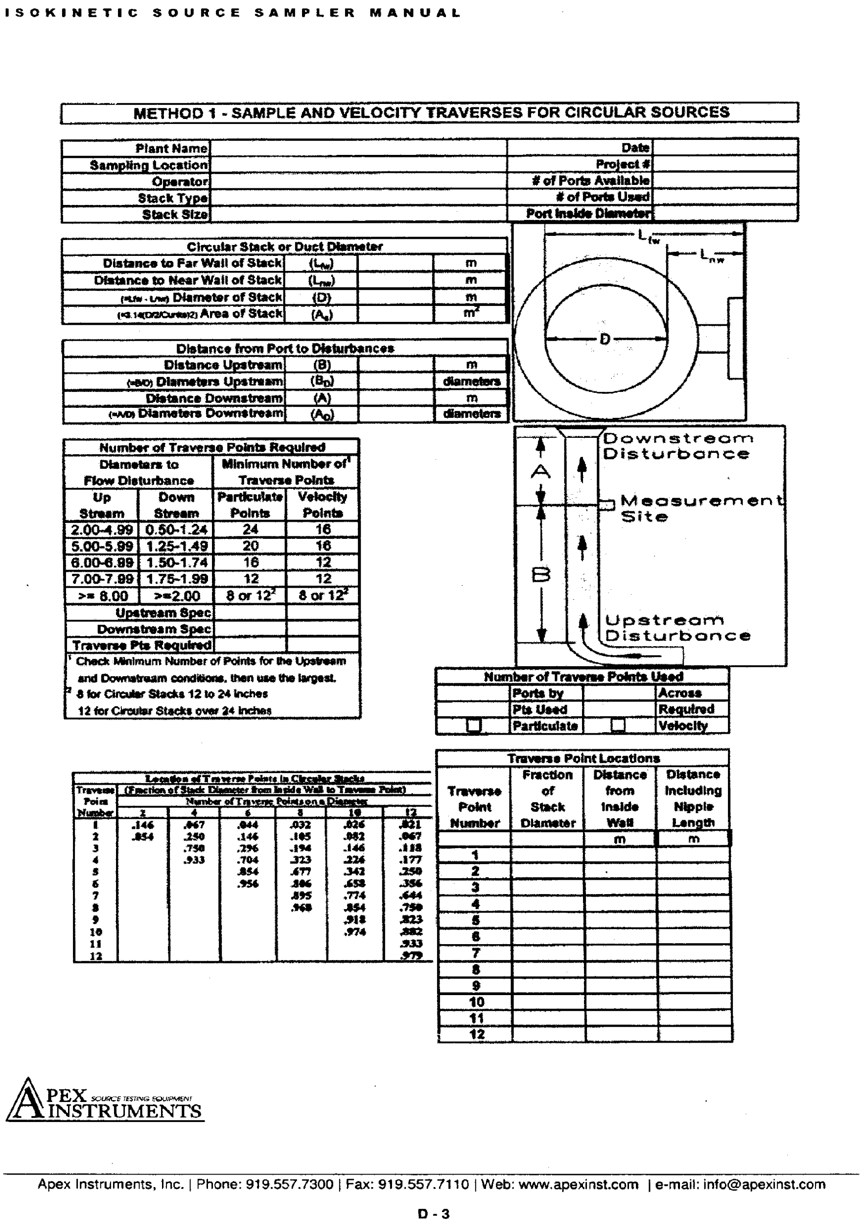


Figure A2. Current flowing in one direction in the induction coil induces a current flow in the opposite direction in the metal charge. This current heats the metal and causes it to melt

Appendix-B
Measuring principles of instruments used and calculation data sheet

B1: Sample and velocity traverses for circular stack (USEPA Method-1)



ISOKINETIC SOURCE SAMPLER MANUAL

METHOD 1 - SAMPLE AND VELOCITY TRAVERSES FOR CIRCULAR SOURCES

Plant Name		Date	
Sampling Location		Project #	
Operator		# of Ports Available	
Stack Type		# of Ports Used	
Stack Size		Port Inside Diameter	

Circular Stack or Duct Diameter			
Distance to Far Wall of Stack	(L_{fw})		m
Distance to Near Wall of Stack	(L_{nw})		m
(=Lfw - Lnw) Diameter of Stack	(D)		m
(=3.14(D/2/[illegible])2) Area of Stack	(A_s)		m^2

Distance from Port to Disturbances			
Distance Upstream	(B)		m
(=B/D) Diameters Upstream	(B_D)		diameters
Distance Downstream	(A)		m
(=A/D) Diameters Downstream	(A_D)		diameters

Number of Traverse Points Required			
Diameters to Flow Disturbance		Minimum Number of[1] Traverse Points	
Up Stream	Down Stream	Particulate Points	Velocity Points
2.00-4.99	0.50-1.24	24	16
5.00-5.99	1.25-1.49	20	16
6.00-6.99	1.50-1.74	16	12
7.00-7.99	1.75-1.99	12	12
>= 8.00	>=2.00	8 or 12[2]	8 or 12[2]
Upstream Spec			
Downstream Spec			
Traverse Pts Required			

[1] Check Minimum Number of Points for the Upstream and Downstream conditions, then use the largest.

[2] 8 for Circular Stacks 12 to 24 inches
12 for Circular Stacks over 24 inches

Number of Traverse Points Used			
	Ports by		Across
	Pts Used		Required
☐	Particulate	☐	Velocity

Location of Traverse Points in Circular Stacks
(Fraction of Stack Diameter from Inside Wall to Traverse Point)

Traverse Point Number	Number of Traverse Points on a Diameter					
	2	4	6	8	10	12
1	.146	.067	.044	.032	.026	.021
2	.854	.250	.146	.105	.082	.067
3		.750	.296	.194	.146	.118
4		.933	.704	.323	.226	.177
5			.854	.677	.342	.250
6			.956	.806	.658	.356
7				.895	.774	.644
8				.968	.854	.750
9					.918	.823
10					.974	.882
11						.933
12						.979

Traverse Point Locations

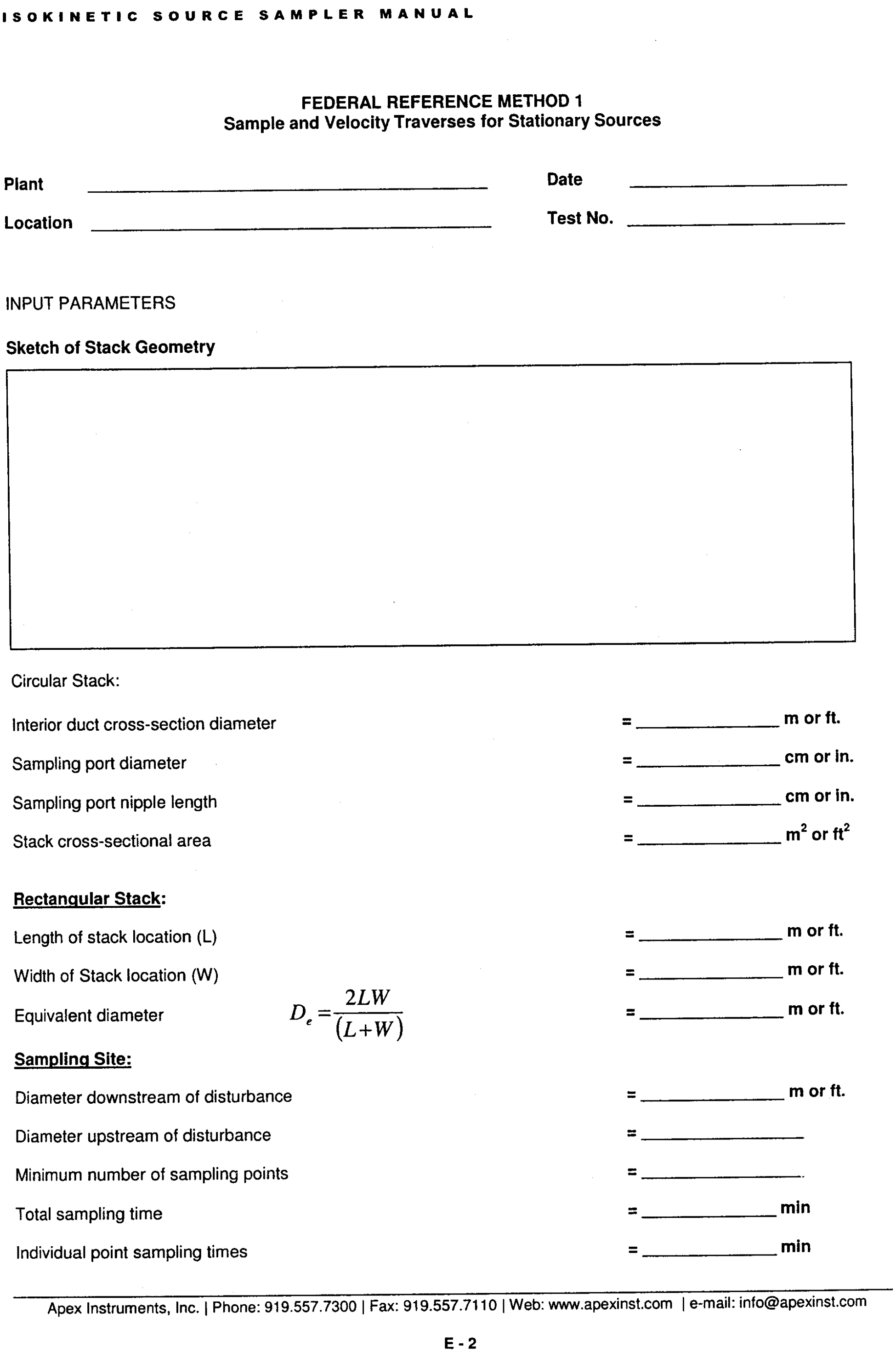
Traverse Point Number	Fraction of Stack Diameter	Distance from Inside Wall	Distance Including Nipple Length
		m	m
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			

APEX SOURCE TESTING EQUIPMENT INSTRUMENTS

Apex Instruments, Inc. | Phone: 919.557.7300 | Fax: 919.557.7110 | Web: www.apexinst.com | e-mail: info@apexinst.com

D - 3

B2: Sample and velocity traverses for stack (Calculation sheet) (USEPA Method-1)



FEDERAL REFERENCE METHOD 1
Sample and Velocity Traverses for Stationary Sources

Plant ____________________ **Date** ____________

Location ____________________ **Test No.** ____________

INPUT PARAMETERS

Sketch of Stack Geometry

Circular Stack:

Interior duct cross-section diameter = ________ **m or ft.**

Sampling port diameter = ________ **cm or in.**

Sampling port nipple length = ________ **cm or in.**

Stack cross-sectional area = ________ **m^2 or ft^2**

Rectangular Stack:

Length of stack location (L) = ________ **m or ft.**

Width of Stack location (W) = ________ **m or ft.**

Equivalent diameter $D_e = \frac{2LW}{(L+W)}$ = ________ **m or ft.**

Sampling Site:

Diameter downstream of disturbance = ________ **m or ft.**

Diameter upstream of disturbance = ________

Minimum number of sampling points = ________.

Total sampling time = ________ **min**

Individual point sampling times = ________ **min**

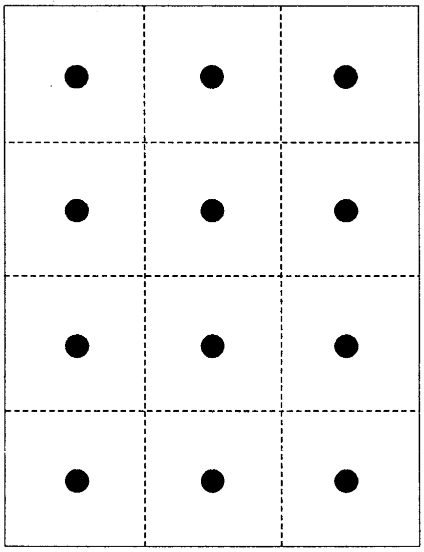
Sample and Velocity Traverses for Stationary Sources
(continued)

Location of Sampling Points:

CIRCULAR

Sample point number	Circular stack % diameter	Distance from sample port opening, in.
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		
11.		
12.		

RECTANGULAR



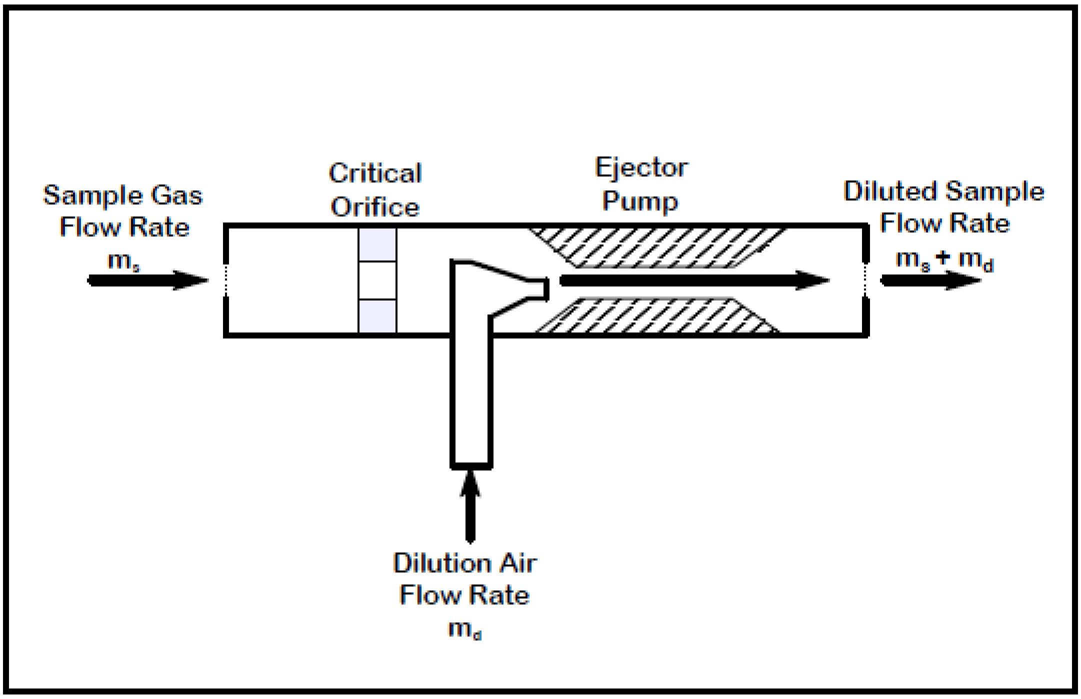
B3 : Stack dilution probe and dilution probe controller, Model 200L (Thermo Environmental Instruments Inc., USA)

Principle of Operation

The Model 200L Single Dilution Probe Controller is utilized in conjunction with various dilution probe configurations. The dilution probe provides the means of the actual dilution process. The dilution probe is where the actual dilution process occurs. Model 200L is designed to measure diluted stack gases by mixing the exhaust gases with pressurized regulated zero air at a known dilution ratio. This method meets the requirements pertained in the EPA CFR Title 40, Part 60.

The dilution ratio is calculated to decrease the water moisture in the sample gas to a percent at which the water moisture remains suspended. The use of dry instrument air for dilution ratios in the order of 100:1 results in samples that is 99% clean and dry zero air. This is an excellent sample for analyses with ambient air analyzers. High accuracy and freedom from interference is assured.

Specifications for 200L Dilution Probe Controller: Operating temperature (5-45°C); Remote Inputs (ability to control zero and 1 to 5 span ports); Output contacts (Zero and up to 5 spans).



Schematic of dilution probe. Sample gas from the stack is drawn into the dilution probe, mixed with clean, dry air, and then sent to gas analyzers in a diluted form.

B4: Stack gas CO_2 analyzer, Model 41C
(Thermo Environmental Instruments Inc., USA)

Principle of Operation

The Model 41C High Level is based on the principle that Carbon dioxide (CO_2) absorbs infrared radiation. Because infrared absorption is a non-linear measurement technique, it is necessary to transform the basic analyzer signal into a linear output. The analyzer uses an exact calibration curve to accurately linearize the instrument output over any range up to a concentration of 2000 ppm.

Specifications: Preset ranges (0-5, 10, 20, 50, 100, 200, 500, 1000, 2000 ppm); Custom ranges (0-5 to 2000 ppm); Lower detectable limit (100 ppb); Precision (± 1 %); Operating temperature (15-35^{o}C).

B5: Stack gas CO, NO and NO2 analyzer, Model 600-2-4-5
(NOVA Analytical Systems Inc., Canada)

Principle of Operation

The Nova Model 600-2-4-5 stack gas analyzer measures CO, NO and NO_2 gases simultaneously. These three gases are detected by electrochemical sensors. Each of these sensors has an anode, cathode and suitable electrolyte sealed inside which when exposed to CO, NO and NO_2 gases, will produce a small output current. This output current is directly proportional to the amount of the given gases in the sample. A pre-amplifier board mounted on top of each sensor boosts this small signal and converts it to an output of 1mV per ppm. This output is then directed from the preamplifier to the main amplifier board where it is corrected for calibration, and then it sends a signal to the display meter on the top panel.

Specifications: Measuring ranges CO: 0-200 ppm, NO: 0-100 ppm and NO_2: 0-20 ppm

B6: Stack gas SOx analyzer, Model 600-8
(NOVA Analytical Systems Inc., Canada)

Principle of Operation

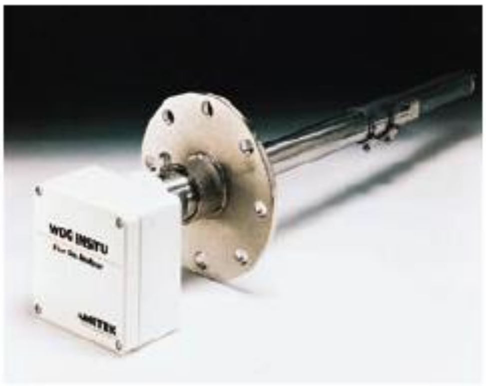
The Nova Model 600-8 stack gas analyzer measures SO_2. SO_2 gas is detected by electrochemical sensor. The sensor has an anode, cathode and suitable electrolyte sealed inside which produces a small output current when it is exposed to SO_2 gas. This output current is directly proportional to the amount of SO_2 in sample gas. A pre-amplifier board mounted on top of each sensor boosts this small signal and converts it to an output of 1mV per ppm. This output is then directed from the preamplifier to the main amplifier board where it is corrected for calibration, and then it sends a signal to the display meter on the top panel.

Specifications: Measuring range: 0-20 ppm

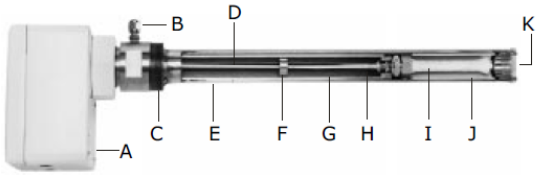
B7: Direct Sensing WDG-INSITU Flue Gas Oxygen Analyzer and Thermox Flue Gas Monitor, 2000 Series (AMETEK Inc., USA)

Principle of Operation

The WDG-Insitu is a direct insertion-type oxygen probe where the zirconium oxide cell is directly in the stream of the products of combustion. The patented WDG-Insitu is designed for applications where the flue gas temperature does not exceed 1250°F (677°C) and where combustibles measurements are not required. The outer probe material is highly resistant to corrosion.



WDG-Insitu



Cross-section of Insitu probe

- **A** NEMA 4X junction box
- **B** 1/4″ compression connection for calibration gas
- **C** 2″ NPT (M) connection for flange adaption
- **D** Inner tube structure
- **E** Outer protection tube (no need to remove once installed)
- **F** Support spiders
- **G** Zirconium oxide cell lead(s)
- **H** Zirconium oxide cell heater/thermocouple
- **I** Zirconium oxide cell with insulation sleeve
- **J** Ceramic sheath
- **K** Protective screen

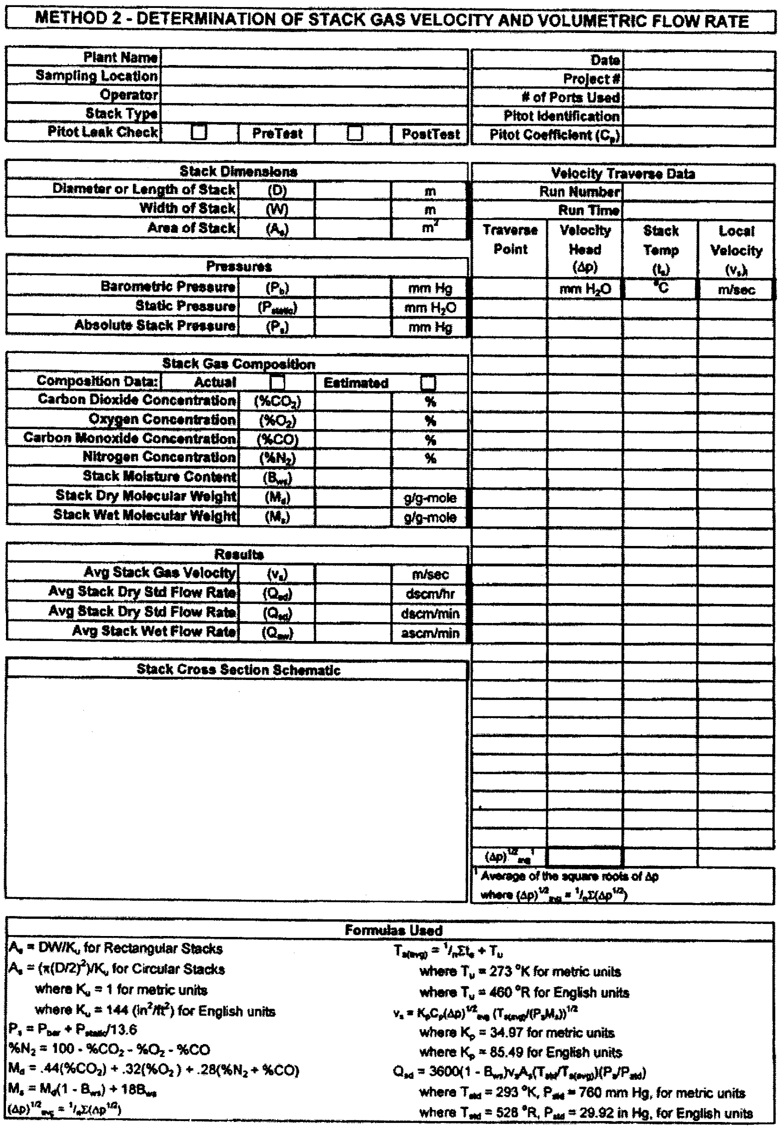
Specifications: O_2 measuring range: 0-1% to 0-100%; Accuracy: ±1%; Max. Flue Gas Temperature: 677^{o}C

Series 2000 Control Unit

B8: Determination of Stack gas Velocity and Volumetric Flow Rate of Stack Gas (Data Sheet)

(USEPA Method-2)

ISOKINETIC SOURCE SAMPLER MANUAL



METHOD 2 - DETERMINATION OF STACK GAS VELOCITY AND VOLUMETRIC FLOW RATE

Plant Name				**Date**	
Sampling Location				**Project #**	
Operator				**# of Ports Used**	
Stack Type				**Pitot Identification**	
Pitot Leak Check	☐	**PreTest**	☐ **PostTest**	**Pitot Coefficient (C_p)**	

Stack Dimensions			
Diameter or Length of Stack	(D)		m
Width of Stack	(W)		m
Area of Stack	(A_s)		m^2

Pressures			
Barometric Pressure	(P_b)		mm Hg
Static Pressure	(P_{static})		mm H_2O
Absolute Stack Pressure	(P_s)		mm Hg

Stack Gas Composition			
Composition Data:	**Actual** ☐	**Estimated** ☐	
Carbon Dioxide Concentration	($\%CO_2$)		%
Oxygen Concentration	($\%O_2$)		%
Carbon Monoxide Concentration	(%CO)		%
Nitrogen Concentration	($\%N_2$)		%
Stack Moisture Content	(B_{ws})		
Stack Dry Molecular Weight	(M_d)		g/g-mole
Stack Wet Molecular Weight	(M_s)		g/g-mole

Results			
Avg Stack Gas Velocity	(v_s)		m/sec
Avg Stack Dry Std Flow Rate	(Q_{sd})		dscm/hr
Avg Stack Dry Std Flow Rate	(Q_{sd})		dscm/min
Avg Stack Wet Flow Rate	(Q_{aw})		ascm/min

Stack Cross Section Schematic

Velocity Traverse Data			
	Run Number		
	Run Time		
Traverse Point	**Velocity Head (Δp)**	**Stack Temp (t_s)**	**Local Velocity (v_s)**
	mm H_2O	°C	m/sec
$(\Delta p)^{1/2}_{avg}$ [1]			

[1] Average of the square roots of Δp where $(\Delta p)^{1/2}_{avg} = {}^1/_n\Sigma(\Delta p^{1/2})$

Formulas Used

$A_s = DW/K_u$ for Rectangular Stacks

$A_s = (\pi(D/2)^2)/K_u$ for Circular Stacks

where $K_u = 1$ for metric units

where $K_u = 144$ (in^2/ft^2) for English units

$P_s = P_{bar} + P_{static}/13.6$

$\%N_2 = 100 - \%CO_2 - \%O_2 - \%CO$

$M_d = .44(\%CO_2) + .32(\%O_2) + .28(\%N_2 + \%CO)$

$M_s = M_d(1 - B_{ws}) + 18B_{ws}$

$(\Delta p)^{1/2}_{avg} = {}^1/_n\Sigma(\Delta p^{1/2})$

$T_{s(avg)} = {}^1/_n\Sigma t_s + T_u$

where T_u = 273 °K for metric units

where T_u = 460 °R for English units

$v_s = K_pC_p(\Delta p)^{1/2}_{avg}\,(T_{s(avg)}/(P_sM_s))^{1/2}$

where K_p = 34.97 for metric units

where K_p = 85.49 for English units

$Q_{sd} = 3600(1 - B_{ws})v_sA_s(T_{std}/T_{s(avg)})(P_s/P_{std})$

where T_{std} = 293 °K, P_{std} = 760 mm Hg, for metric units

where T_{std} = 528 °R, P_{std} = 29.92 in Hg, for English units

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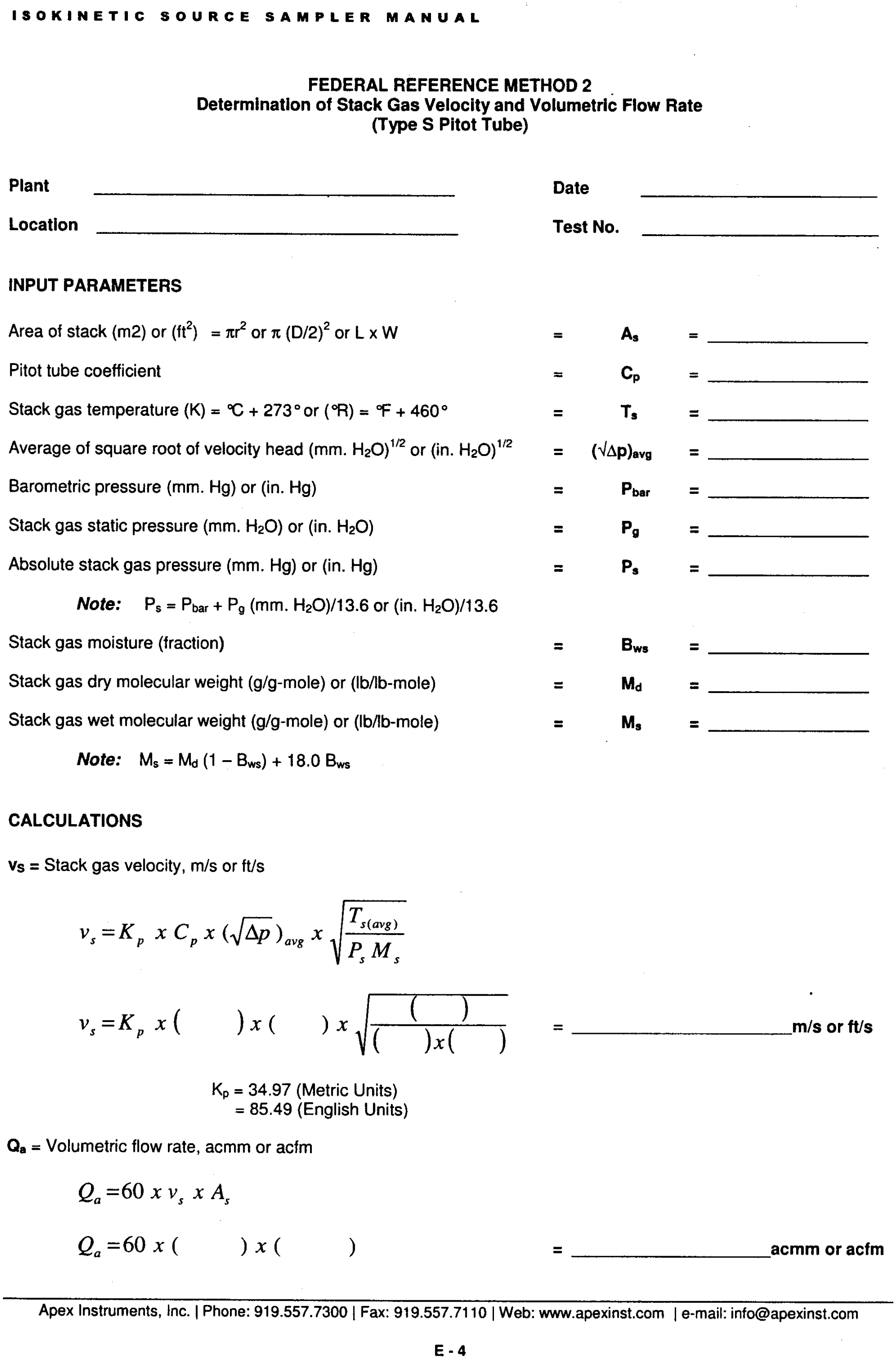
B9: Determination of Stack gas Velocity and Volumetric Flow Rate of Stack Gas (Calculation sheet) (USEPA Method-2)



FEDERAL REFERENCE METHOD 2
Determination of Stack Gas Velocity and Volumetric Flow Rate
(Type S Pitot Tube)

Plant ______________________ **Date** ______________

Location ______________________ **Test No.** ______________

INPUT PARAMETERS

Area of stack (m2) or (ft^2) = πr^2 or π $(D/2)^2$ or L x W = **A_s** = ____________

Pitot tube coefficient = **C_p** = ____________

Stack gas temperature (K) = °C + 273° or (°R) = °F + 460° = **T_s** = ____________

Average of square root of velocity head (mm. $H_2O)^{1/2}$ or (in. $H_2O)^{1/2}$ = **$(\sqrt{\Delta p})_{avg}$** = ____________

Barometric pressure (mm. Hg) or (in. Hg) = **P_{bar}** = ____________

Stack gas static pressure (mm. H_2O) or (in. H_2O) = **P_g** = ____________

Absolute stack gas pressure (mm. Hg) or (in. Hg) = **P_s** = ____________

Note: $P_s = P_{bar} + P_g$ (mm. H_2O)/13.6 or (in. H_2O)/13.6

Stack gas moisture (fraction) = **B_{ws}** = ____________

Stack gas dry molecular weight (g/g-mole) or (lb/lb-mole) = **M_d** = ____________

Stack gas wet molecular weight (g/g-mole) or (lb/lb-mole) = **M_s** = ____________

Note: $M_s = M_d (1 - B_{ws}) + 18.0 B_{ws}$

CALCULATIONS

v_s = Stack gas velocity, m/s or ft/s

$$v_s = K_p \; x \; C_p \; x \; (\sqrt{\Delta p})_{avg} \; x \; \sqrt{\frac{T_{s(avg)}}{P_s M_s}}$$

$$v_s = K_p \; x \; (\qquad) \; x \; (\qquad) \; x \; \sqrt{\frac{(\quad)}{(\quad) x (\quad)}}$$ = ______________ **m/s or ft/s**

K_p = 34.97 (Metric Units)
= 85.49 (English Units)

Q_a = Volumetric flow rate, acmm or acfm

$$Q_a = 60 \; x \; v_s \; x \; A_s$$

$$Q_a = 60 \; x \; (\qquad) \; x \; (\qquad)$$ = ______________ **acmm or acfm**

Determination of Stack Gas Velocity and Volumetric Flow Rate
(continued)

Q_d = Dry volumetric flow meter, scmm or scfm

$$Q_d = 60\ x\ (1-B_{ws})\ x\ v_s\ x\ A_s$$

$$Q_d = 60\ x\ (1-(\quad\quad))\ x\ (\quad\quad)\ x\ (\quad\quad)$$ = ________________**scmm or scfm**

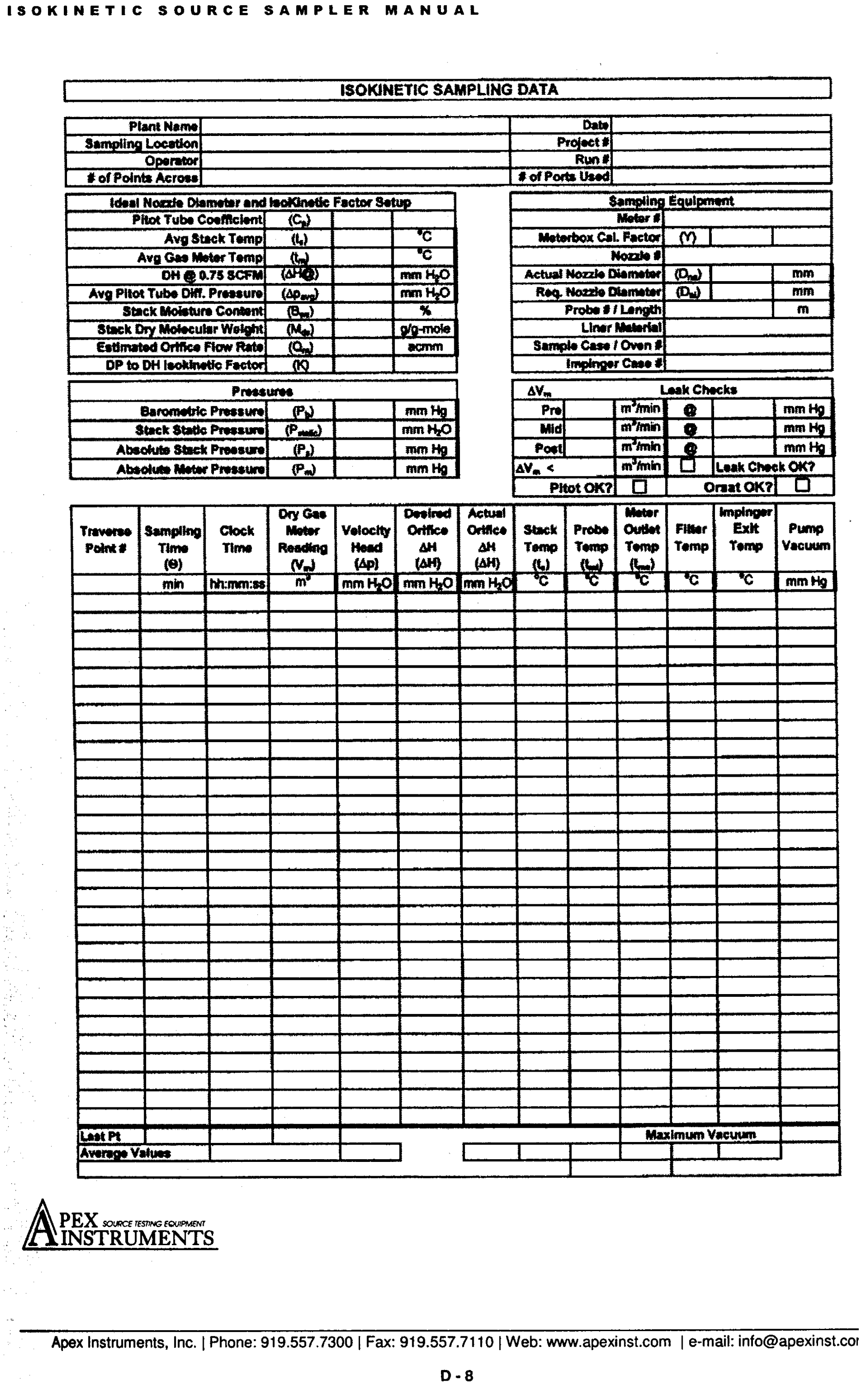
Q_{sd} = Volumetric flow rate, dscmm or dscfm

$$Q_{sd} = 60\ x\ (1-B_{ws})\ x\ v_s\ x\ A_s\ x\ \frac{T_{std}}{T_s}\ x\ \frac{P_s}{P_{std}}$$

$$Q_{sd} = 60\ x\ (1-(\quad\quad))\ x\ (\quad\quad)\ x\ (\quad\quad)\ x\ \frac{T_{std}}{(\quad\quad)}\ x\ \frac{(\quad\quad)}{P_{std}}$$

= ________________**dscmm or dscfm**

B10: USEPA reference method 5
Isokinetic sampling data sheet



ISOKINETIC SOURCE SAMPLER MANUAL

ISOKINETIC SAMPLING DATA

Plant Name		Date	
Sampling Location		Project #	
Operator		Run #	
# of Points Across		# of Ports Used	

Ideal Nozzle Diameter and IsoKinetic Factor Setup			
Pitot Tube Coefficient	(C_p)		
Avg Stack Temp	(t_s)		°C
Avg Gas Meter Temp	(t_m)		°C
DH @ 0.75 SCFM	($\Delta H@$)		mm H_2O
Avg Pitot Tube Diff. Pressure	(Δp_{avg})		mm H_2O
Stack Moisture Content	(B_{ws})		%
Stack Dry Molecular Weight	(M_{ds})		g/g-mole
Estimated Orifice Flow Rate	(Q_m)		acmm
DP to DH Isokinetic Factor	(K)		

Sampling Equipment			
Meter #			
Meterbox Cal. Factor	(Y)		
Nozzle #			
Actual Nozzle Diameter	(D_{na})		mm
Req. Nozzle Diameter	(D_{ni})		mm
Probe # / Length			m
Liner Material			
Sample Case / Oven #			
Impinger Case #			

Pressures			
Barometric Pressure	(P_b)		mm Hg
Stack Static Pressure	(P_{static})		mm H_2O
Absolute Stack Pressure	(P_s)		mm Hg
Absolute Meter Pressure	(P_m)		mm Hg

ΔV_m		Leak Checks			
Pre		m^3/min	@		mm Hg
Mid		m^3/min	@		mm Hg
Post		m^3/min	@		mm Hg
ΔV_m <		m^3/min	☐	Leak Check OK?	
Pitot OK?	☐		Orsat OK?	☐	

Traverse Point #	Sampling Time (Θ)	Clock Time	Dry Gas Meter Reading (V_m)	Velocity Head (Δp)	Desired Orifice ΔH (ΔH)	Actual Orifice ΔH (ΔH)	Stack Temp (t_s)	Probe Temp (t_{sol})	Meter Outlet Temp (t_{mo})	Filter Temp	Impinger Exit Temp	Pump Vacuum
	min	hh:mm:ss	m^3	mm H_2O	mm H_2O	mm H_2O	°C	°C	°C	°C	°C	mm Hg
Last Pt										Maximum Vacuum		
Average Values												

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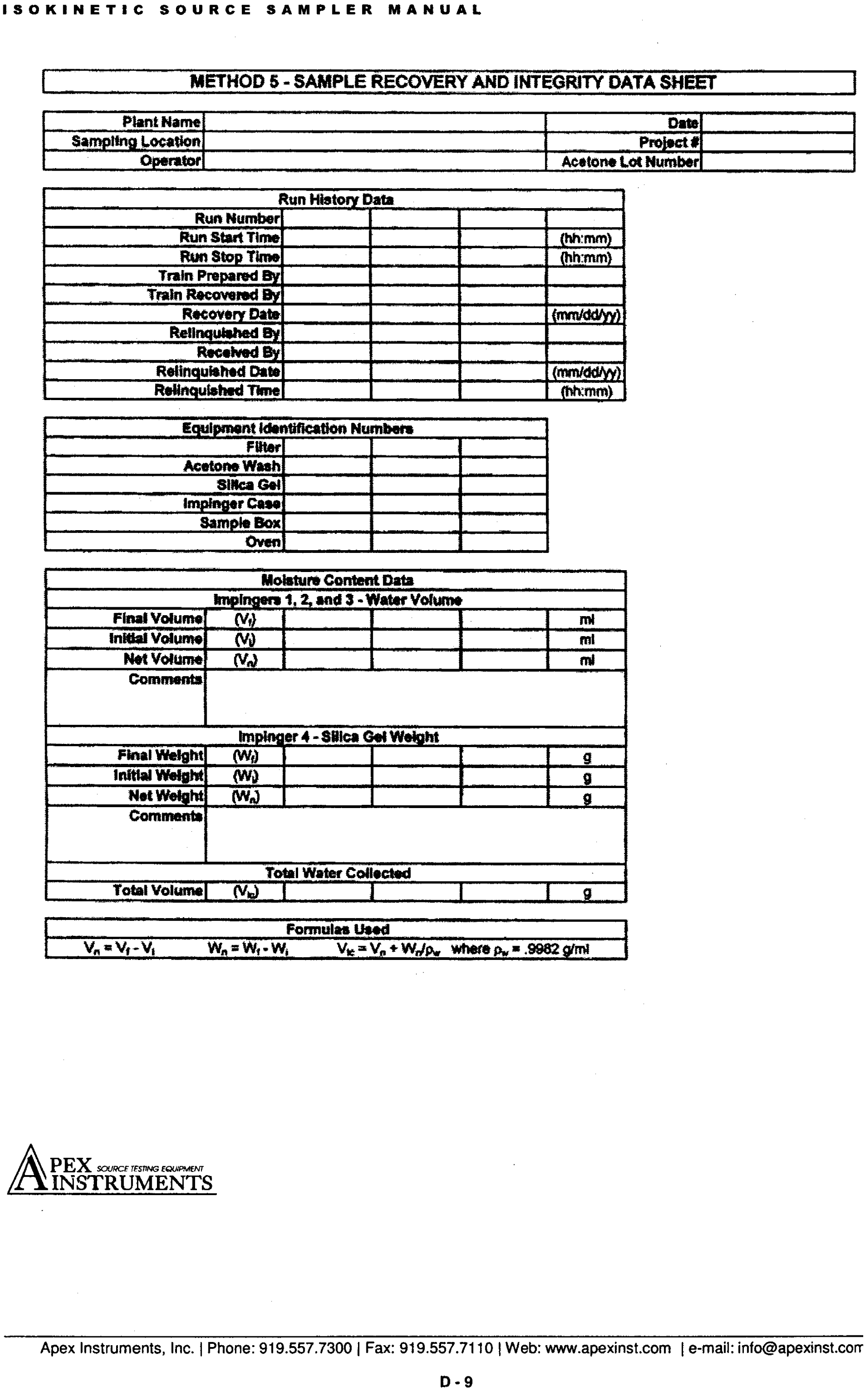
B11: USEPA reference method 5
Sample recovery and integrity data sheet



METHOD 5 - SAMPLE RECOVERY AND INTEGRITY DATA SHEET

Plant Name		**Date**	
Sampling Location		**Project #**	
Operator		**Acetone Lot Number**	

Run History Data				
Run Number				
Run Start Time				(hh:mm)
Run Stop Time				(hh:mm)
Train Prepared By				
Train Recovered By				
Recovery Date				(mm/dd/yy)
Relinquished By				
Received By				
Relinquished Date				(mm/dd/yy)
Relinquished Time				(hh:mm)

Equipment Identification Numbers			
Filter			
Acetone Wash			
Silica Gel			
Impinger Case			
Sample Box			
Oven			

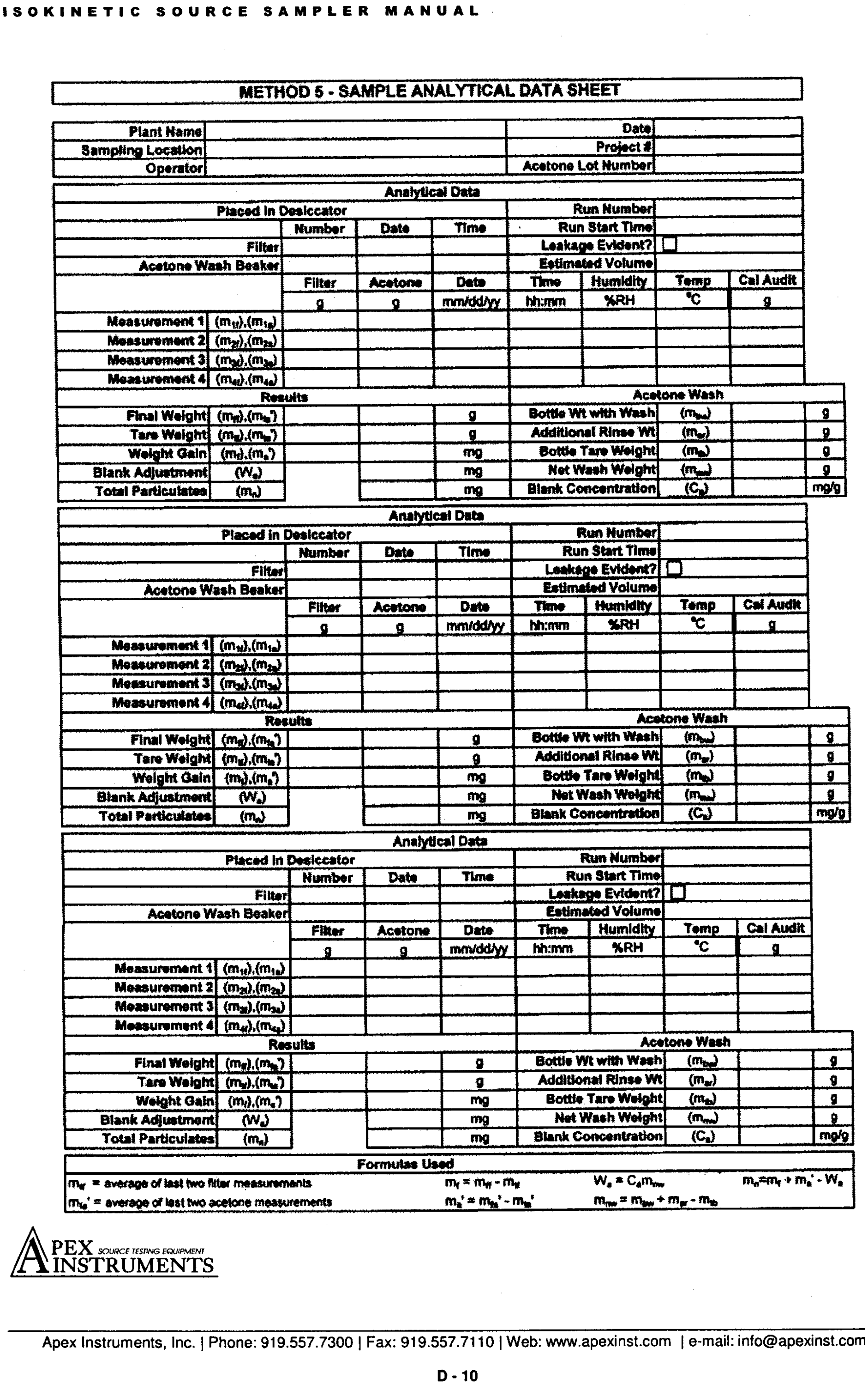
Moisture Content Data					
Impingers 1, 2, and 3 - Water Volume					
Final Volume	(V_f)				ml
Initial Volume	(V_i)				ml
Net Volume	(V_n)				ml
Comments					
Impinger 4 - Silica Gel Weight					
Final Weight	(W_f)				g
Initial Weight	(W_i)				g
Net Weight	(W_n)				g
Comments					
Total Water Collected					
Total Volume	(V_{lc})				g

Formulas Used

$V_n = V_f - V_i$ $W_n = W_f - W_i$ $V_{lc} = V_n + W_n/\rho_w$ where ρ_w = .9982 g/ml

APEX SOURCE TESTING EQUIPMENT
INSTRUMENTS

B12: USEPA reference method 5
Sample analytical data sheet



METHOD 5 - SAMPLE ANALYTICAL DATA SHEET

Plant Name		Date	
Sampling Location		Project #	
Operator		Acetone Lot Number	

Analytical Data								
Placed in Desiccator					Run Number			
		Number	Date	Time	Run Start Time			
Filter					Leakage Evident?	☐		
Acetone Wash Beaker					Estimated Volume			
		Filter	Acetone	Date	Time	Humidity	Temp	Cal Audit
		g	g	mm/dd/yy	hh:mm	%RH	°C	g
Measurement 1	$(m_{1f}),(m_{1a})$							
Measurement 2	$(m_{2f}),(m_{2a})$							
Measurement 3	$(m_{3f}),(m_{3a})$							
Measurement 4	$(m_{4f}),(m_{4a})$							

Results					Acetone Wash			
Final Weight	$(m_{ff}),(m_{fa}')$			g	Bottle Wt with Wash	(m_{bw})		g
Tare Weight	$(m_{tf}),(m_{ta}')$			g	Additional Rinse Wt	(m_{ar})		g
Weight Gain	$(m_f),(m_a')$			mg	Bottle Tare Weight	(m_{tb})		g
Blank Adjustment	(W_a)			mg	Net Wash Weight	(m_{nw})		g
Total Particulates	(m_n)			mg	Blank Concentration	(C_a)		mg/g

Analytical Data								
Placed in Desiccator					Run Number			
		Number	Date	Time	Run Start Time			
Filter					Leakage Evident?	☐		
Acetone Wash Beaker					Estimated Volume			
		Filter	Acetone	Date	Time	Humidity	Temp	Cal Audit
		g	g	mm/dd/yy	hh:mm	%RH	°C	g
Measurement 1	$(m_{1f}),(m_{1a})$							
Measurement 2	$(m_{2f}),(m_{2a})$							
Measurement 3	$(m_{3f}),(m_{3a})$							
Measurement 4	$(m_{4f}),(m_{4a})$							

Results					Acetone Wash			
Final Weight	$(m_{ff}),(m_{fa}')$			g	Bottle Wt with Wash	(m_{bw})		g
Tare Weight	$(m_{tf}),(m_{ta}')$			g	Additional Rinse Wt	(m_{ar})		g
Weight Gain	$(m_f),(m_a')$			mg	Bottle Tare Weight	(m_{tb})		g
Blank Adjustment	(W_a)			mg	Net Wash Weight	(m_{nw})		g
Total Particulates	(m_n)			mg	Blank Concentration	(C_a)		mg/g

Analytical Data								
Placed in Desiccator					Run Number			
		Number	Date	Time	Run Start Time			
Filter					Leakage Evident?	☐		
Acetone Wash Beaker					Estimated Volume			
		Filter	Acetone	Date	Time	Humidity	Temp	Cal Audit
		g	g	mm/dd/yy	hh:mm	%RH	°C	g
Measurement 1	$(m_{1f}),(m_{1a})$							
Measurement 2	$(m_{2f}),(m_{2a})$							
Measurement 3	$(m_{3f}),(m_{3a})$							
Measurement 4	$(m_{4f}),(m_{4a})$							

Results					Acetone Wash			
Final Weight	$(m_{ff}),(m_{fa}')$			g	Bottle Wt with Wash	(m_{bw})		g
Tare Weight	$(m_{tf}),(m_{ta}')$			g	Additional Rinse Wt	(m_{ar})		g
Weight Gain	$(m_f),(m_a')$			mg	Bottle Tare Weight	(m_{tb})		g
Blank Adjustment	(W_a)			mg	Net Wash Weight	(m_{nw})		g
Total Particulates	(m_n)			mg	Blank Concentration	(C_a)		mg/g

Formulas Used

m_{ff} = average of last two filter measurements

m_{fa}' = average of last two acetone measurements

$m_f = m_{ff} - m_{tf}$

$m_a' = m_{fa}' - m_{ta}'$

$W_a = C_a m_{nw}$

$m_{nw} = m_{bw} + m_{ar} - m_{tb}$

$m_n = m_f + m_a' - W_a$

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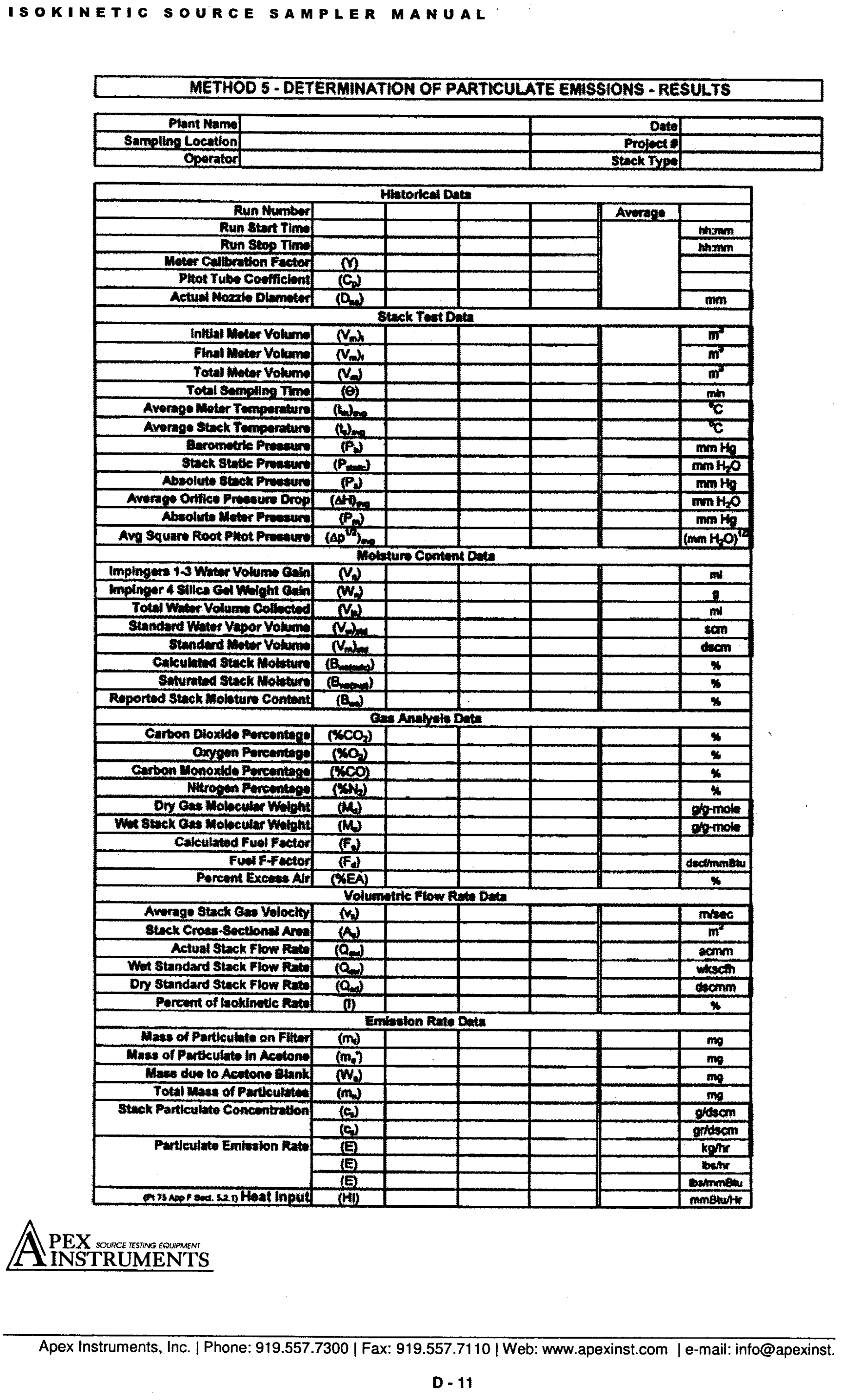
B13: USEPA reference method 5
Particle emission data sheet



ISOKINETIC SOURCE SAMPLER MANUAL

METHOD 5 - DETERMINATION OF PARTICULATE EMISSIONS - RESULTS

Plant Name		Date	
Sampling Location		Project #	
Operator		Stack Type	

Historical Data						
Run Number					Average	
Run Start Time						hh:mm
Run Stop Time						hh:mm
Meter Calibration Factor	(Y)					
Pitot Tube Coefficient	(C_p)					
Actual Nozzle Diameter	(D_{na})					mm
Stack Test Data						
Initial Meter Volume	$(V_m)_i$					m^3
Final Meter Volume	$(V_m)_f$					m^3
Total Meter Volume	(V_m)					m^3
Total Sampling Time	(Θ)					min
Average Meter Temperature	$(t_m)_{avg}$					°C
Average Stack Temperature	$(t_s)_{avg}$					°C
Barometric Pressure	(P_b)					mm Hg
Stack Static Pressure	(P_{static})					mm H_2O
Absolute Stack Pressure	(P_s)					mm Hg
Average Orifice Pressure Drop	$(\Delta H)_{avg}$					mm H_2O
Absolute Meter Pressure	(P_m)					mm Hg
Avg Square Root Pitot Pressure	$(\Delta p^{1/2})_{avg}$					$(mm\ H_2O)^{1/2}$
Moisture Content Data						
Impingers 1-3 Water Volume Gain	(V_a)					ml
Impinger 4 Silica Gel Weight Gain	(W_a)					g
Total Water Volume Collected	(V_{lc})					ml
Standard Water Vapor Volume	$(V_w)_{std}$					scm
Standard Meter Volume	$(V_m)_{std}$					dscm
Calculated Stack Moisture	$(B_{ws(calc)})$					%
Saturated Stack Moisture	$(B_{ws(sat)})$					%
Reported Stack Moisture Content	(B_{ws})					%
Gas Analysis Data						
Carbon Dioxide Percentage	$(\%CO_2)$					%
Oxygen Percentage	$(\%O_2)$					%
Carbon Monoxide Percentage	(%CO)					%
Nitrogen Percentage	$(\%N_2)$					%
Dry Gas Molecular Weight	(M_d)					g/g-mole
Wet Stack Gas Molecular Weight	(M_s)					g/g-mole
Calculated Fuel Factor	(F_o)					
Fuel F-Factor	(F_d)					dscf/mmBtu
Percent Excess Air	(%EA)					%
Volumetric Flow Rate Data						
Average Stack Gas Velocity	(v_s)					m/sec
Stack Cross-Sectional Area	(A_s)					m^2
Actual Stack Flow Rate	(Q_{aw})					acmm
Wet Standard Stack Flow Rate	(Q_{sw})					wkscfh
Dry Standard Stack Flow Rate	(Q_{sd})					dscmm
Percent of Isokinetic Rate	(I)					%
Emission Rate Data						
Mass of Particulate on Filter	(m_f)					mg
Mass of Particulate in Acetone	(m_a')					mg
Mass due to Acetone Blank	(W_a)					mg
Total Mass of Particulates	(m_n)					mg
Stack Particulate Concentration	(c_s)					g/dscm
	(c_s)					gr/dscm
Particulate Emission Rate	(E)					kg/hr
	(E)					lbs/hr
	(E)					lbs/mmBtu
(Pt 75 App F Sect. 5.2.1) Heat Input	(HI)					mmBtu/Hr

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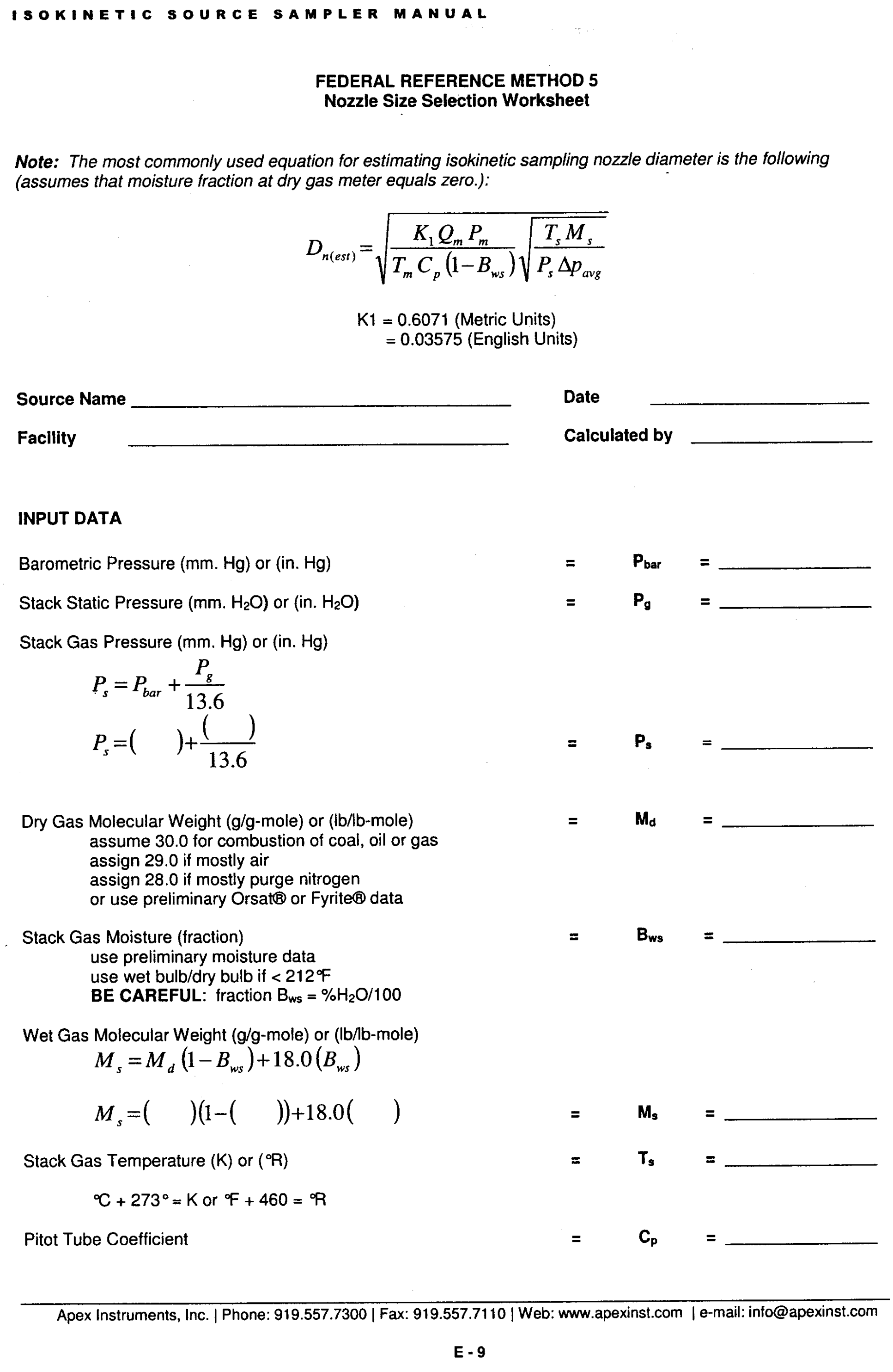
B14: USEPA reference method 5
Nozzle size selection worksheet



ISOKINETIC SOURCE SAMPLER MANUAL

FEDERAL REFERENCE METHOD 5
Nozzle Size Selection Worksheet

Note: *The most commonly used equation for estimating isokinetic sampling nozzle diameter is the following (assumes that moisture fraction at dry gas meter equals zero.):*

$$D_{n(est)} = \sqrt{\frac{K_1 Q_m P_m}{T_m C_p (1 - B_{ws})}} \sqrt{\frac{T_s M_s}{P_s \Delta p_{avg}}}$$

K1 = 0.6071 (Metric Units)
= 0.03575 (English Units)

Source Name ______________________ **Date** ______________

Facility ______________________ **Calculated by** ______________

INPUT DATA

Barometric Pressure (mm. Hg) or (in. Hg) = **P_{bar}** = ______________

Stack Static Pressure (mm. H_2O) or (in. H_2O) = **P_g** = ______________

Stack Gas Pressure (mm. Hg) or (in. Hg)

$$P_s = P_{bar} + \frac{P_g}{13.6}$$

$$P_s = (\quad) + \frac{(\quad)}{13.6}$$

= **P_s** = ______________

Dry Gas Molecular Weight (g/g-mole) or (lb/lb-mole) = **M_d** = ______________
assume 30.0 for combustion of coal, oil or gas
assign 29.0 if mostly air
assign 28.0 if mostly purge nitrogen
or use preliminary Orsat® or Fyrite® data

Stack Gas Moisture (fraction) = **B_{ws}** = ______________
use preliminary moisture data
use wet bulb/dry bulb if < 212°F
BE CAREFUL: fraction $B_{ws} = \%H_2O/100$

Wet Gas Molecular Weight (g/g-mole) or (lb/lb-mole)

$$M_s = M_d (1 - B_{ws}) + 18.0 (B_{ws})$$

$$M_s = (\quad)(1 - (\quad)) + 18.0(\quad)$$

= **M_s** = ______________

Stack Gas Temperature (K) or (°R) = **T_s** = ______________

°C + 273° = K or °F + 460 = °R

Pitot Tube Coefficient = **C_p** = ______________

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Nozzle Size Selection Worksheet
(continued)

Average Velocity Head (mm. H_2O) or (in. H_2O) = Δp_{avg} = ____________

v = calculation of inside square root term

$$v = \sqrt{\frac{T_s\, M_s}{P_s\, \Delta p_{avg}}}$$

$$v = \sqrt{\frac{(\quad)x(\quad)}{(\quad)x(\quad)}}$$

= v = ____________

Sampling Flow Rate (cfm or lpm) = Q_m = ____________
assume 0.75 cfm
assume 21.24 lpm

Dry Gas Meter Temperature (K or °R) = T_m = ____________
use ambient temp + 25°F + 460 = °R

Dry Gas Meter Pressure (mm Hg or in. Hg) = P_m = ____________
use P_{bar} + ($\Delta H_@$)/13.6

CALCULATION OF NOZZLE SIZE

Estimated Nozzle Diameter (mm or inches)

$$D_{n(est)} = \sqrt{\frac{K_1\, Q_m\, P_m}{T_m\, C_p\, (1 - B_{ws})}\sqrt{\frac{T_s\, M_s}{P_s\, \Delta p_{avg}}}}$$

$$D_{n(est)} = \sqrt{\frac{K_1\ x(\quad)x(\quad)x(\quad)}{(\quad)x(\quad)x\,(1-(\quad))}}$$

= $D_{n(est)}$ = ____________

K_1 = 0.6071 (Metric Units)
= 0.03575 (English Units)

Actual Nozzle Diameter Chosen (mm or inches) = D_n = ____________

Nozzle Size Selection Worksheet
(continued)

K-FACTOR CALCULATION

ΔH = Isokinetic Rate Orifice Pressure Differential

$$\Delta H = K x \Delta p$$

$$K = \frac{\Delta H}{\Delta p} = K_6\ D_n^4\ \Delta H_{@}\ C_p^2\,(1-B_{ws})^2\ \frac{M_d\,T_m\,P_s}{M_s\,T_s\,P_m}$$

$$K = \frac{\Delta H}{\Delta p} = K_6\ (\quad)^4\,(\quad)\,(\quad)^2\,(1-(\quad))^2\,\frac{(\quad)(\quad)(\quad)}{(\quad)(\quad)(\quad)} \qquad = \underline{\qquad\qquad}$$

K_6 = 8.038x10^{-5} (Metric Units)
= 846.72 (English Units)

CHECK CALCULATIONS FOR SUFFICIENT SAMPLE VOLUME AND ISOKINETIC RATE 90-110%

Stack Gas Velocity (m/s or ft/sec) = v_s = ______________
from preliminary velocity run
convert to m/min or ft/min **v_s x 60 sec/min** = $v_{s(fpm)\,or(mpm)}$ = ______________

Estimated Sampling Time (minutes) = θ = ______________

multiply number of traverse points by minutes/point = __________**total min.**

CALCULATION OF ACTUAL SAMPLING RATE

$Q_{m(std)}$ = Actual Sampling Rate (dscmm or dscfm)

$$Q_{m(std)} = \frac{100(1-B_{ws})P_s\ v_{s(fpm)or(mpm)}\ D_n^2}{1039T_s}$$

$$Q_{m(std)} = \frac{100(1-(\quad))(\quad)(\quad)(\quad)^2}{1039(\quad)} \qquad = \underline{\qquad\qquad}$$

$V_{m(std)}$ = Total Gas Sample Volume to be Collected (dscm or dscf)

$$V_{m(std)} = Q_{m(std)}\ x\ \theta \qquad = \underline{\qquad\qquad}$$

Based on applicable regulations for this source:

Will there be sufficient sample volume (dscf)? ☐ **yes** ☐ **no**

Will there be sufficient sampling time (minutes)? ☐ **yes** ☐ **no**

Nozzle Size Selection Worksheet
(continued)

Check Intermediate Isokinetic Sampling Rate

$$\%\mathrm{I}_i = \frac{100 T_s\, V_{m(std)}\, P_{std}}{60 T_{std}\, v_s\, \theta\, A_n\, P_s \left(1 - B_{ws}\right)} = \frac{K_4\, T_s\, V_{m(std)}}{P_s\, v_s\, A_n\, \theta \left(1 - B_{ws}\right)}$$

$$\%\mathrm{I}_i = \frac{K_4(\quad)(\quad)(\quad)}{(\quad)(\quad)(\quad)(\quad)(1-(\quad))}$$ = ______________

K_4 = 4.320 (Metric Units)
= 0.09450 (English Units)

Check Final Isokinetic Sampling Rate

A_n = Nozzle Area $\frac{\pi}{4} D_n^2$ = __________in^2 or mm^2

$$\%\mathrm{I}_f = \frac{100 T_{s(avg)} \left[K_3 V_{lc} + \left(\frac{V_{m(tot)}}{T_{m(avg)}} \right) \left(P_{bar} + \frac{\Delta H}{13.6} \right) \right]}{60\, \theta\, v_{s(avg)}\, P_s\, A_n}$$

$$\%\mathrm{I}_f = \frac{100(\quad) \left[K_3(\quad) + \left(\frac{(\quad)}{(\quad)} \right) \left((\quad) + \frac{(\quad)}{13.6} \right) \right]}{60(\quad)(\quad)(\quad)(\quad)}$$ = ______________

K_3 = 0.003454 (Metric Units)
= 0.002669 (English Units)

B15: USEPA Reference Method 4
Moisture content determination in stack gas

A. Preparation
   1. Use at least the following number of traverse points and locate them according to reference method-1.
      A) 8 for circular duct less than 60 cm (24 inches) diameter
      B) 9 for rectangular ducts less than 60 cm (24 inches) equivalent diameter
      C) 12 for all other cases
   2. Transfer about 100 ml of water into the first two impingers. Leave the third impinge empty, and weigh each impinge to ± 0.5g.
   3. Transfer about 200-300 g of silica gel into the fourth impinge, and weigh to ± 0.5 g.
   4. Determine the sampling rate to collect more than or equals to 0.741 sm3 (21 scf) at less than or equals to 21 lpm (0.75 cfm) simultaneously with the pollutant emission rate test run (and for the same length of time).
   5. If the gas stream is saturated or contains moisture droplets, attach a temperature sensor (± 1.3oC) to the probe or check the saturation moisture at the measured stack temperature.

B. Sampling
   1. Assemble and set up the sampling train (Isokinetic Source Sampler XC 500 Series, Apex Instruments Inc., USA).
   2. Turn on the probe heater and (if applicable) the filter heating system to temperatures of about 120oC. Allow time for the temperatures to stabilize. Place crushed ice in the ice box around the impingers.
   3. Check the leak of the sampling train
   4. Position the probe tip at the first traverse point. Sample at a constant flow rate. Record data on a field data sheet.
   5. Traverse the cross section, sampling at each traverse point for an equal period of time.
   6. Add more ice to maintain a temperature less than or equals to 20oC at the impinge exit.
   7. At the completion of sampling, disconnect the probe from the first impinge.

C. Sample recovery
   1. Disassemble the impinge glassware and weigh each impinge to ± 0.5 g. Record weighing data on field data sheet
   2. Verify constant sampling rate
   3. Calculate the stack moisture percentage

D. Moisture content of saturated stack gas
   1. Measure the stack gas temperature at each traverse point. Calculate the average stack gas temperature
   2. Determine the saturation moisture content by a) using saturation vapor pressure tables or equations or b) using a psychrometric chart and making appropriate corrections if stack pressure is different from that of chart
   3. Use the lower of this value or the value from Section C.

B16: High Volume Ambient PM$_{10}$ Sampler (Model 1200/VFC), Graseby Andersen, **USA**

Principle of operation

The Volumetric Flow Controller (VFC) is a dimensional venturi device used to control gas flow. When applied to a high volume air sampler, this flow control principal incorporates a smooth-wall venturi orifice that gradually opens to a recovery section. Vacuum is provided by a motor downstream of the venturi. Over 95% of the energy lost in differential pressures across the restricting orifice is recovered in this design.

Flow control is accomplished by occluding or restricting and thus accelerating the air flow through the venturi . At some point in the flow stream, the air velocity will equal the acoustic velocity or speed of sound, and critical flow will be achieved. As long as downstream changes are small, all conditions at the venturi (including the flow rate) are determined by upstream conditions. This condition is referred to as “chocking” and is a distinctive characteristic of all VFCs. The PM10/VFC utilizes this principle of choked or critical flow to maintain a constant actual flow rate of 40 ACFM (1.3ACMM) over the sample period. Since critical flow through the venturi is not greatly affected by changes in the filter loading, ambient temperature oo barometric pressure, a stable volumetric flow rate is maintained as long as power is provided to the sampler blower motor.

The orifice used in this system can also be described as a well documented Critical Venturi Meter (CVM). Basically, a CVM is a specially machined nozzle or restriction device designed to react to a specific pressure ratio expressed in absolute terms. When air reaches the speed of sound in the throat (smallest diameter) of the CVM, a sound pressure barrier is set up that will not allow more air through under the existing temperature and pressure conditions. This is the “critical flow” point of the meter, thus the name Critical Venturi Meter. Simply put, the Volumetric Flow controller regulates flow at a constant but unadjustable rate without any moving parts or electronic components.

Figure B8. Andersen High Volume PM$_{10}$ Sampler

Appendix-C

Calibration of the Equipments Used

Gas Analyzer Calibration (Calibration Date: February 19, 2013)

Before carrying out analysis of the stack gas, all the analyzers were calibrated against standard gases using dynamic gas calibrator and dilution controller. The model numbers of the analyzers calibrated and their working ranges are shown in Table c1.

Table c1. Manufacturer and working range of the analyzers used for this study

Analyzer	Manufacturer	Model number	Analysis Range
CO	Nova Analytical System Inc.	600-2-4-5	0-200 ppm
NO			0-100 ppm
NO_2			0-20 ppm
SO_2		600-8	0-20 ppm
O_2	Thermox Flue Gas Monitor, AMETEK	Series 2000	0-21 %
CO_2	Thermo Environmental Instruments Inc.	41 C	0-2000 ppm
Dynamic Gas Calibrator[1]		146C	_
Dilution Controller		200L	Dilution Factor: 100
CO Reactor		1150	_

The concentrations of the standard gases used for calibration of the gas analyzers are given in Table c2.

Table c2. Standard gas composition

Cylinder	Constituents	Composition
A	Nitric oxide (NO)	790 ppm
	Sulfur dioxide	770 ppm
	Carbon monoxide	730 ppm
	Nitrogen dioxide	770 ppm
	Nitrogen	Balance
B	Carbon dioxide	16.2 %
	Oxygen	2.02%
	Nitrogen	Balance

Zero air preparation:

Zero air was prepared from ambient air. The pollutants and moisture present in the ambient air were removed using different adsorption units and CO reactor.

Calibration System:

---

[1] *Gas mixtures of different concentrations are prepared with the help of this equipment using span gas and zero air*.

Block diagram of the calibration set-up using dynamic calibrator is shown in Figure c1.

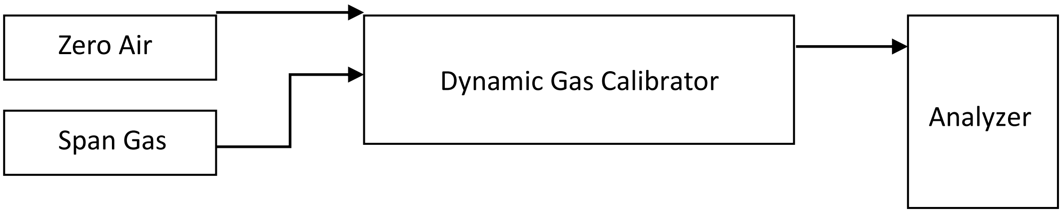

Figure c1: Block diagram of calibration set-up

Procedure of Calibration for Gas measuring modules:

- The instrument was allowed to warm up before starting any experiment.
- Zero point of the analyzer was calibrated using zero gas prepared earlier passing through the dynamic gas calibrator at a definite flow rate.
- The analyzer was calibrated within its working range of analysis by diluting the span gas with the help of zero air at a definite flow rate.

The same procedure was followed during the calibration of oxygen analyzer. Zero point was checked by pure nitrogen and the span gas was used for checking the correctness of the reading of the analyzer.
The dilution factor of the dilution controller was calibrated using span gas and zero air.
Calibration curves for different gas measuring modules are shown in Figures c2 to c7.

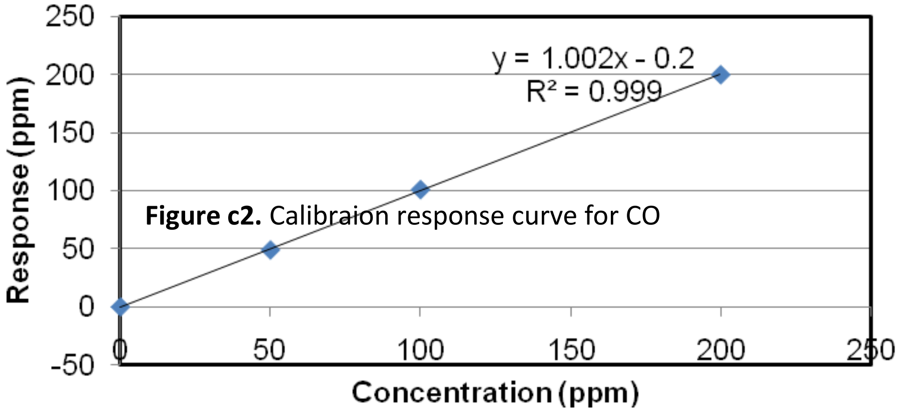

Figure c2. Calibraion response curve for CO

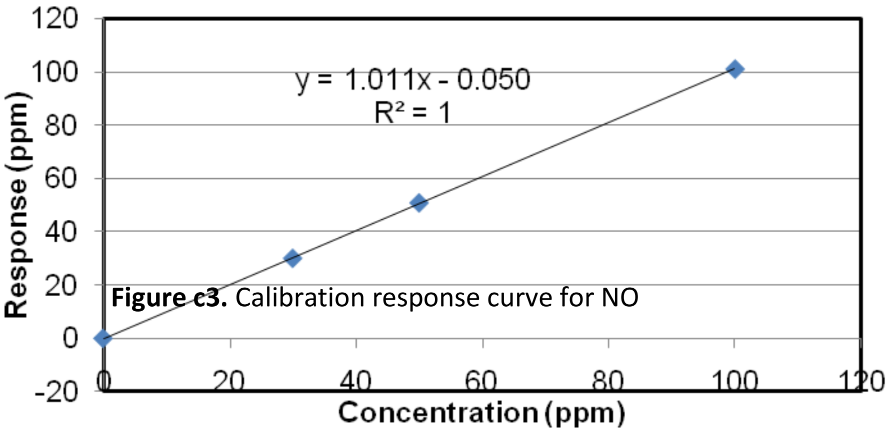

Figure c3. Calibration response curve for NO

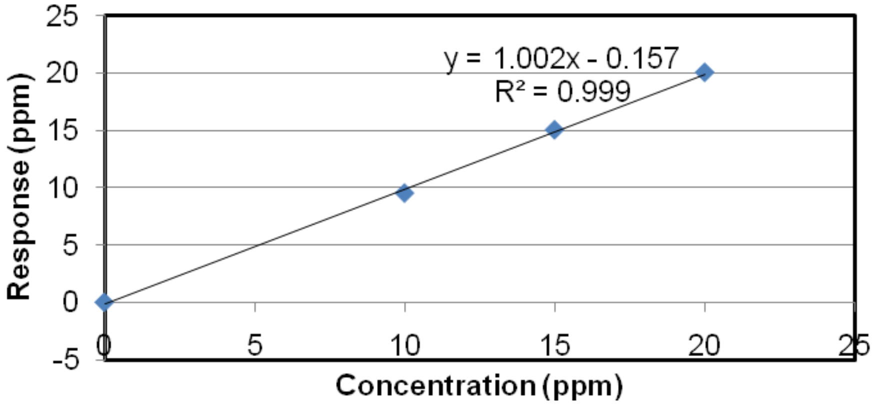

Figure c4. Calibration response curve for NO_2

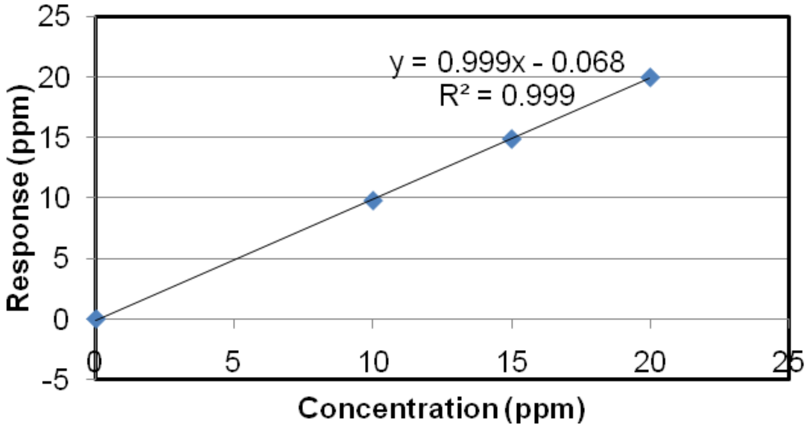

Figure c5. Calibration response curve for SO_2

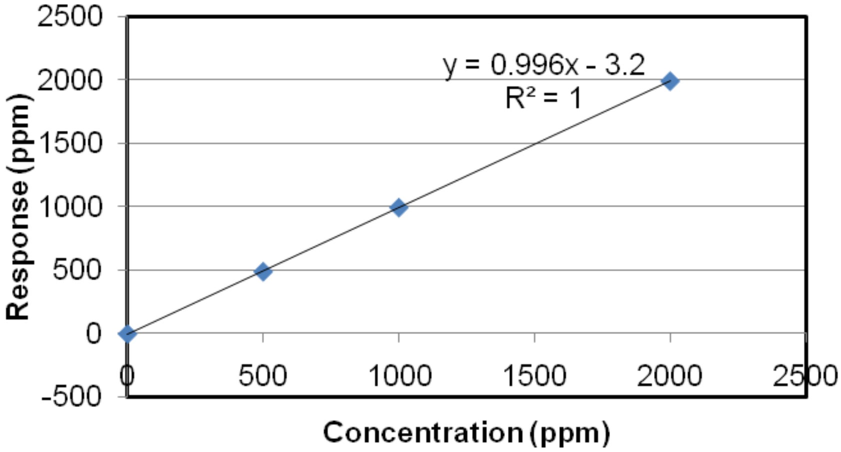

Figure c6. Calibration response curve for CO_2

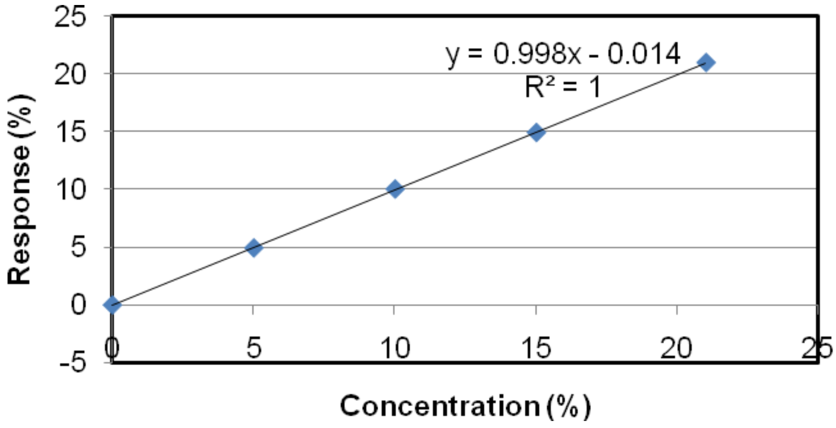

Figure c7. Calibration response curve for O_2

Flow Rate Calibration of Iso-kinetic sampler (Calibration Date: February 20, 2013)
Manufacturer: Apex Instruments, USA
Model No: 572

Table c3. Flow Calibration Data for Iso-kinetic Sampler

Obs. No.	**Source Sampler Console Meter Reading (L/min)**	**Wet Gas Meter Reading (L/min)**	**Dry Gas Flow rate after water vapor correction (L/min)**	**Correction Factor, Y**	**Average Correction Factor**
01	16.90	17.39	17.078	1.0106	1.0037
02	19.00	19.30	18.95	0.9976	
03	21.05	21.37	20.98	0.9970	
04	22.23	22.53	22.45	1.01	

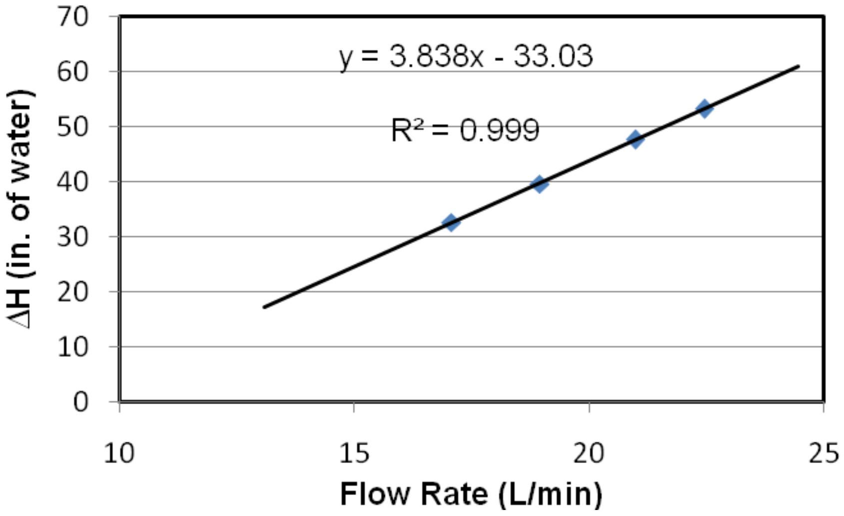

Figure c8. Sampler orifice pressure differential vs. actual flow rate

Isokinetic Sampler Flow Calibration Procedure

i. The suction inlet of the isokinetic sampler was connected with the outlet of a standard wet gas flow meter keeping the inlet open to ambient air. Air was sucked through the inlet of the wet test meter and passed through the isokinetic sampler at a set flow rate.
ii. The wet gas flow meter reading was taken for a fixed time and the saturated vapor pressure correction was applied to this flow rate of wet test meter to get the actual dry gas flow rate. Also, corresponding flow rate through the dry gas meter and orifice pressure differential of isokinetic sampler were measured.
iii. For Calibration Factor Y, the ratio of the corrected (saturated vapor pressure corrected) reading of the calibration meter (wet test meter) to the dry gas meter of the isokinetic sampler was calculated.
Therefore the average correction factor was obtained. If the average correction factor is multiplied with sampler console meter reading, corrected/actual volumetric flow rate can be obtained. Actual volumetric flow rate can also be obtained using Figure c8 just by using sampler orifice pressure differential.

Flow Rate Calibration of High Volume Sampler (Calibration Date: February 23, 2013)
Manufacturer: Graseby Andersen
Model No: 1200 /VFC HVPM10
Orifice ID: G28A

Orifice relationship: $Q(orifice) = \frac{1}{m}[\sqrt{\Delta P(\frac{T_a}{P_a})} - b]$

Where, m=0.9171 and b=-0.007585, Ta=ambient temperature, K, Pa=ambient pressure, inch of H_2O, ΔP=orifice pressure differential

Sampler Calibration

Table c4. Sampler calibration worksheet (T_a= 303 K, P_a= 754 mm Hg)

No.	Orifice Pressure differential inch of H_2O	Actual flow rate through standard orifice ambient condition Qo (m^3/min)	Sampler Pressure differential inch of H_2O, (Pf)	P0/Pa = (1-Pf/Pa)	Actual Sampler flow rate(Equation), Q_a (m^3/min)	Diff (%)
1	3	1.1935	8.8	0.9782	1.1927	0.06
2	2.86	1.1651	13	0.9678	1.1657	0.05
3	2.76	1.1445	16.2	0.9599	1.1451	0.06
4	2.64	1.1191	20.5	0.9492	1.1175	0.15
5	2.48	1.0844	25.8	0.9361	1.0834	0.10

Relationship between pressure ratio (Po/Pa) and actual flow rate through sampler is shown on Figure c8.

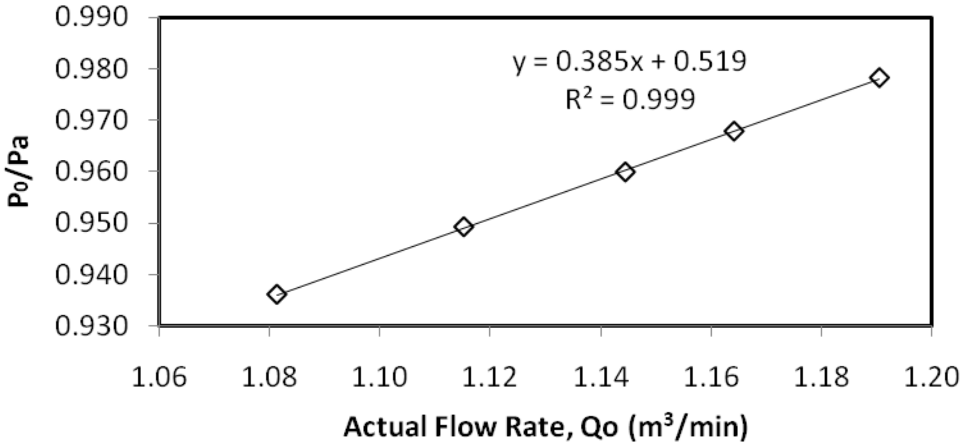

Figure c8. Actual sampler flow rate vs pressure ratio

Sampler calibration relationship: $\frac{P_0}{Pa} = 0.385\ Q_a + 0.519$

Slop, m = 0.385,   Intercept, b = 0.519

Calibration of Semi-micro balance

Model: AUW220D by Shimadzu, Japan (Dual range auto-calibration)
Capacity: 220g/82g, Minimum display: 0.1 mg/0.01 mg
The balance is automatically calibrated with two inbuilt standard weights.
Two control charts of the balance are shown in Figures c9 and c10.

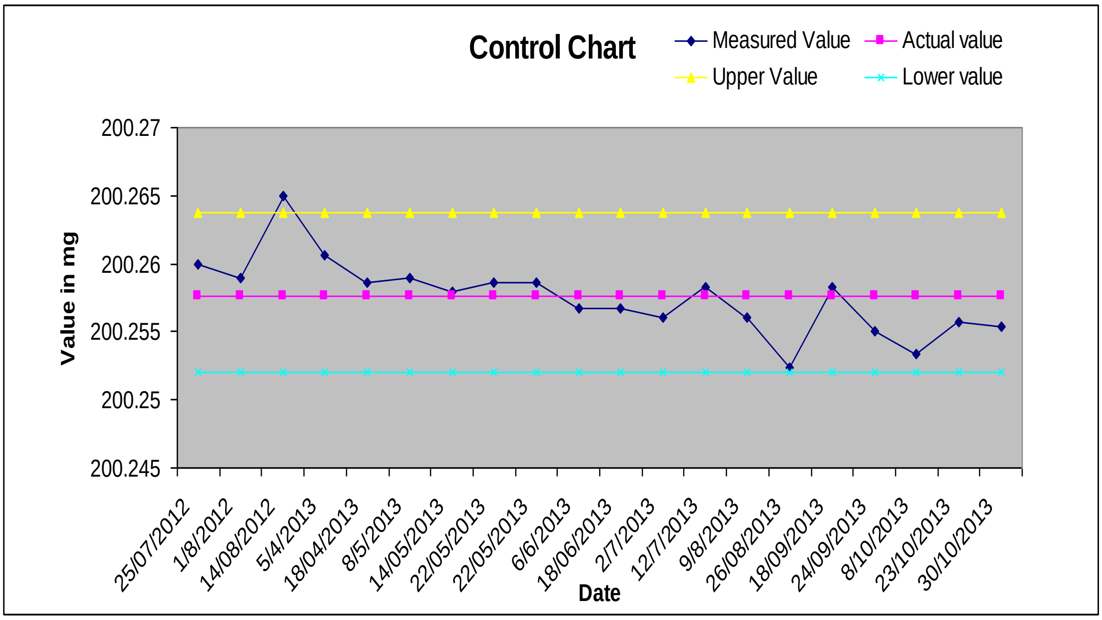

Figure c9. Control chart for standard weight 200.258 with 2 STD.

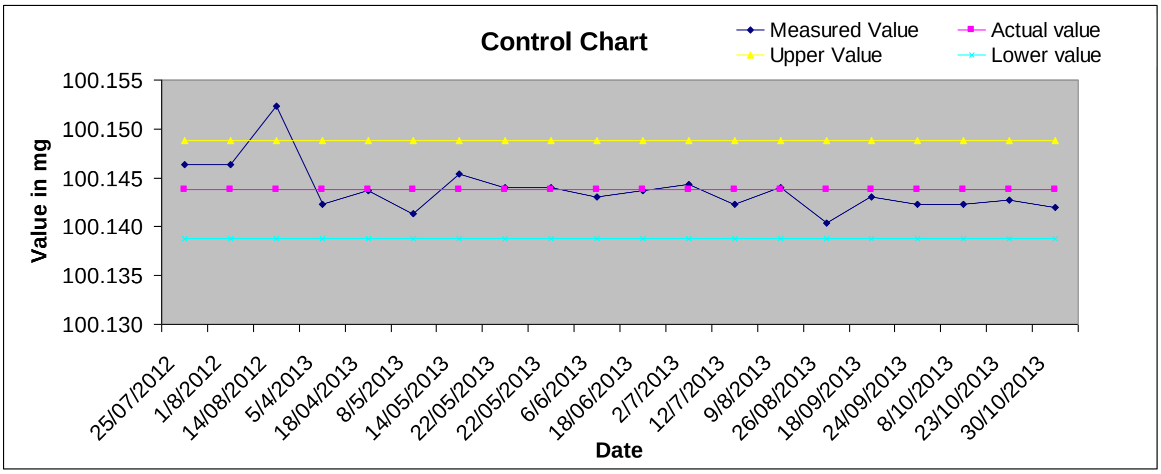

Figure c10. Control chart for standard weight 100.144 with 2 STD

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ABSTRACT

As part of the Bangladesh Air Pollution Studies (BAPS) under Clean Air & Sustainable Environment Project (CASE), stack emission measurements were made on several days at a steel mill and a ceramic industry, both located in the outskirts of Dhaka city. The measurements were made by ChE-BUET Team of the Bangladesh University of Engineering & Technology (BUET), Dhaka. The team has access to all the sophisticated equipment and expertise for emission measurements at industrial stacks. All equipment used were calibrated as per manufacturers' instructions. USEPA/ASTM approved methods were followed for all measurements.

NORWEGIAN TITLE

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