



Casting Emission Reduction Program

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Method Comparison

Dilution Tunnel Sampling System and Impinger Method 201A/202

for the

Determination of Condensable,

Particulate Matter

from a Ferrous

Metal Foundry

Technikon # 1410-212 GA

August 2004

(revised for public distribution)

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UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

DAIMLER CHRYSLER *Ford Motor Company* General Motors

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Executive Summary

Field results suggest that the Method 202 work up of Method 5 and Method 201A impinger solutions greatly overestimate condensible particulate material emitted from stacks. An alternative sampling method that uses a dilution tunnel better reproduces the physicochemical processes experienced by emissions as they exit a stack, and can therefore more accurately measure stack emissions. The sampling methodology of a dilution tunnel permits both condensible and filterable particulate to be collected simultaneously. This report contains the results of preliminary testing to evaluate and compare the two sampling methodologies (Method 201A/202 and dilution tunnel) for the collection of particulate emissions from pouring, cooling, and shakeout processes using a No-Bake® phenolic urethane mold with 1.8% binder. The impinger method for collection of condensible particulate matter, based on a modified EPA Method 201A/202 protocol, was conducted by Technikon, LLC personnel, while the Dilution Tunnel Sampling Method was operated by personnel from Desert Research Institute (DRI). The DRI Source Dilution Sampling System is similar to that of EPA Conditional Test Method 39. Testing was conducted at Technikon's Research Foundry. Emission results are reported in both pounds of particulate matter (PM) per ton of metal poured and pounds of analyte per pound of binder used.

The testing performed involved the simultaneous collection of continuous stack samples using both a modified Method 201A/202 sampling train and a Dilution Tunnel Sampling train in a parallel sampling configuration over a seventy-five minute process period that included metal pouring, cooling, shakeout, and post shakeout intervals. PM emission samples from both methods were collected on filters and analyzed gravimetrically. Condensible PM (CPM) was collected in the impinger portion of a Method 5 type sampling train for the modified Method 201A/202. Additionally, particulate matter less than 2.5 μm in aerodynamic diameter (PM_{2.5}) from the Dilution Tunnel Sampling Method was analyzed for 40 elements using energy dispersive x-ray fluorescence (ED-XRF), organic and inorganic carbon was determined by a DRI Model 2001 thermal/optical carbon analyzer, and particle size and number distributions were measured by an Electric Low Pressure Impactor (ELPI) that collected data continuously during testing. Ion chromatography was used for the analysis of gaseous ammonia and chloride, nitrate, sulfate, and ammonia ions.

Process and stack parameters were measured and included the weights of the casting and mold; Loss on Ignition (LOI) values for the mold prior to the test; metallurgical data; and stack temperature, pressure, volumetric flow rate and moisture content. The process parameters were maintained within prescribed ranges in order to ensure the reproducibility of the sampling runs. Continuous monitoring of the total gaseous organic concentration (TGOC) of the emissions was conducted according to US EPA Method 25A. The mass emission rate of each parameter or target compound was calculated using laboratory analytical results, the measured source data, the weight of binder used and the weight of each casting.

Results from the Method 201A/202 samples were two (2) to seven (7) times the comparable dilution sampling results.

It must be noted that the results from the reference and product testing performed are not suitable for use as emission factors or for other purposes other than evaluating the relative emissions associated with the use of alternative materials, equipment, or manufacturing processes. The emissions are unique to the

specific castings produced, materials used, and testing methodology associated with these tests. These measurements should not be used as the basis for estimating emissions from actual commercial foundry applications.

1.0 Introduction

1.1 Background

Technikon LLC is a privately held contract research organization located in McClellan, California, a suburb of Sacramento. Technikon offers emissions research services to industrial and government clients specializing in the metal casting and mobile emissions areas. Technikon operates the Casting Emission Reduction Program (CERP). CERP is a cooperative initiative between the Department of Defense (US Army) and the United States Council for Automotive Research (USCAR). Its purpose is to evaluate alternative casting materials and processes that are designed to reduce air emissions and/or produce more efficient casting processes. Other technical partners directly supporting the project include: the American Foundry Society (AFS); the Casting Industry Suppliers Association (CISA); the US Environmental Protection Agency (US EPA); and the California Air Resources Board (CARB).

1.2 Technikon Objectives

The primary objective of Technikon is to evaluate materials, equipment, and processes used in the production of metal castings. Technikon's facility was designed to evaluate alternate materials and production processes designed to achieve significant air emission reductions, especially for the 1990 Clean Air Act Amendment. The facility has two principal testing arenas: a Research Foundry designed to measure airborne emissions from individually poured molds, and a Production Foundry designed to measure air emissions in a continuous full scale production process. Each of these testing arenas has been specially designed to facilitate the collection and evaluation of airborne emissions and associated process data.

The Research Foundry provides simultaneous detailed individual emission measurements following methods based on US EPA protocols for the melting, pouring, sand preparation, mold making, and core making processes.

It must be noted that the reference and product testing performed is not suitable for use as emission factors or for purposes other than evaluating the relative emission reductions associated with the use of alternative materials, equipment, or processes. The emissions measurements are unique to the specific castings produced, materials used, and testing methodology associated with these tests, and should not be used as the basis for estimating emissions from actual commercial foundry applications.

1.3 Report Organization

This report has been designed to document the methodology and results of a specific test plan that was used to evaluate and compare particulate emissions from two different stack PM collection methods. Section 2 of this report includes a summary of the methodologies used for data collection and analysis, emission calculations, QA/QC procedures, and data management and reduction methods. Specific data collected during this test are summarized in Section 3 of this report, with detailed data included in Appendix B of this report. Section 4 of this report contains a discussion of the results.

Appendix A contains the detail of the approved test and sampling plans. Detailed emissions data are presented in Appendix B. Process data for the test is included in Appendix C of this report. Appendix D contains the report submitted to Technikon by DRI. Appendix E is a glossary of terms.

The raw data for this test series are included in a data binder that is maintained at the Technikon facility.

1.4 Specific Test Plan and Objectives

The objectives sought in this test were to demonstrate and qualitatively measure the gravimetric differences between the impinger catch from a modified Method 201A/202 method and the particulate sampled using a Dilution Tunnel Sampling Method for emissions from the casting process. Table 1-1 provides a summary of the test plan.

Table 1-1 Test Plan Summary

	Test Plan
Type of Process Tested	Comparison of Particulate Matter from Impinger Residue and Dilution Tunnel Method Filter Catch
Test Plan Number	1410 220 GA
Parting Spray System	None
Metal Poured	Iron
Casting Type	4 on Gear
Number of Molds Poured	8
Test Dates	2/24/04 - 2/27/04
Emissions Measured	Particulate Matter, TGOC, 40 Elements, Organic and Elemental Carbon, soluble ions
Process Parameters Measured	Total Casting and Mold Weights, Metallurgical data, % LOI, Stack Temperature, Moisture Content, Sand Temperature, Pressure, and Volumetric Flow Rate

2.0 Test Methodology

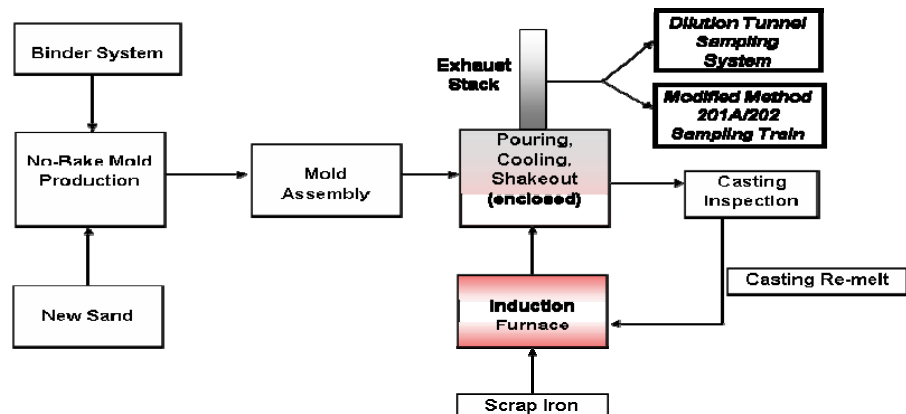
2.1 Description of Process and Testing Equipment

Current EPA methods for sampling PM emissions from stationary sources utilize filters and/or impinger trains for catching both filterable and condensible particulates. In general, the exhaust is withdrawn isokinetically from the source and either total PM or PM10 is collected on a glass fiber filter maintained at a specified temperature, and/or the gas stream passes through a series of water impingers to collect condensible PM. The PM mass is determined from the summation of the mass of particles collected on the filter and the mass of PM condensate after the removal of water. The impinger methods generally are thought to overestimate PM emissions because non-condensable gases as well as condensed particles are collected in the impinger train. It is also believed that stand alone filter methods generally underestimate PM because vapors which can nucleate or grow upon cooling and dilution after emission from the stack are not accounted for.

The Dilution Tunnel Sampling Method was developed to remedy these discrepancies. Dilution tunnel methods of this type have the potential to more accurately represent particulate concentrations from stack emissions as they better simulate the natural processes of particulate formation in the atmosphere. In these methods, after leaving the stack, hot exhaust is rapidly cooled and mixed with ambient air allowing gases to nucleate both homogeneously and heterogeneously, and condense on pre-existing particles in processes analogous to those that occur naturally in the atmosphere.

In this test, simultaneous collection of continuous stack emissions was accomplished using a modified Method 201A/202 Sampling train (particle cyclone separator followed by an inline glass fiber filter and impinger train) and a Dilution Tunnel Sampling System in a parallel sampling configuration. A standard button hook type sampling probe was used to isokinetically remove sample from the stack. At the probe outlet, a “Y” connector split the flow into the inlets of both sampling trains. A schematic of the foundry and sampling components is shown in Figure 2-1.

Figure 2-1 Research Foundry Process



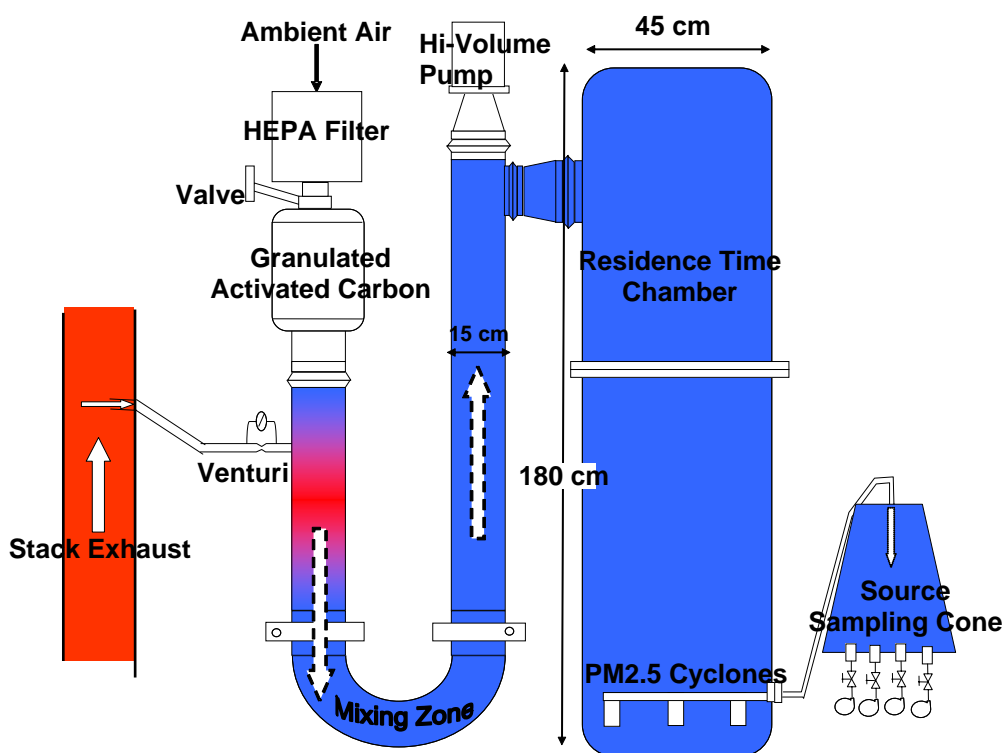
The DRI dilution tunnel system, referred to as The DRI Source Dilution Sampling System and shown schematically in Figure 2-2, draws 20-25 liters per minute (lpm) of sample through a venturi flow meter. Concurrently, ambient air at a flowrate sufficient to obtain a predetermined target dilution ratio passes through a high-efficiency

particle arresting (HEPA) filter to remove PM, followed by a granulated activated carbon (GAC) bed to remove gaseous species and volatilized PM. The clean, cool ambient air is mixed with the sample gas. At the end of the mixing zone, the diluted sample is drawn into an aging chamber where nucleation and particle growth may occur.

At the outlet of the aging chamber, PM larger than $2.5 \mu\text{m}$ in aerodynamic diameter is removed by PM_{2.5} cyclones. To better correlate resultant particulate masses between the two methods, a modified Method 201A/202 that also utilized a PM_{2.5} cyclone was employed for several of the runs.

To ensure the collection of sufficient condensible particulate matter for gravimetric analysis in the impinger train, several runs were sampled for the duration of two mold processes, whereas one mold process supplied sufficient sample for the dilution tunnel. Each discrete mold process consisted of a seventy-five minute test period that included metal pouring, cooling, shakeout, and post shakeout phases.

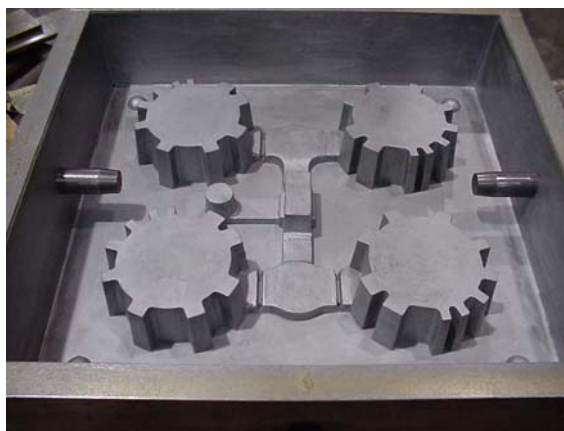
Figure 2-2 DRI Source Dilution Sampling System



2.2 Description of Testing Program

The specific steps used in this sampling program are summarized below:

1. **Test Plan Review and Approval:** The proposed test plan was reviewed and approved by the Technikon staff.
2. **Mold and Metal Preparation:** The 4-on irregular gear No-Bake® molds were prepared to a standard composition by the Technikon production team. Iron was melted in a 1000 lb. Ajax induction furnace. The amount of metal melted was determined from the poured weight of the casting and the number of molds to be poured. The metal composition was prescribed by a metal composition worksheet. The weight of metal poured into each mold was recorded on the process data summary sheet.
3. **Individual Sampling Events:** Replicate tests were performed on eight (8) mold packages. The mold packages were placed into an enclosed test stand that was heated to approximately 85°F. Iron was poured through an opening in the top of the emission enclosure.



4-On Gear Pattern



Continuous emission samples for the Method 201A/202 Sampling train and the Dilution Tunnel Sampling System were simultaneously collected during the forty-five minute pouring and cooling process, during the fifteen-minute shakeout of the mold, and for an additional fifteen minute period following shakeout. The total sampling time was seventy-five minutes.



Parallel Sampling Setup

4. **Process Parameter Measurements:** Table 2-1 lists the process parameters that were monitored during each test. The analytical equipment and methods used are also listed.

Table 2-1 Measured Process Parameters

Parameter	Analytical Equipment and Methods
Mold Weight	Cardinal 748 Platform Scale (Gravimetric)
Casting Weight	Ohaus MP-2 Platform Scale (Gravimetric)
Binder Weight	Ohaus MP-2 Platform Scale (Gravimetric)
LOI, % at Mold and Shakeout	Denver Instruments XE-100 Analytical Scale (AFS procedure 5100-00-S)
Metallurgical Parameters	
Pouring Temperature	Electro-Nite DT 260 (T/C Immersion Pyrometer)
Carbon/Silicon and Fusion Temperature	Electro-Nite DataCast 2000 (Thermal Arrest)
Alloy Weights	Ohaus MP2 Scale
Mold Compactability	Dietert 319A Sand Squeezer (AFS Procedure 2221-00-S)

5. **Air Emissions Analysis:** The specific sampling and analytical methods used in the Research Foundry tests are based on the US EPA reference methods shown in Table 2-2. The details of the specific testing procedures and their variance from the reference methods are included in the Technikon Standard Operating Procedures.

Table 2-2 Emission Sampling and Analytical Methods

Measurement Parameter	Test Method*
Port Location	EPA Method 1
Number of Traverse Points	EPA Method 1
Gas Velocity and Temperature	EPA Method 2
Filterable and Condensable PM	EPA Method 201A/202 and dilution tunnel sampling
VOCs Concentration	EPA Method 25A

*These methods were specifically modified to meet the testing objectives of the CERP Program.

6. **Data Reduction, Tabulation and Preliminary Report Preparation:** The analytical results of the emissions tests provided the mass of filterable and/or condensible particulate in the sample. Filterable PM was determined gravimetrically. CPM was determined by weighing the residues of the organic and aqueous extracted fractions from the impinger train. The sum of both fractions represents the total CPM for the impinger train method. PM collected and measured from the dilution tunnel method represents both filterable and condensible particulate. The mass of the analyte emitted was calculated by multiplying the mass of analyte in the sample with the ratio of total stack gas volume to sample volume. The total stack gas volume was calculated from the measured stack gas velocity and duct diameter, and corrected to dry standard conditions using the measured stack pressures, temperatures, gas molecular weight and moisture content. The total mass of analyte was then divided by the weight of the casting obtained or binder used to provide emissions data in pounds of analyte per ton of metal and pounds of analyte per pound of binder.

The results of each of the sampling events are included in Appendix B of this report. The results of each test are also shown in Tables 3-1 through 3-3.

7. **Report Preparation and Review:** The Preliminary Draft Report is reviewed by the Process Team and Emissions Team to ensure its completeness, consistency with the test plan, and adherence to the prescribed QA/QC procedures. Appropriate observations, conclusions and recommendations are added to the report to produce a Draft Report. The Draft Report is reviewed by the Vice President-Measurement Technologies, the Vice President-Operations, the Manager-Process Engineering, and the Technikon President. Comments are incorporated into a draft Final Report prior to final signature approval and distribution.

2.3 Quality Assurance and Quality Control (QA/QC) Procedures

Detailed QA/QC and data validation procedures for the process parameters, stack measurements, and laboratory analytical procedures are included in the Technikon Emissions Testing and Analytical Testing Standard Operating Procedures. In order to ensure the timely review of critical quality control parameters, the following procedures are followed:

- Immediately following the individual sampling events performed for each test, specific process parameters are reviewed by the Manager - Process Engineering to ensure that the parameters are maintained within the prescribed control ranges. Where data are not within the prescribed ranges, the Manager - Process Engineering and the Vice President - Operations determine whether the individual test samples should be invalidated or flagged for further analysis following review of the laboratory data.
- The source (stack) and sampling parameters, analytical results and corresponding laboratory QA/QC data are reviewed by the Emissions Measurement Team to confirm the validity of the data. The VP-Measurement Technologies reviews and approves the recommendation, if any, that individual sample data should be invalidated. Invalidated data are not used in subsequent calculations.
- After each sampling run, filters and other PM collected from the sampling train and sample cone were placed in clean sample bags or vials and jars as appropriate, and stored at reduced

temperature. Both the filterable and condensible PM were weighed and extracted as soon as possible after testing.

3.0 Test Results

The average PM emission results for the modified Method 201A/202, in pounds per ton of metal poured and pounds per pound of binder, are presented in Tables 3-1 and 3-2, respectively, for six of the eight pours. The tables include calculated lb/ton and lb/lb values for both filterable and condensible particulate from the various collected size fractions, as well as the organic and inorganic components extracted from the condensible fraction collected from the impinger train.

Table 3-3 includes PM results for the dilution tunnel method for five of the eight pours. A direct comparison of the mass ratio of the PM_{2.5} size fraction for both methods, which includes filterable and condensible portions, is included in Table 3-4. PM data from the first two pours, sample numbers GA-1A and 1B, were suspect due to plugging of the filter and are therefore not included in these tables. Sample number GA-2A included data only from the pouring and partial cooling of the mold due to a power failure from an area-wide blackout caused by bad weather. However, this shortened pour presented a unique opportunity to measure the PM resulting from these two processes alone, without the contribution from the shakeout process. In addition, sampling for this test used only a PM 10 cyclone, whereas the later tests used both PM 10 and PM 2.5 cyclones.

Table 3- 5 is a summary of the averages of the key process parameters during each mold.

Figures 3-1 to 3-4, and Figure 3-6 to 3-7 present the emissions data from Tables 3-1 to 3-5 in graphical form. Figure 3-5 shows representative chemical analysis of the PM collected by the Dilution Tunnel Sampling Method, in this case for sample GA-3A. Figure 3-8 compares the PM 2.5 mass distribution for nine Size fractions. Additional analysis, including elemental analysis, carbon analysis, and ELPI results for PM_{2.5} mass fractions are presented and discussed in detail in the Final Report from DRI attached as Appendix D to this report.

**Table 3-1 Summary of Test GA
Average PM Emission Results from
Impinger Method – lb/tn Metal**

Sample Number	GA 2A	GA 3A & 3 B	GA 3C	GA 4A & 4B
>PM10	0.0915	6.5804	4.2558	6.1784
PM10	1.2377	NA	NA	NA
2.5<PM<10	NA	0.5951	0.4552	0.4078
PM2.5	NA	0.3647	0.3044	0.5354
Post Impinger Filter	0.0967	0.0033	0.0000	0.0058
Condensibles	1.2585	4.2948	3.0748	3.4106
Total <PM2.5	1.3551	4.6628	3.3792	3.9518
Total Filterable	1.4259	7.5435	5.0154	7.1275
Total PM	2.6844	11.8384	8.0902	10.5380
Total <PM10	2.5929	5.2580	3.8344	4.3596
Organic	1.2188	4.2249	2.9734	3.2695
Aqueous	0.0397	0.0699	0.1015	0.1411

**Table 3-2 Summary of Test GA
Average PM Emission Results from
Impinger Method – lb/lb Binder**

Sample Number	GA 2A	GA 3A & 3 B	GA 3C	GA 4A & 4B
>PM10	0.0010	0.0595	0.0344	0.0644
PM10	0.0129	NA	NA	NA
2.5<PM<10	NA	0.0054	0.0037	0.0043
PM2.5	NA	0.0033	0.0025	0.0056
Post Impinger Filter	0.0010	0.0000	0.0000	0.0001
Condensibles	0.0131	0.0388	0.0249	0.0356
Total <PM2.5	0.0141	0.0422	0.0273	0.0412
Total Filterable	0.0149	0.0682	0.0406	0.0743
Total PM	0.0280	0.1071	0.0654	0.1099
Total <PM10	0.0270	0.0476	0.0310	0.0454
Organic	0.0127	0.0382	0.0240	0.0341
Aqueous	0.0004	0.0006	0.0008	0.0015

**Table 3-3 Summary of Test GA
Average PM2.5 Emission Results
Dilution Tunnel Method**

Dilution Tunnel Summary		
Sample Number	lb/tn metal	lb/lb binder
GA-2A	0.1944	0.0020
GA-3A	1.1980	0.0127
GA-3C	0.8355	0.0068
GA-4A	1.8303	0.0194
GA-4B	1.2248	0.0126

**Table 3-4 Comparison Summary of
Test GA Average PM2.5 Emission
Results from Impinger Method to
Dilution Tunnel Method**

Ratio Impinger Method to Dilution Tunnel		
Sample Number	lb/tn metal	lb/lb binder
GA-2A	6.97	7.07
GA-3A	3.89	3.32
GA-3C	4.04	4.04
GA-4A	2.16	2.13
GA-4B	3.23	3.28

Table 3-5 Summary of Test Plan GA Average Key Process Parameters

No-Bake® Mix/Make/Cure	Test Dates				
	2/24/04	2/25/04	2/26/04	2/26/04	2/27/04
Emissions Sample #	Average GA01a,b	Average GA02a	Average GA03a,b	Average GA03c	Average GA04a,b
Production Sample #	GA01,2	GA03	GA04,5	GA06	GA07,8
Sand Dispensing Rate, lbs/15 sec	30	30	30	30	30
Binder Part 1 + Part 3 Programmed Average Dispensing Rate, gms/15 sec	136.1	136.1	136.1	136.1	136.1
Binder Part 2 Programmed Average Dispensing Rate, gms/15 sec	110.8	110.8	110.8	110.8	110.8
Calculated Standard % Binder	1.78	1.78	1.78	1.78	1.78
Calculated % Binder (BOS)	1.81	1.81	1.81	1.81	1.81
Mold Weight, lbs	332.0	328.5	327.8	332.0	329.4
Calculated Total Binder Weight, lbs	5.91	5.85	5.84	5.91	5.86
1800F LOI, %	1.90	1.81	1.59	1.73	1.75
Sand Temperature, deg F	ND	ND	ND	ND	ND
Dogbone Core 2 hr. Tensile Strength, psi	94	98	74	110	78
No-Bake® PCS					
Emissions Sample #	Average GA01a,b	GA02a	Average GA03a,b	GA03c	Average GA04a,b
Production Sample #	GA01,2	GA03	GA04,5	GA06	GA07,8
Pouring Temp, deg F	2623	2721	2635	2623	2637
Pouring Time, sec.	48	68	41	29	44
Cast Weight (all metal inside mold), lbs.	120.8	122.0	105.5	95.6	113.9
Process Air Temperature in Hood, deg F	119	124	121	134	123
Mold Temperature when placed in hood, deg F	ND	ND	ND	ND	ND
Ambient Temperature, deg F	67	64	66	66	66
Mold Age When Poured, hr	22	43	55	48	39
Test Length, min	75	36	75	75	71

Note 1: Power outage after 36 minutes

Note 2: GA05, 6 only three cavities filled.

Note 3: Pyrometer was read as 2621: actual 2721

**Note 1
Note 3**

Note 2

Note 2

Figure 3-1 Graphical Summary of Test GA Average PM Emission Results from Impinger Method – Relative Percent lb/tn Metal

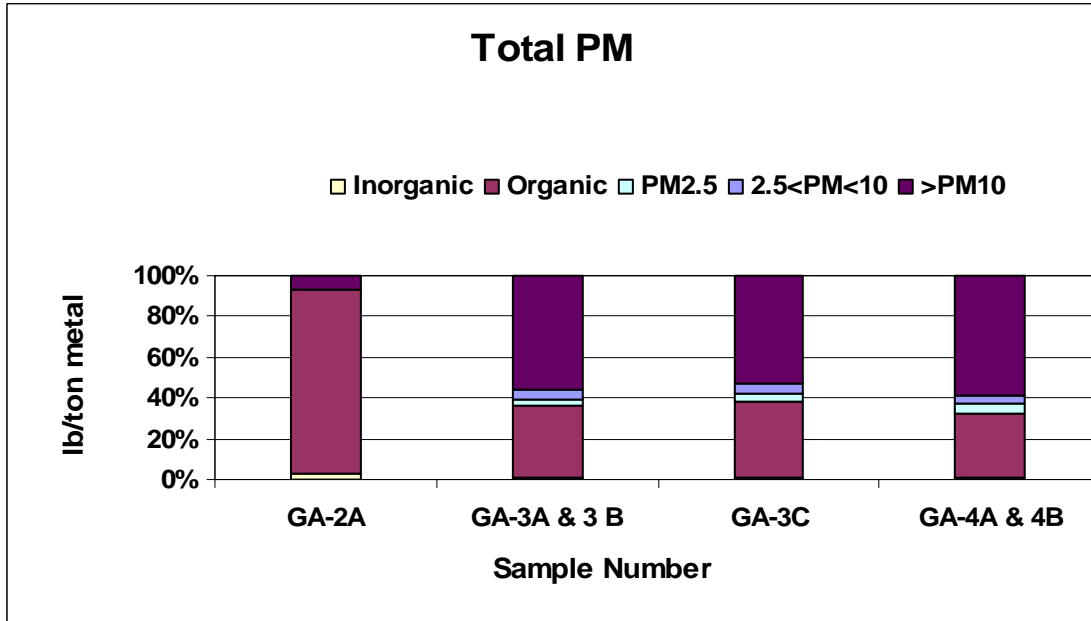


Figure 3-2 Graphical Summary of Test GA Average PM Emission Results from Impinger Method – Relative Percent lb/lb Binder

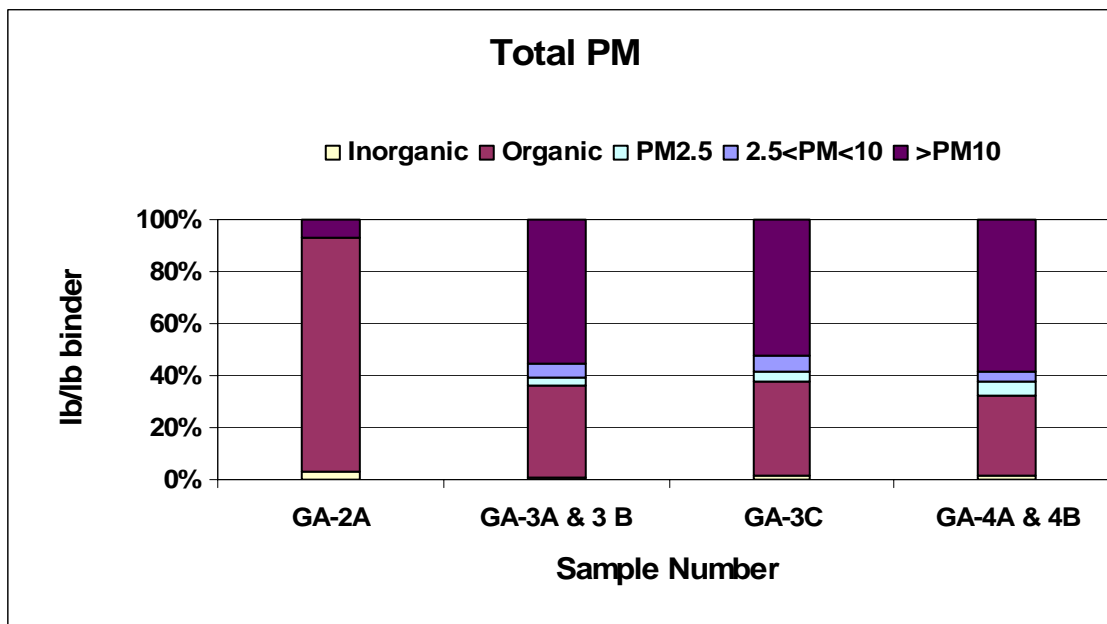


Figure 3-3 Graphical Summary of Test GA Average PM Emission Results from Dilution Tunnel Method – lb/ton Metal

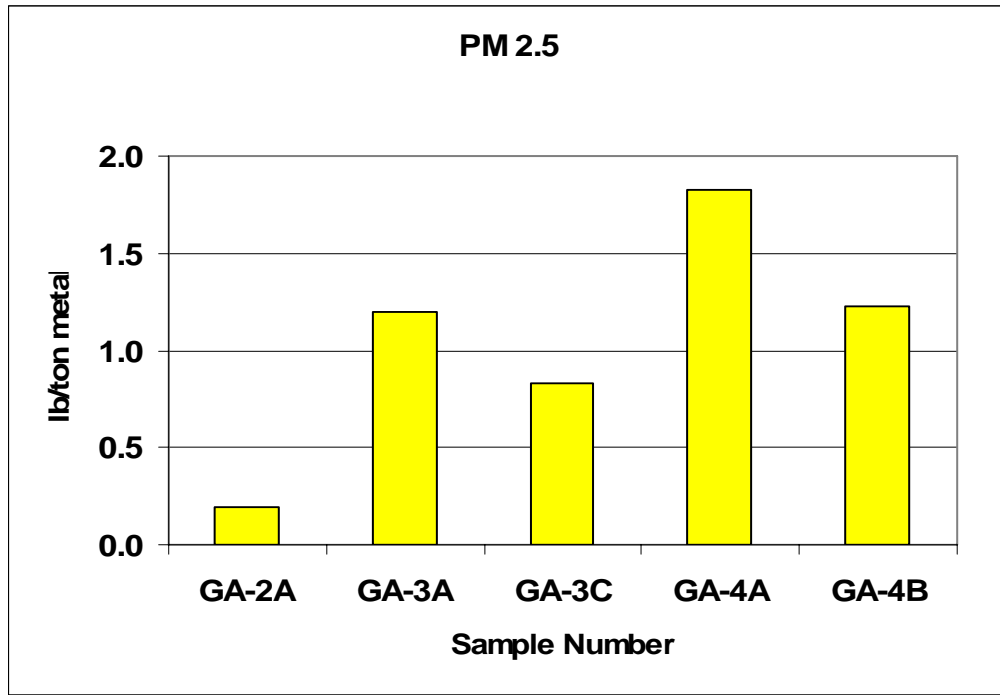


Figure 3-4 Graphical Summary of Test GA Average PM Emission Results from Dilution Tunnel Method – lb/lb Binder

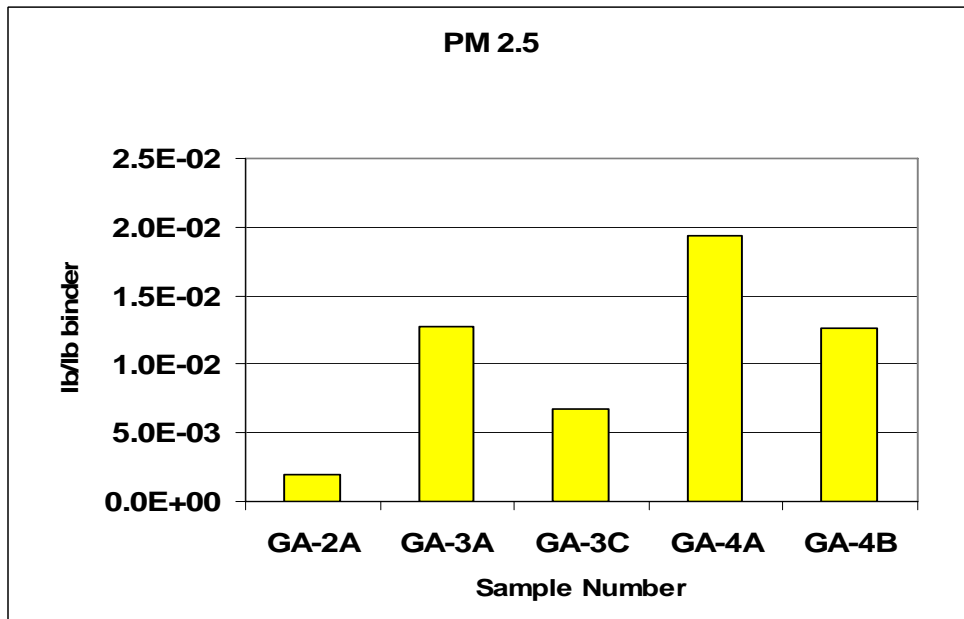


Figure 3-5 Chemical Analysis of PM from Sample GA-3A Obtained by Dilution Tunnel Sampling

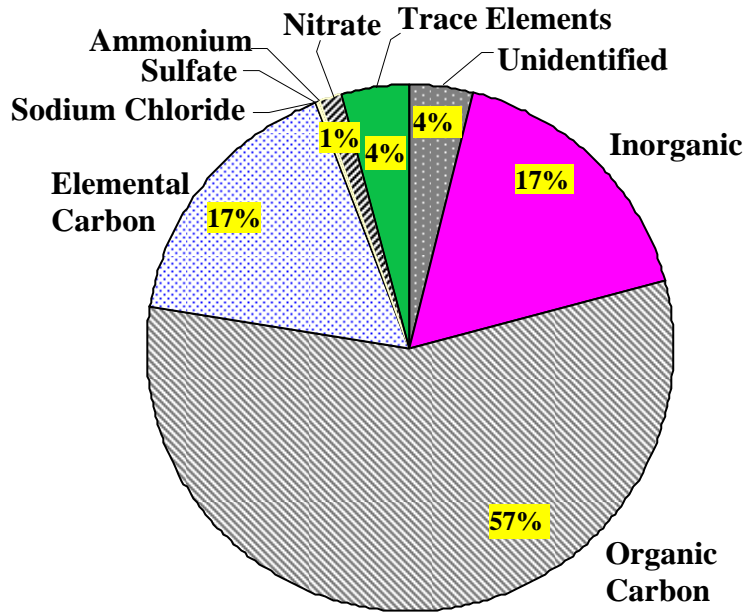


Figure 3-6 Method Comparison of PM_{2.5} Emissions, lb/tn Metal

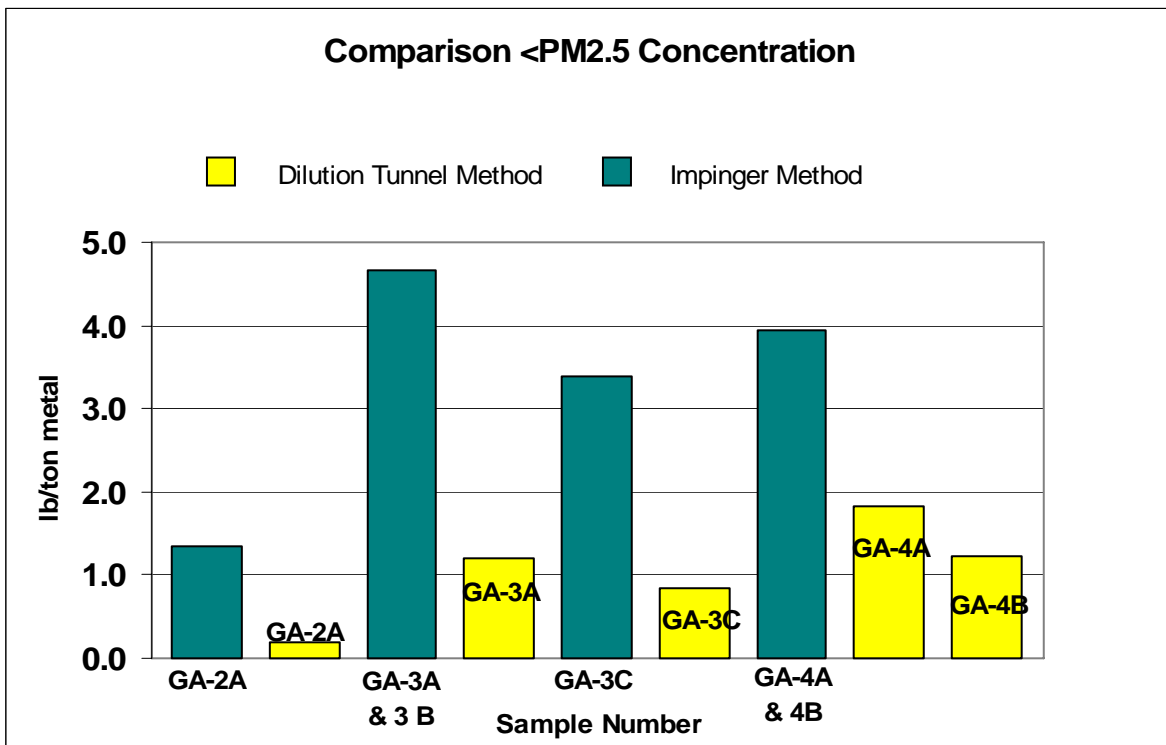


Figure 3-7 Comparison of PM_{2.5} Emissions, lb/lb Binder

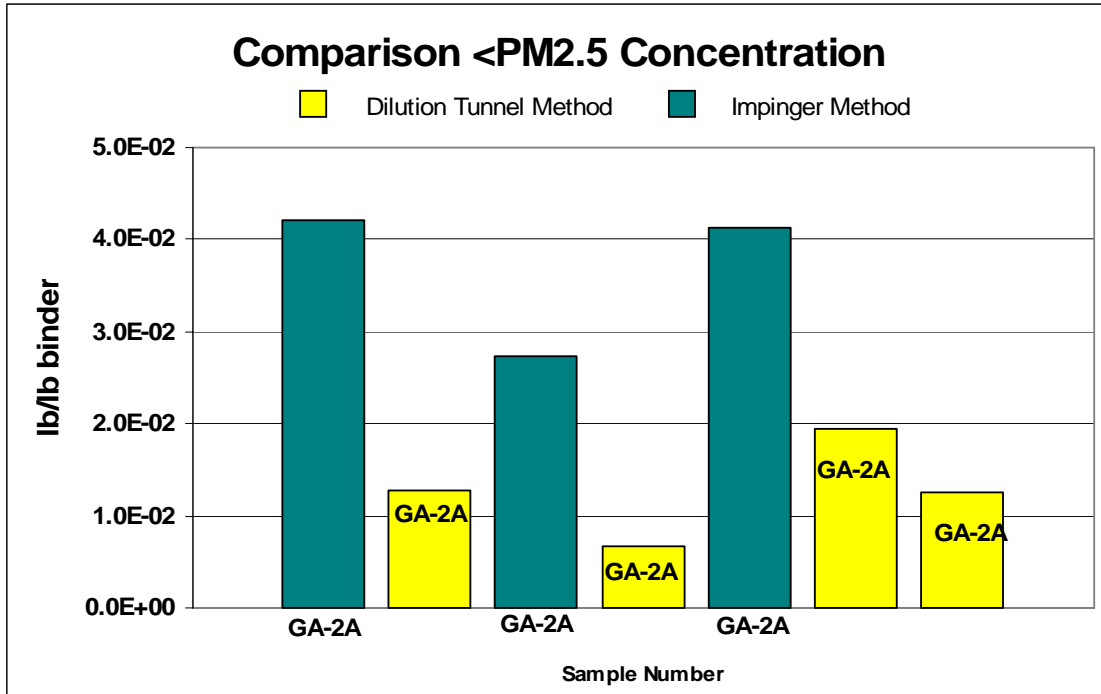
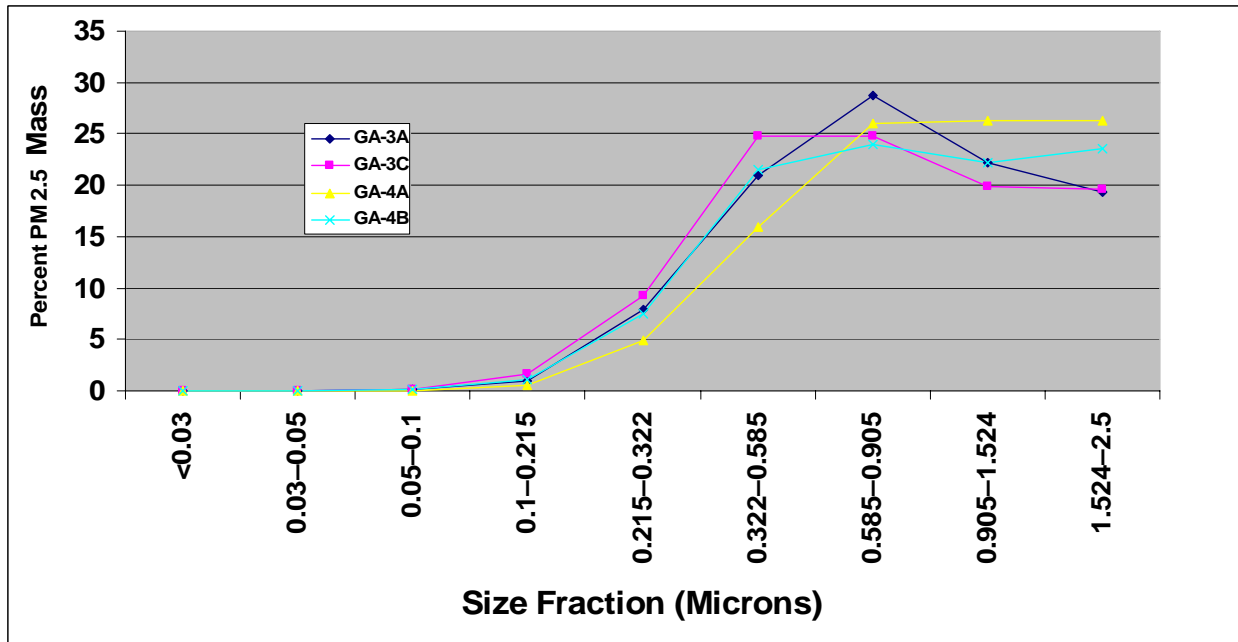


Figure 3-8 Percent PM_{2.5} Mass Distribution by Size Fraction as Determined by ELPI



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4.0 Discussion of Results

Figures 3-1 and 3-2 show the mass data of Tables 3-1 and 3-2 in lb/ton metal and lb/lb binder, respectively, normalized to 100 percent. In comparing the three runs sampled under similar conditions using the same PM10/PM2.5 cyclone sampler and impinger train it is readily apparent from the mass results that excellent reproducibility was obtained: for each of these runs, 52-59% of the filterable mass consisted of particles larger than PM10, 4-6% are intermediate particles larger than PM2.5 and smaller than PM10, and 3-5% were less than PM2.5. Condensible particulate contributed 32-38% to the total particulate mass, with the organic containing portion contributing 96-98%, the balance consisting of inorganic particulate.

If PM10 rather than total PM is considered, the proportionate contributions increase to 9-12% and 7-12% for intermediate PM and PM2.5, respectively, while that for condensible PM increases to 79-82% of the total particulate mass.

Although Sample GA-2A test conditions varied from the others in the shortened testing period that was composed of pouring and partial cooling before the run was terminated due to a plant wide power failure, as well as in the use of a single PM 10 cyclone, the condensible PM2.5 fraction contribution remained consistent with the other samples at 97% organic and 3% inorganic.

Because the Dilution Tunnel Sampling Method uses a PM2.5 cyclone, further discussion will focus on results related to PM2.5. There is also no distinction in this method between condensible or filterable particulate as both are collected on the filters after the cyclones. Comparisons to the impinger method are therefore based on both filterable and condensible PM2.5.

On a lb/ton metal basis, the Dilution Tunnel Sampling Method resulted in PM2.5 concentrations ranging from 0.84 to 1.8 as is shown in Table 3-3 and Figure 3-3 for samples GA-3A, -3C, -4A, and -4B. Table 3-3 also shows that concentrations on a lb/lb binder basis for these samples ranged from 0.0068 to 0.0194. Figure 3-4 graphically illustrates these results. The pouring and cooling processes illustrated by Sample GA-2A resulted in an approximate ten-fold decrease in PM2.5.

Comparing the total PM2.5 mass ratio results for all the samples run under identical conditions, which excludes sample GA-2A, the impinger method shows an over-estimation of 2.16 to 4.04 times that obtained by the Dilution Tunnel Sampling Method, as shown in Table 3-4 and in Figures 3-6 and 3-7. For the pouring and cooling processes sampled by GA-2A, the mass ratio increases to over seven times.

The comparative mass fraction of PM2.5 is less than the other size fractions regardless of which particulate size range is considered, although as the size fraction under examination decreases the proportionate amount of PM2.5 increases. It is not unexpected that the mass of PM2.5 is less than that of the larger particles since in general the mass of fine particulate is less than that of coarse particulate. Results from the ELPI, as reported in the DRI report, indicate the PM2.5

mass for these samples is composed mainly of particles larger than 0.215 μm , which is illustrated in the graph in Figure 3.8.

The resultant chemical analysis and elemental speciation conducted by DRI on the PM_{2.5} collected from the Dilution Tunnel Sampling Method represented by sample GA-3A is shown in Figure 3-5 as a pie chart. As illustrated by this figure, most of the PM_{2.5} mass for the samples was found to be composed of organic carbon (35 - 60%), elemental carbon (20-30 %), inorganic materials (10 - 20 %), and other elements (4-10%). Unidentified materials range from 0-20% of the total mass. This unidentified fraction is the difference between the gravimetric mass and the reconstructed mass determined through chemical speciation. Details of the chemical speciation and mass reconstruction are given in the DRI report located in Attachment 1.

5.0 Future Work

Additional work is needed to substantiate and enhance the results reported herein. Two major components of the work should be:

- A comprehensive comparison sampling series between the Dilution Tunnel Sampling Method and Method 201A/202
- A chemical and physical characterization of the material collected by each sampling method

The section of the DRI report includes four (4) recommended research activities that are encompassed by the tasks above. The fifth recommendation assumes that particulate emissions from production foundry will be similar to that experienced in the Technikon research foundry and will need to be verified.

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**APPENDIX A APPROVED TEST PLAN AND SAMPLE PLAN FOR
TEST SERIES GA**

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TECHNIKON TEST PLAN

- > **CONTRACT NUMBER:** 1410 **TASK NUMBER:** 220 **Series:** GA
- > **SITE:** Emission Collection Hood.
- > **TEST TYPE:** Comparison of Method 5/201 back half catch prepared via Method 202 and a Dilution Sampling System (DSS) CTM 39 or similar filter catch
- > **METAL TYPE:** Class 30 gray iron
- > **MOLD TYPE:** 4-on No-Bake gear; HA 6000, 6433, 17-727, 1.8% binder bos
- > **NUMBER OF MOLDS:** 16, 4 per sampling run
- > **CORE TYPE:** None
- > **SAMPLE RUNS:** 4
- > **TEST DATE:** **START:** February 18, 2004
FINISHED: February 27, 2004

TEST OBJECTIVES:

Compare gravimetrically the dilution sampling system (DSS) filter catch with residue from Method 202 preparation of Method 5 back half.

VARIABLES:

The pattern shall be the 4-on gear. The mold shall be made with Wexford W450 sand. The No-Bake mold binder will be 1.8% total binder (BOS) in 55/45 ratio of part I/part II and the activator is 7% of part 1. Molds will be poured with iron at $2,630 \pm 10^{\circ}\text{F}$. Mold cooling will be 45 minutes followed by 15 minutes of shakeout, or until no more material remains to be shaken out. The emission sampling shall be a total of 75 minutes. Casting hangers will not be used.

BRIEF OVERVIEW:

The emissions will be sampled isokinetically at a point ~ 90% of the distance from the wall to the center of the duct. The extracted sample will pass through an insulated filter and split into two streams. One stream will go to a Method 5 cold box with four (4) impingers and the other stream will go to a dilution sampling system (DSS). The sampling line(s) will be insulated until the sample enters the collection device. The Method 5 impinger catch will be analyzed according to Method 202 and the total residue (organic + inorganic) will be compared to the DSS filter catch.

SPECIAL CONDITIONS:

The initial sand temperature into the hood shall be maintained at 80-90°F. The system process air temperature shall be at least 110°F.

Series GA

Comparison of Impinger Methods 201A/202 Dilution Sampling System for a Phenolic Urethane Iron No-Bake® Process Instructions

A. Experiment:

- 1) Measure & compare particulate matter concentrations from a split emission stream of an Iron No-Bake® Phenolic Urethane binder using method 201A/202 to the a dilution Sampling System (DDS) filter catch.

B. Materials:

- 1) No-Bake® molds: Wexford W450 Lakesand and
- 2) 1.8% (BOS) HA International Techniset® No-Bake® Phenolic-Urethane core binder composed of number 6000 part I resin (55%), 6433 part II co-reactant (45%), & 17-727 part III activator at 7% of part 1. This binder is designed for iron applications.
- 3) Metal: Class 30 Gray cast iron.

Caution: Observe all safety precautions attendant to these operations as delineated in the Pre-production operating and safety instruction manual.

C. Mold requirements

- 1) Make Twelve (12) gear molds according to standards determined in test series CW & CP capability studies.

D. Phenolic Urethane No-Bake® Sand preparation:

- 1) Load the Kloster core sand mixer with Wexford W450 sand having no more than a 15°F temperature range.
- 2) The phenolic urethane No-Bake® sand shall be 1.8% total resin (BOS), Part I/Part II ratio 55/45, Part III at 7% of Part I.
- 3) Calibrate the Kloster No-Bake® sand mixer to dispense 240 pounds of sand /min more or less.

E. Calibrate the resin pumps:

- 1) Premix Part I resin and Part III activator in a 100:7 weight ratio.
- 2) Part I +Part III: Based on the actual measured sand dispensing rate calibrate the Part I resin + Part III activator to be 56.67% of 1.8% (1.020% BOS) total binder.
- 3) Part II: Based on the actual measured sand dispensing rate calibrate the Part II co-reactant to be 43.33% of 1.8 % (0.780% BOS) total binder.
- 4) All calibrations to have a tolerance of +/- 1% of the calculated value.

F. Dog bones:

- 1) Make 12 dogbones for each mold according to the protocol establish in capability study CW.

- 2) Place the core box on the vibrating compaction table.
- 3) Start the Kloster mixer and waste a few pounds of sand.
- 4) Flood the core box with sand then stop the mixer.
- 5) Strike off the core box to ½ inch deep
- 6) Turn on the vibrating compaction table for 10 seconds.
- 7) Screed off most of the excess sand.
- 8) Screed the core box a second time moving very slowly in a back and forth manner to remove **all** excess sand.

Note: It is important to neither gouge the sand nor leave excess sand in center neck portion of the dogbone or the test results will be affected

- 9) Set aside for about 6-7 minutes or until hard to the touch.
- 10) Carefully remove the cores from the core box by separating the corebox components.
- 11) Perform tensile tests on 12 bones at 2 hours after the dogbone manufacture. Store the dogbones at 80-90°F.
- 12) Report the average and standard deviation for each set of twelve (12) for each mold.
- 13) Weigh each dogbone and record the weight to the nearest 0.1 grams using the PJ 4000 electronic scale at the time it is tensile tested.

Note: Maintain the correlation between the reported weight of a dogbone and its tensile strength.

- 14) Bag three (3) dogbones, after tensile testing, from each mold for running 1800°F core LOI. Report the average value for each mold.

G. No-Bake® mold making: 4 on gear core box.

- 1) Inspect the box for cracks and other damage. Repair before use.
- 2) Prepare the core box halves with a light coating of Ashland Zipslip® IP 78. Allow to fully dry.
- 3) Place the drag core box on the vibrating compaction table.
- 4) Begin filling the box.
- 5) When the box is about 3/4 full start the table vibration.
- 6) Manually spread the sand around the box as it is filling.
- 7) Strike off the box until it is full.
- 8) Allow the vibrator to run an additional 10 seconds after the box is full.
- 9) Strike off the core box so that the core mold is 5-1/2 inches thick.
- 10) Set the core box aside for 5 to 6 minutes or until it is hard to the touch.
- 11) Invert the box and place on a transport pallet. The pallet itself shall be on steel tie straps and in turn on a piece of polyethylene film big enough to wrap it up.
- 12) Remove the pivot hole pins.
- 13) Remove the core mold half by tapping lightly on the box with a soft hammer.
- 14) Set the drag core box aside.

- 15) Immediately roll the drag mold half parting line up and return to the transport pallet.
- 16) Place the cope core box on the vibrating compaction table.
- 17) Follow steps F3-F13 except that the cope mold is 5 inches thick.
- 18) Rotate the unboxed core to set it on edge.
- 19) Drill vent holes as per template.
- 20) Blow out both mold halves.
- 21) Apply a 1/4-3/8 inch glue bead of Foseco Core Fix 8 one inch (1) in from the outer edge of the mold.
- 22) Immediately close cope onto drag. Visually check for closure.
- 23) Install two (2) steel straps, one on either side of the pouring cup, with 4 metal corner protectors each to hold the mold tightly closed.
- 24) Prior to pouring, glue a pouring basin over the sprue hole with Foseco Core-Fix 8 or equivalent no emission water base refractory adhesive
- 25) Weigh and record the weight of the sand only from the closed mold and pour basin.
- 26) Wrap and seal the mold with polyethylene film until time to load the mold into the emission hood.
- 27) Store the mold for next day use at 80-90°F .

H. Emission hood:

- 1) Loading.
 - a) Saw cut the mold, as much as is prudent, across each face to facilitate fracture during shakeout.
 - b) Hoist the mold onto the shakeout deck fixture within the emission hood with the pouring cup side toward the furnace.
 - c) Do not install hanger rods for this experiment.
 - d) Close and seal the emission hood and lock the ducts together.
 - e) Attach the heated ambient air duct to plenum
 - f) Wait to pour until the process air thermocouple is in the range 120-130°F.
 - g) Record the ambient & process ambient air temperature.
- 2) Shakeout.
 - a) After 45 minutes of cooling time has elapsed turn on the shakeout unit and run for a full 15 minutes as prescribed in the emission test plan.
 - b) Turn off the shakeout. The emission sampling will continue for an additional 15 minutes or a total of 75 minutes
 - c) Wait for the emission team to signal that they are finished sampling.
 - d) Open the hood, remove the castings
 - e) Clean core sand out of the waste sand box, off the shakeout, and the floor.
 - f) Weigh and record cast metal weight.
 - g) Immediately load the next prepared mold and close the hood.

I. Melting:

- 1) Initial charge:

- a) Charge the furnace according to the Generic Start Up Charge for Pre-production heat recipe bearing effectivity date 18 Mar 1999.
 - b) Place part of the steel scrap on the bottom, followed by carbon alloys, and the balance of the steel.
 - c) Place a pig on top on top.
 - d) Bring the furnace contents to the point of beginning to melt over a period of 1 hour at reduced power.
 - e) Add the balance of the metallics under full power until all is melted and the temperature has reached 2600 to 2700°F.
 - f) Slag the furnace and add the balance of the alloys.
 - g) Raise the temperature of the melt to 2700 oF and take a DataCast 2000 sample. The temperature of the primary liquidus (TPL) must be in the range of 2200-2350°F.
 - h) Hold the furnace at 2500-2550oF until near ready to tap.
 - i) When ready to tap raise the temperature to 2700°F and slag the furnace.
 - j) Record all metallic and alloy additions to the furnace & tap temperature. Record all furnace activities with an associated time. Record Data Cast TPL, TPS, CE, C, & Si.
- 2) Back charging.
- a) If additional iron is desired back charge according to the Generic Pre-production Last Melt heat recipe bearing effectivity date 18 Mar 1999.
 - b) Charge a few pieces of steel first to make a splash barrier, followed by the carbon alloys.
 - c) Follow the above steps beginning with H.1.e
- 3) Emptying the furnace.
- a) Pig the extra metal only after the last emission measurement is complete to avoid contaminating the air sample.
 - b) Cover the empty furnace with ceramic blanket to cool.
- J. Pouring:
- 1) Preheat the ladle.
 - a) Tap 400 pounds more or less of 2700°F metal into the cold ladle.
 - b) Casually pour the metal back to the furnace.
 - c) Cover the ladle.
 - d) Reheat the metal to 2780 +/- 20°F.
 - e) Tap 450 pounds more or less of iron into the ladle while pouring inoculating alloys onto the metal stream near its base.
 - f) Cover the ladle to conserve heat.
 - g) Move the ladle to the pour position, open the emission hood pour door and wait until the metal temperature reaches 2630 +/- 10°F.
 - h) Commence pouring keeping the sprue full.
 - i) Upon completion close the hood door, return the extra metal to the furnace, and cover the ladle.
 - j) Record Pouring temperature and pour duration.

K. Casting cleaning

- 1) Spin blast set up.
 - a) Load the spin blast shot storage bin with 460 steel shot.
 - b) Turn on the spin blast bag house.
 - c) Turn on the spin blast machine.
 - d) Increase the magnetic feeder so that the motor amperage just turns to 12 amps from 11 amps.
 - e) Record the shot flow and the motor amperage for each wheel

- 2) Cleaning castings. Castings are being clean for weighing purposes only.
 - a) Place the four (4) castings from a single mold on one (1) casting basket.
 - b) Process each rotating basket for eight (8) minutes.
 - c) Remove and remark casting ID on each casting.

L. Rank order evaluation.

- 1) A rank order evaluation is not required for this experiment.

Steven Knight
Mgr. Process Engineering

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APPENDIX B TEST SERIES GA DETAILED EMISSION RESULTS

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Test Series GA Detailed Emission Results

Technikon Sample Number	Cast Weight (lb)	Avg SCFM (ft ³ /min)	Impinger Flow Rate (l/min)	Test Time (min.)	PM Sample Weight (mg)	Sample Volume (l)	PM Concentration mg/l	lb/tn metal	lb/lb binder
GA-1A and 1B	241.6	241.5	16.3	150	142.0	2445	0.0581	1.087	0.011
GA-2A	122	253	15	37	72.9	555	0.1314	1.258	0.013
GA-3A & 3 B	211.1	240	13	150	393.3	1950	0.201A7	4.295	0.039
GA-3C	95.6	239	12	75	118.2	900	0.1313	3.075	0.025
GA-4A & 4B	242.9	235	12.5	150	352.9	1875	0.1882	3.411	0.036

lb/tn metal

Technikon Sample Number	>PM10	PM10	2.5<PM<10	PM2.5	Post impinger filter	Condensibles	Total <PM2.5	Total Filterable	Total PM	Total <PM10	Organic	Aqueous
GA-2A	9.15E-02	1.24E	NA	NA	9.67E-02	1.26E+00	1.36E+00	1.43E+00	2.68E+00	2.59E+00	1.219E+00	3.970E-02
GA-3A & 3 B	6.58E+00	NA	5.95E-01	3.65E-01	3.28E-03	4.29E+00	4.66E+00	7.54E+00	1.18E+01	5.26E+00	4.225E+00	6.989E-02
GA-3C	4.26E+00	NA	4.55E-01	3.04E-01	0.00E+00	3.07E+00	3.38E+00	5.02E+00	8.09E+00	3.83E+00	2.973E+00	1.015E-01
GA-4A & 4B	6.18E+00	NA	4.08E-01	5.35E-01	5.80E-03	3.41E+00	3.95E+00	7.13E+00	1.05E+01	4.36E+00	3.269E+00	1.411E-01

lb/lb binder

Sample Number	>PM10	PM10	2.5<PM<10	PM2.5	Post impinger filter	Condensibles	Total <PM2.5	Total Filterable	Total PM	Total <PM10	Organic	Aqueous
GA-2A	9.54E-04	1.29E-02	NA	NA	1.01E-03	1.31E-02	1.41E-02	1.49E-02	2.80E-02	2.70E-02	1.271E-02	4.140E-04
GA-3A & 3 B	5.95E-02	NA	5.38E-03	3.30E-03	2.96E-05	3.88E-02	4.22E-02	6.82E-02	1.07E-01	4.76E-02	3.821E-02	6.321E-04
GA-3C	3.44E-02	NA	3.68E-03	2.46E-03	0.00E+00	2.49E-02	2.73E-02	4.06E-02	6.54E-02	3.10E-02	2.405E-02	8.206E-04
GA-4A & 4B	6.44E-02	NA	4.25E-03	5.58E-03	6.04E-05	3.56E-02	4.12E-02	7.43E-02	1.10E-01	4.54E-02	3.408E-02	1.471E-03

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APPENDIX C TEST SERIES GA DETAILED PROCESS DATA

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Test GA Detailed Process Data

No-Bake® Mix/Make/Cure											
Test Dates	2/23/04	2/23/04	Average GA01 a,b	2/23/04	2/23/04	2/24/04	Average GA03 a,b	2/24/04	2/25/04	2/26/04	Aver- age GA04 a,b
Emissions Sample #	GA01a	GA01b		GA02a	GA03a	GA03b		GA03c	GA04a	GA04b	
Production Sample #	GA01	GA02		GA03	GA04	GA05		GA06	GA07	GA08	
Sand Dispensing Rate, lbs/15 sec	30	30	30	30	30	30	30	30	30	30	30
Binder Part1 + Part3 Dispensing Rate, gms/15 sec	136.1	136.1	136.1	136.1	136.1	136.1	136.1	136.1	136.1	136.1	136.1
Binder Part 2 Dispensing Rate, gms/15 sec	110.8	110.8	110.8	110.8	110.8	110.8	110.8	110.8	110.8	110.8	110.8
Calculated Standard % Binder	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78
Calculated % Binder (BOS)	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81
Mold Weight, lbs	331.0	333.0	332.0	328.5	319.0	336.5	327.8	332.0	320.5	333.5	329.4
Calculated Total Binder Weight, lbs	5.89	5.93	5.91	5.85	5.68	5.99	5.84	5.91	5.71	5.94	5.86
1800°F LOI, % (Note 1)	1.93	1.87	1.90	1.81	1.77	1.40	1.59	1.73	1.70	1.76	1.75
Sand Temperature, deg F	ND	ND	NA	ND	ND	ND	NA	ND	ND	ND	NA
Dogbone Core 2 hr. Tensile Strength, psi	101	86	94	98	93	55	74	110	22	51	78

Note 5

Note 4

Note 1: 1800°F LOI is the net sample weight difference when combusted at 1800F for 2 hours and includes decomposition of carbonates that originate in the source sand.

Note 4: Interrupted resin flow from Kloster mixer, resin content may be less than stated

Note 5: Low tensile and low LOI are indicators that one or both binder components were deficient relative to the calibration

Test GA Detailed Process Data

No-Bake® PCS											
Test Dates	2/24/04	2/24/04	Aver- age GA01 a,b	2/25/04	2/26/04	22/26/04	Aver- age GA03 a,b	2/26/04	2/27/04	2/27/04	Aver- age GA04 a,b
Emissions Sample #	GA01a	GA01b		GA02a	GA03a	GA03b		GA03c	GA04a	GA04b	
Production Sample #	GA01	GA02		GA03	GA04	GA05		GA06	GA07	GA08	
Pouring Temp, deg F	2624	2621	2622.50	2721	2635	2635	2635	2623	2627	2629	2637
Pouring Time, sec.	47	48	47.50	68	48	34	41	29	37	39	44
Cast Weight (all metal inside mold), Lbs.	120.7	120.9	120.8	122.0	120.6	90.5	105.5	95.6	120.9	122.0	113.9
Process Air Temperature in Hood, deg F (Note 2)	115	122	118.50	124	123	118	121	134	131	119	123
Mold Temperature when placed in hood, deg F	ND	ND	NA	ND	ND	ND	NA	ND	ND	ND	NA
Ambient Temperature, deg F	67	67	67	64	65	66	66	66	66	67	66
Mold Age When Poured, hr	21.0	23.0	22.0	43.0	65.3	44.3	55	47.7	45.6	22.9	39.0
Test Length, Min	75	75	75.00	36	75	75	75	75	75	75	71

Note 3

Note 6

Note 6

Note 2: Process air in the hood is ambient air infiltrated under the hood and controlled heated air from an oven blended at the base of the hood and measured at the level of the mold.

Note 3: Misread pyrometer as 2621 (2721 as read is actual) , interrupted pour, power outage

Note 6: Only 3 of 4 cavities filled. One cavity misran. Core sand from ingate of one cavity broke off in the pattern and was not noticed for two molds.

APPENDIX D GLOSSARY

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Glossary

BO	Based on ().
BOS	Based on Sand.
HAP	Hazardous Air Pollutant defined by the 1990 Clean Air Act Amendment
HC as Hexane	Calculated by the summation of all area between elution of Hexane through the elution of Hexadecane. The quantity of HC is performed against a five-point calibration curve of Hexane by dividing the total area count from C6 through C16 to the area of Hexane from the initial calibration curve.
I	Data rejected based on data validation considerations
NA	Not Applicable
ND	Non-Detect
NT	Lab testing was not done
PCS	Pouring, Cooling, Shakeout
POM	Polycyclic Organic Matter (POM) including Naphthalene and other compounds that contain more than one benzene ring and have a boiling point greater than or equal to 100 degrees Celsius.
PM10	Particulate matter with an aerodynamic diameter less than 10µm.
PM2.5	Particulate matter with an aerodynamic diameter less than 2.5µm.
TGOC as Propane	Weighted to the detection of more volatile hydrocarbon species, beginning at C ₁ (methane), with results calibrated against a three-carbon alkane (propane).
VOC	Volatile Organic Compound

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ATTACHMENT 1	DESERT RESEARCH INSTITUTE REPORT – CHARACTERIZATION OF PARTICULATE EMISSIONS FROM CASTING PROCESSES USING A DILUTION SAMPLING SYSTEM
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**Characterization of Particulate Emissions from Casting Processes Using a
Dilution Sampling System**

Final Report

Submitted to

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June 25, 2004

Executive Summary

A study to characterize particulate emissions from casting processes was conducted in the Research Foundry Facility at Technikon LLC (McClellan, CA). Five sets of samples were collected from February 25 to 27, 2004, with the Desert Research Institute (DRI) Source Dilution Sampling System. In these tests, the mold pattern was the 4-on irregular gear and was made with Wexford W450 Lakesand. The mold binder was 1.8% total binder (BOS) HA International Techniset® No-Bake® Phenolic-Urethane binder composed of number 6000 Part I resin (55%), 6433 part II co-reactant (45%), and 17-727 part III activator at 7% of Part I. Molds were poured with Class 30 gray cast iron at 1,427-1,482°C.

Results from chemical analysis suggest that the majority of PM_{2.5} mass emitted from the foundry process during the testing using the above condition was composed of carbonaceous compounds (organic carbon [OC] and elemental carbon [EC]). OC was 37–67% and EC 17–30%. Oxides of Al, Si, Ca and Fe were 8–20% of PM_{2.5} mass and trace elements were 3–6%. High PM_{2.5} mass concentrations of 35–100 mg/m³ were found in the Pre-Production Foundry stack. In addition, results suggest a dilution ratio of 60 or higher for future study.

Different chemical speciation profiles in particulate matter (PM) were observed between combined mold pouring and cooling, and combined pouring/cooling/shakeout processes. PM_{2.5} mass emitted from pouring is only 15–25% of that from each discrete mold. The results suggest different PM emission mechanisms between pouring and shakeout. Vaporization, thermal decomposition of organic materials, flame formations, if any, and the variability of mold breakup during shakeout may greatly affect PM formation. PM_{2.5} emission rates and speciation profiles obtained in these tests should not be used for PM_{2.5} inventory development.

The observations in this study suggest that the detailed chemical speciation for size-segregated PM samples at different sub processes needs to be investigated for a better understanding of PM emission mechanisms. In addition, the applicability and repeatability of the dilution method for air pollutant inventory development from a full-scale foundry needs to be validated.

Introduction

Accurate emission factors are essential for the determination of emission inventories and to manage and track permitting changes in foundry processes. Conflicting emission factors make permitting changes to existing sources and new sources a lengthy and costly process. For stationary sources in general, U.S. Environmental Protection Agency (EPA) methods use a hot filter followed by impinger trains to determine the particulate matter (PM) mass emission rates of pre-existing and condensible PM (CPM). The sample is withdrawn isokinetically from the source and collected on a glass-fiber filter maintained at a specified temperature (by an applicable subpart of the standards or approved by EPA for a particular application). The gas stream subsequently passes through a series of two water impingers¹. Samples collected in the impingers are extracted with methylene chloride to separate organic condensate from water-soluble material. Both fractions are evaporated to dryness at room temperature, and CPM is the total weight of both residues. The PM mass is determined from the summation of the mass of particles collected on the filter and the mass of condensate after the removal of uncombined water. These batch collection and analysis techniques require multiple steps and are labor intensive.

Meanwhile, dilution tunnel methods (i.e., EPA Method 5G), can be used for EPA certification of emissions from wood combustion. For example, the procedure developed for the determination of PM emissions from mobile sources employs a dilution tube to dilute tailpipe emissions with ambient air maintained at a constant relative humidity (RH) and temperature (ISO 8178).^{2, 3} The emissions are sampled isokinetically from this dilution tunnel at a constant temperature of 37°C and collected on filter media. The use of a dilution sampling system mimics rapid cooling and mixing of the hot sample with ambient air, which results in gases nucleating homogeneously and heterogeneously or condensing on pre-existing particles.

The Casting Emission Reduction Program (CERP), operated by Technikon LLC, evaluates data about the emission of PM mass and chemical profiles from the casting process. To achieve this goal a dilution sampler method similar to U.S. EPA Conditional Test Method 39 was used. This method consisted of filtered dilution air, sample mixing, and a residence chamber.

This report presents qualitative results for characterizing particulate emissions from casting operations using a DRI Source Dilution Sampling System. In addition, emission rates determined by the dilution method can be compared to rates determined by the EPA hot filter/impinger method, which was conducted in parallel to the DRI Source Dilution Sampling System.

Experimental Test Method and Facility

Test Facility

The dilution sampling tests were performed in Technikon's Research Foundry, (which is designed to measure air emissions from individual poured molds). The facility is used to evaluate the impact on air emissions from proposed alternative materials, equipment, or processes, prior to further validation at a full-scale foundry. Measurements at the Research Foundry were taken during the pouring, cooling, and shakeout processes for discreet molds under tightly controlled conditions. The sample was withdrawn from approximately the center of the 15.240 cm (6 inch) diameter stack at a port one meter above ground level. The extracted sample was split into two streams. One of the two streams was directed to the DRI Source Dilution Sampling System, and the other went to the EPA hot filter/impinger train sampling system, as illustrated in Figure 2-1.

The molds were prepared by the Technikon CERP testing team to a standard composition. Technikon determined and recorded the following data: the weight of the metal and binder; the number of cavities poured; the percent loss-on-ignition (LOI); the percent of clay in the mold before pouring and after shakeout; pouring temperature; and casting weights. In these tests, the mold pattern was the 4-on irregular gear and was made with Wexford W450 Lakesand. The mold binder was 1.8% total binder (BOS) HA International Techniset® No-bake Phenolic-Urethane binder composed of number 6000 Part I resin (55%), 6433 part II co-reactant (45%), and 17-727 part III activator at 7% of Part I. Molds were poured with Class 30 gray cast iron at 1,427–1,482°C (2,600–2,700°F)

Stack conditions such as stack gas velocity and temperature, gas density and molecular weight, gas moisture, and absolute pressure in the stack, were monitored and recorded by Technikon during these tests. The initial sand temperature into the hood was maintained at 26.7–32.2 °C (80–90°F) and the system process air temperature was at least 43°C (110°F). No particulate removal equipment was installed in the stack before the point at which the sample was extracted.

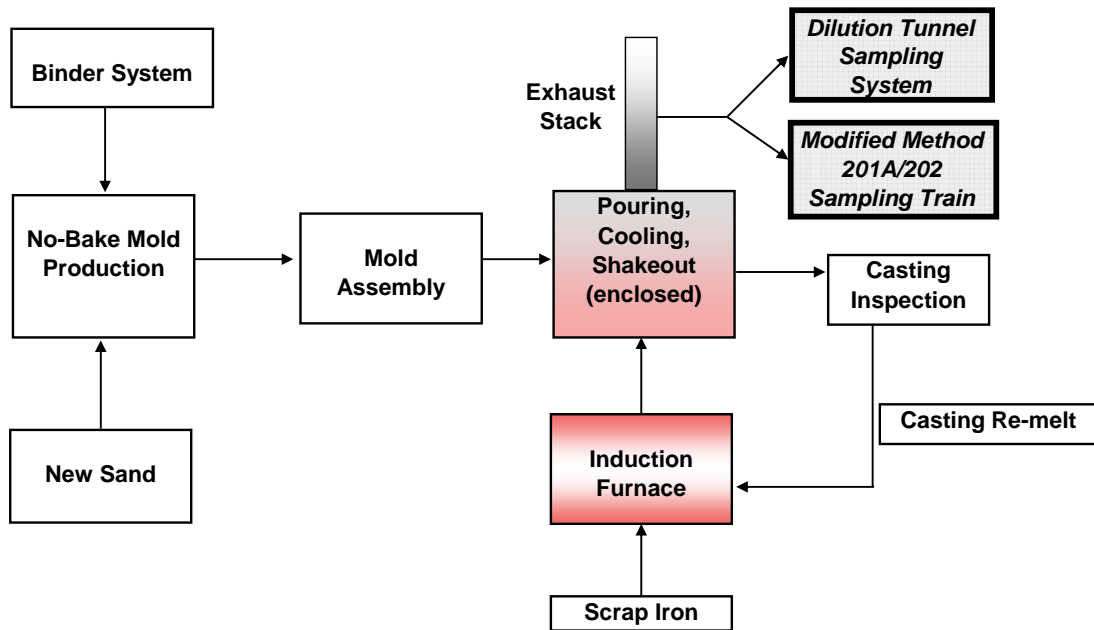


Figure 0-1. Schematic of the sampling setup in the Pre-Production Foundry at the Technikon Research Foundry (McClellan, CA) in February 2004.

DRI Source Dilution Sampling System

The DRI Source Dilution Sampling System, shown in Figure 2-2, is similar to that of EPA Conditional Test Method 39. It was installed at the Technikon Research Foundry. A detailed characterization of the dilution sampler is described elsewhere.⁴ The DRI source dilution sampling system has been used in research applications for stationary and mobile source emissions.⁵⁻²¹ The dilution sampler draws 20-25 liters per minute (LPM) of sample through a Venturi Flowmeter. The sample line is heated at a temperature slightly higher than that of the sample temperature to reduce particle thermophoretic losses and gas condensation on the wall. Ambient air passes through a high-efficiency particle arresting (HEPA) filter to remove PM, followed by a granulated activated carbon (GAC) bed to remove gaseous species and volatilized PM. The clean, cool ambient air dilutes the sample gas in the U-shaped mixing zone (15 cm in diameter and 207 cm long). At the end of the mixing zone, 226 LPM of diluted sample is drawn into an aging chamber 45 cm in diameter and 183 cm in height for a total aging time of 60–90 seconds, in which the particles cool, coagulate, and grow by condensation. For this study, the dilution air ratio was adjusted to target an average of 20–60. (The excess flow is removed by a high-volume pump.) PM larger than 2.5 μm in aerodynamic diameter in the diluted sample is removed by PM_{2.5} cyclones (Bendix 240).²² PM_{2.5} then enters the Teflon-coated source sampling cone, where filters collect it for physicochemical characterization in the laboratory.

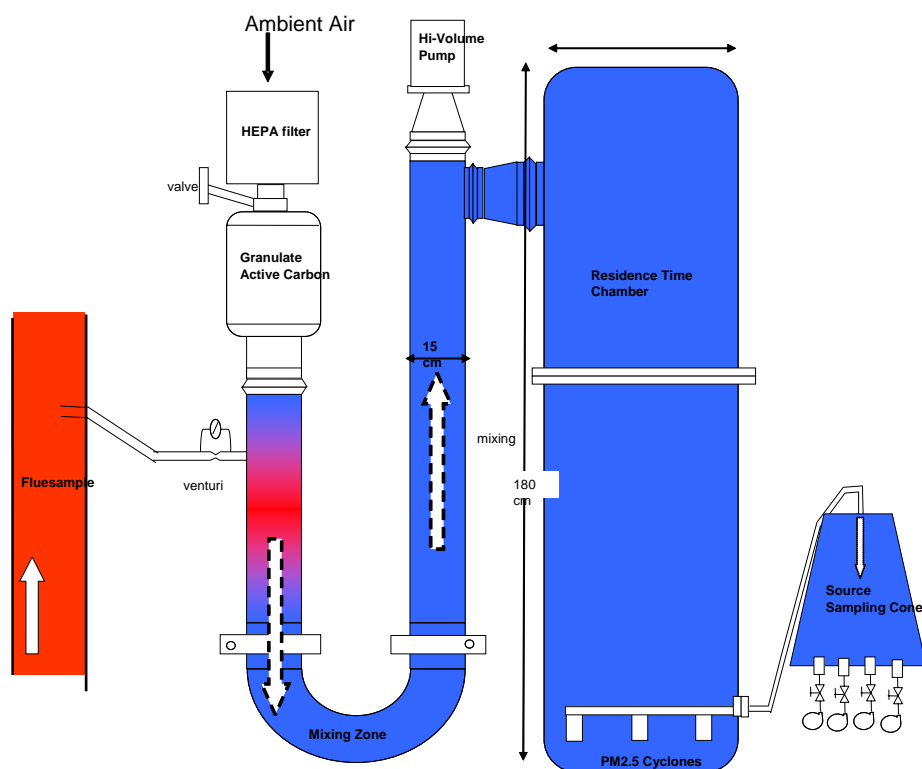


Figure 0-2. Schematic of the DRI Source Dilution Sampling System.

The base of the source sampling cone has 13 filter holders/sampling ports. For each of the dilution sampling tests, two filter packs and an Electrical Low Pressure Impactor (ELPI, Dekati, Finland) were connected to filter holder ports in the source-sampling cone. Field blanks consisting of identical filter pack configurations used an additional two sampling ports. The filter holders are made by Savillex of Perfluoralkoxy (PFA) Teflon to minimize their reaction with the sample; they contain redesigned filter backing trays that reduce flow restriction and provide uniform deposition.

The configurations of filter sampling ports used in the DRI Source Dilution Sampling System include: 1) polyolefin-ringed Teflon membranes (Gelman [Ann Arbor, MI], 2.0 μm pore size, [#R2PJ047] for mass and elemental analysis) followed by a pre-fired quartz-fiber filter (Pallflex [#2500QAOT-UP]) to quantify volatilized carbon; 2) a pre-fired quartz-fiber filter for water soluble ions (Cl^- , NO_3^- , SO_4^{2-} , NH_4^+) and carbon analyses followed by a cellulose-fiber filter (Whatman 31ET) impregnated with citric acid to collect gaseous ammonia (NH_3); and 3) ELPI.

Measurements of time-integrated $\text{PM}_{2.5}$ mass were used to estimate emission rates of air pollutants measured in the dilution sampling method. Particle size distribution measurements of ELPI characterized peak emissions in each discrete mold process. The integrated ELPI measurements were compared to integrated $\text{PM}_{2.5}$ mass, which serves as the baseline.

The flow rate through each Teflon/quartz and quartz/citric acid impregnated cellulose filter pack was 51 lpm; the rate was 10 lpm for ELPI. The flow rates were monitored during sampling by calibrated mass flow meter. The filter packs were equipped with quick-release connectors to minimize contamination. A data acquisition system monitored and recorded the flow rates of the venturi flow meter and high-volume pump, the temperature and relative humidity of the ambient air, and the diluted sample.

The DRI Source Dilution Sampling System was provided, installed, and operated by DRI personnel during test periods at Technikon's Research Foundry. Cleaning of the dilution sampling system prior to testing took place at DRI. Both the interior and exterior of the sampling system were cleaned with distilled de-ionized water (DDW) and Kimwipes® to remove debris, and by acetone to remove organic matter. To ensure complete removal of organics and of the acetone used for cleaning, the sampling system was assembled and baked at up to 150°C in heating blankets for six hours. During the baking process, the dilution sampling probe was sealed so that only a small flow rate (<10 lpm) passed through the HEPA/GAC system. Prior to sampling, the HEPA/GAC was replaced to ensure adequate clean air for dilution.

A total of five runs were conducted under the same emission conditions; (1) to determine PM_{2.5} mass emission rates and chemical abundance from the foundry process, (2) to offer a comparison with rates and abundance determined by EPA hot filter/impinger methods, and (3) as a preliminary study to optimize the dilution air ratios of the sampling system for samples from the Research Foundry. A sample collection schedule for the DRI Source Dilution Sampling System and EPA hot filter/impinger methods is shown in Table 2-1. Each dilution sampling run consisted of one complete mold in process of 75 minutes (45 minutes of pouring and cooling, 15 minutes of shakeout, and 15 minutes after shakeout), except DRI Run 2, which sampled only 36 minutes during pouring and cooling due to a regional power failure caused by a storm. Additional sampling time of 2–3 minutes for filter media sampling before and after each run was added to adjust the target dilution air ratio before sampling and to include the 90-second aging time needed for particles to age in the sampling system.

Date	Technikon Number	DRI Run Number	Sample Time (min)	Duct Flowrate (scfm)	Cast Wt. (lb)	Binder Wt. (lb)
2/25/2004	GA-2A	Run 2	36	253.0	122.0	5.85
2/26/2004	GA-3A	Run 3	75	236.0	120.6	5.680
2/26/2004	GA-3C	Run 4	75	239.0	95.6	5.910
2/27/2004	GA-4A	Run 5	75	233.0	120.9	5.710
2/27/2004	GA-4B	Run 6	75	237.0	122.0	5.940

Table 0-1. Daily schedule for comparisons of the dilution sampling method and EPA hot filter/impinger train methods at the Technikon Research Facility from February 25 to 27, 2004 (1 cfm = 28.37 LPM).

Sample Analysis

These five runs included measurements for PM_{2.5} mass, elements, inorganic ions (Cl⁻, NO₃⁻, and SO₄⁼, NH₄⁺), organic carbon (OC) and elemental carbon (EC) fractions, gaseous ammonia, and real-time particle size distribution. PM_{2.5} mass measured was determined as the difference between pre- and post-sampling masses measured on 47-mm diameter polytetrafluoroethylene (PTFE) filters.²³ After gravimetric analysis, samples collected on the PTFE filters were analyzed by energy dispersive X-ray fluorescence (ED-XRF, Epsilon 5, PanAnalytical, the Netherlands) for the following 40 elements: sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), arsenic (As), selenium (Se), bromine (Br), rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), molybdenum (Mo), palladium (Pd), silver (Ag), cadmium (Cd), indium (In), tin (Sn), antimony (Sb), barium (Ba), gold (Au), mercury (Hg), thallium (Tl), lead (Pb), lanthanum (La), and uranium (U).²⁴

Water-soluble anions (Cl⁻, NO₃⁻, and SO₄⁼), a cation (NH₄⁺), NH₃, OC, and EC were determined from the deposit on a quartz-fiber filter collected in parallel with a PTFE filter. Each quartz-fiber filter was cut in half, and one half was placed in a polystyrene extraction vial with 15 ml of DDW. The extraction vials were capped and sonicated for 60 minutes, shaken for 60 minutes, then aged overnight to assure complete extraction of the deposited material. After extraction, these solutions were stored under refrigeration prior to analysis. Cl⁻, NO₃⁻, and SO₄⁼ were measured by ion chromatography (IC) with a Dionex 500x (Dionex, Sunnyvale, CA). Approximately 2 ml of the filter extract was injected into the IC system.²⁵ An Astoria 2 automated colorimetric (AC) system (Astoria-Pacific, Clackamas, OR) was used to measure NH₄⁺ concentration by the indolphenol method.

OC and EC are quantified following the Interagency Monitoring of Protected Visual Environments (IMPROVE) protocol²⁶ on portions of the quartz-fiber filters using a DRI Model 2001 thermal/optical carbon analyzer. These thermal evolution methods are based on the principle that

different types of carbon-containing particles are converted to gases under different temperature and oxidation conditions.

Fine particle size distributions of diluted samples were measured by ELPI, which uses a unipolar corona charger to impart a positive charge on the measured aerosol and separates particles by impaction at size fractions of <0.03, 0.03–0.05, 0.05–0.1, 0.1–0.215, 0.215–0.322, 0.322–0.585, 0.585–0.905, 0.905–1.524, and 1.524–2.5 μm . The impaction substrates are electrically isolated with Teflon supports, and the accumulating charge on each of the substrates is measured by an array of electrometers. The measured current on each of the stages is proportional to the number of particles depositing on the stage, which can be converted to mass. The response time for ELPI is 1 second, so that rapid changes of particle distribution in a complete casting cycle can be characterized.

Results

PM_{2.5} Mass Emission Rate determined by DRI Source Dilution Sampling System

Table 3-1 compares emissions of PM_{2.5} measured by filter samplers and ELPI for these five runs. The average dilution air ratio applied to these tests ranged from 26 to 60. The average ELPI PM_{2.5} mass concentrations show reasonable agreement with filter media. PM_{2.5} mass concentrations measured by ELPI are approximately 77 to 95% of those determined by filter samplers, and a ratio of 0.73 was observed for Run 2. This result shows that ELPI can be used as a semi-quantitative tool for PM_{2.5} mass concentrations by applying a factor of 1.175 for binders and materials used in this study.

Table 0-2. PM_{2.5} mass concentrations determined by filter sampler and ELPI.

DRI Run	Date	Start Time	End Time	Time (min)	Volume (m3) at STP	Average Dilution Air Ratio	mass Conc. (ug/m3) by filter	Filter Mass Conc (ug/m3)	ELPI mass conc (ug/m3)	PM2.5 ELPI/ Filter Samples	Fraction of PM2.5 from Pouring / Cooling*
2	2/25/2004	9:50	10:35	36	1.47	26.25	2.58E+04	991.14	723.00	0.73	NA
3	2/26/2004	9:00	10:20	75	3.26	31.81	6.56E+04	2050.98	1837.00	0.90	0.267
4	2/26/2004	15:05	16:24	75	3.32	44.00	3.56E+04	809.46	771.00	0.95	0.200
5	2/27/2004	11:30	12:50	75	3.07	42.10	1.01E+05	2404.12	1841.00	0.77	0.153
6	2/27/2004	13:52	3:08	75	3.04	60.30	6.69E+04	1114.34	871.00	0.78	0.179

* The fraction is the PM_{2.5} mass emitted from pouring to PM_{2.5} from each mold determined by integrating ELPI Concentration in each sub-process

The PM_{2.5} mass emission rate during different sub-processes (i.e., mainly pouring/cooling to shakeout/after-cooling), can be compared by integrating the PM_{2.5} mass concentrations measured by ELPI. The results show that PM_{2.5} emitted from the pouring and cooling is approximately 20%, as shown in Table 3-1. An average PM_{2.5} mass concentration of 1,114 µg/m³ was observed on filter samples for Run 6, which suggests a dilution air ratio of 60 or higher should be used in the dilution method for PM sampling from foundry processes.

PM_{2.5} mass emission rates measured by the sampling system ranged from 0.84 to 1.83 lb PM_{2.5}/tn metal (or 0.0068 to 0.0194 lb PM_{2.5} / lb binder), as shown in Table 3-2. The calculation of PM_{2.5} emission rates determined by the DRI Source Dilution Sampling System is in Appendix A.

Although each mold was prepared within similar parameters, PM_{2.5} emission rates varied: PM_{2.5} emission rates varied by a factor of 2.2 in the sampling system with the same dilution air ratio (DRI Run 4 and Run 5). The reason for the variability of PM_{2.5} mass emission in these tests is not clear due to the limited number of samples that were collected. However, it is suspected to be caused by 1) 20% less cast weight used in Run 4, and 2) process variation.

Table 0-3. PM_{2.5} mass emission rates determined by the DRI Source Dilution Sampling System.

DRI Sample Number	lb/tn metal	lb/lb binder
Run 2	0.1944	0.0020
Run 3	1.1980	0.0127
Run 4	0.8355	0.0068
Run 5	1.8303	0.0194
Run 6	1.2248	0.0126

Mass Fraction of Segregated PM Size Ranges Measured by ELPI

Table 3-3 shows mass fractions for PM_{2.5} in different size ranges as reviewed by ELPI. Ultra fine particles (PM_{0.1}), which are formed through nucleation of condensable species and chemical reactions, compose less than 0.1% of PM_{2.5} mass. A mass mode is observed at the size range of 0.322–1.524 μm.

Table 0-4. PM_{2.5} mass fraction at different size ranges determined by ELPI.

	PM size range (um)								
	<0.03	0.03-0.05	0.05-0.1	0.1-0.215	0.215-0.322	0.322-0.585	0.585-0.905	0.905-1.524	1.524-2.5
Run 3	0.0%	0.0%	0.1%	1.0%	7.9%	21.0%	28.7%	22.2%	19.3%
Run 4	0.0%	0.0%	0.2%	1.7%	9.2%	24.8%	24.8%	19.9%	19.6%
Run 5	0.0%	0.0%	0.0%	0.5%	4.9%	15.9%	26.0%	26.3%	26.3%
Run 6	0.0%	0.0%	0.1%	1.1%	7.5%	21.5%	24.0%	22.2%	23.6%

PM_{2.5} Speciation Profiles

The emission factors of chemical speciation in PM_{2.5} for each test are shown in Appendices B-1 and B-2. It should be emphasized that these chemical speciation profiles are only for this series of tests, and should not be used for general emission inventory development.

The major component of PM_{2.5} mass for each mold (i.e. Run 3 to Run 6) is carbonaceous material (67–90%) which is composed of OC (37–67%) and soot EC (17–30%). Al, Si, Fe, and Ca compose 8–20% of PM_{2.5} mass, and trace elements are 3-6%. The unidentified mass is 0–20% of the PM_{2.5} mass. Reconstructed mass in Run 6 exceeds 5.5% of gravimetric mass, the reason for that is attributed to the empirical factor of 1.3 used in determining OC. Calculations for reconstructed mass are in Appendix B-3. Due to potential process variation, the profiles of emitted carbonaceous compounds may differ and a different factor may be needed for OC. The most abundant species emitted from the molding process were oxides of Silicone (5–15%), and Iron (2–5%). Other species identified were Manganese, Aluminum, Sulfur, Calcium, Copper, Zinc and Ammonia in the range of 0.2-0.3% of total PM_{2.5} mass for Runs 3-6.

In Run 2 (i.e., pouring and partial cooling), the OC fraction decreases to 15%, compared to 40–65% for other samples. Emission factors of transition elements (Mn, Fe, Cu, and Zn) in pouring are approximately 4–5 times higher than the average of a complete mold, and are 30% of PM_{2.5} mass. The result suggests two different PM emission mechanisms of chemical species in pouring and shakeout.

The potential sampling bias of organic compounds on a quartz-fiber filter can be quantified by using a quartz-fiber filter as a backup (BK) downstream of the PTFE filter. The amount of total carbon (TC) collected on the BK quartz-fiber filter is approximately 2–5% of the PM_{2.5} mass. Compared to TC determined on quartz-fiber filter, the potential sampling bias of TC is approximately 10%, which can be contributed either from particle volatilization or the adsorption of gases. The source of sampling bias for carbonaceous compounds requires further investigation.

Process Variation of PM_{2.5} Emissions

The process variations of PM_{2.5} mass concentration, PM_{2.5} number concentration, and stack conditions for each run are shown in Appendix C. The highest emission rate of PM_{2.5} mass, number concentration, THC, CO concentration, and stack temperature occurred during the shakeout process. These THC, CO, and temperature results showed variations from run to run in this study. The variation of the PM_{2.5} mass emission rates discussed previously is probably due to process variation, not the dilution air ratio that was applied.

Strong correlations were observed among PM_{2.5} mass concentration, PM_{2.5} particle number concentration, THC, CO, and stack temperature. In general, PM_{2.5} mass concentration increases as THC concentration increases in the processes. PM_{2.5} number concentration increases when THC concentration increases during pouring but decreases during shakeout.

The source of condensible species for PM emission greatly depends on casting processes, including chemical reactions, vaporization, thermal-decomposition, and combustion of organic materials in the binder. These condensible species will either nucleate to ultra fine particles or condense onto pre-existing particles. The mass of ultra fine particles is small compared to large particles with the same number concentrations. (Yet, it is sensitive to process variation due to the sole source of condensible species for their formation.) The high THC concentrations in shakeout imply less condensible species available for particle nucleation, which can not be observed if mass concentration is used for monitoring process variations. Instead, variations of ultra fine particle number concentration will be more sensitive to process variation.

Conclusions

Total carbonaceous compounds measured by dilution method are 70–90% PM_{2.5} mass. Oxides of Al, Si, Ca and Fe were found to be 8–20% of PM_{2.5} mass, and trace elements 3–6%. PM_{2.5} mass emitted in pouring is only 15–25% of that from each complete mold process. The mass fraction of ultra fine particles (less than 0.1µm) in PM_{2.5} is small. PM_{2.5} emission rates and speciation profiles obtained in these tests should not be used for PM_{2.5} inventory development. Chemical speciation profiles show different PM sources and formation mechanisms between pouring and shakeout. Vaporization and thermal-decomposition of organic materials, and the variability of mold breakup during shakeout, can greatly affect the paths of sources for PM formation.

Recommendations

The following research activities are recommended to develop knowledge for better emission reductions and process controls in the casting process:

- Determine the repeatability of the measurements in the dilution sampling system when the same dilution air ratio is used. (These tests were to optimize operating parameters [i.e., dilution air ratio] for dilution sampling in a foundry.)
- Collect size-segregated PM samples from the dilution sampling system to determine the enrichment of chemical species at different sub-processes (i.e., for pouring and shakeout).
- Validate the applicability of the dilution sampling method in the full scale foundry for source emissions from a foundry process.
- Determine the enrichments of PM_{2.5} mass and all measured species emitted from the foundry process to the ambient background in the full-scale foundry for emission inventory development.
- A dilution air ratio of 60 or higher should be used in the dilution sampling method for PM emissions from a foundry process.

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APPENDIX A

Calculation of PM_{2.5} emission rate determined by DRI Source Dilution Sampling System

$$PM_{2.5}EmissionRate = In - StackPM_{2.5}MassConcentration * StackFlowRate / BinderWeight$$

or

$$PM_{2.5}EmissionRate = In - StackPM_{2.5}MassConcentration * StackFlowRate / CastWeight$$

whereas

$$In - StackPM_{2.5}MassConcentration = \frac{MassCollectedOnFilter}{FlowRate * SamplingTime} * averageDilutionAirRatio$$

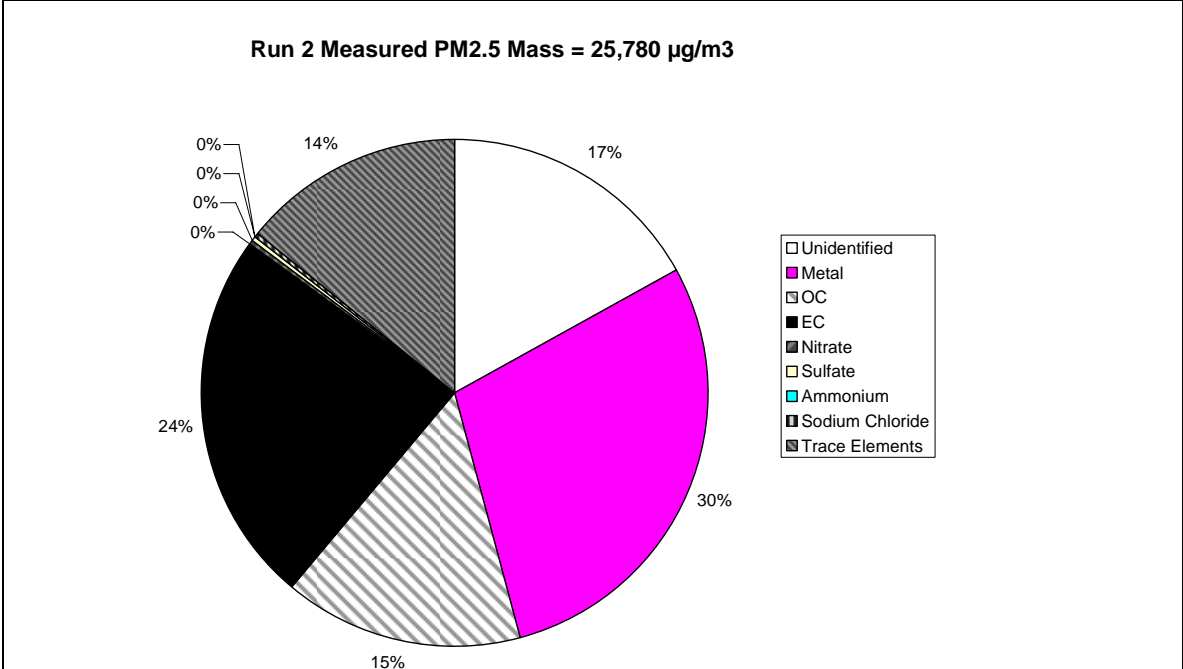
and

$$DilutionAirRatio = \frac{\sum(Q_{filters} + Q_{ELPI} + Q_{byPassFlow})atSTP}{Q_{venturi} * (293.13K / stackTemp @ K)}$$

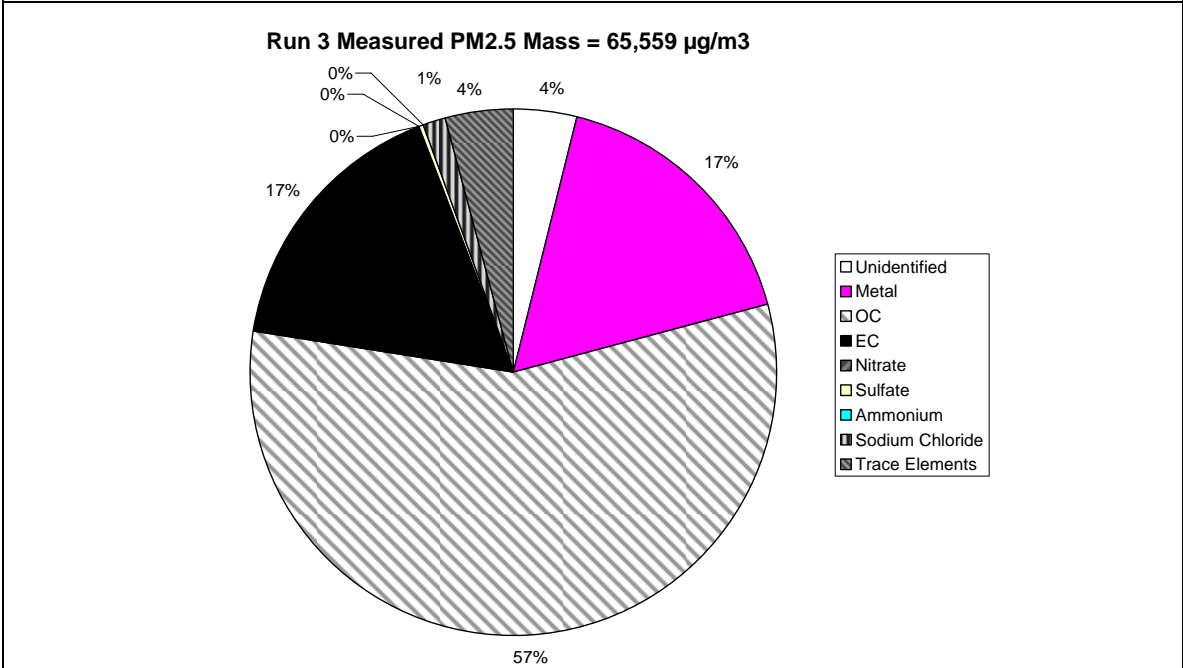
APPENDIX B-1

PM_{2.5} chemical abundance in the Research Foundry by DRI Source Dilution Sampling System. (Calculations of reconstructed PM_{2.5} mass are in Appendix B-3.)

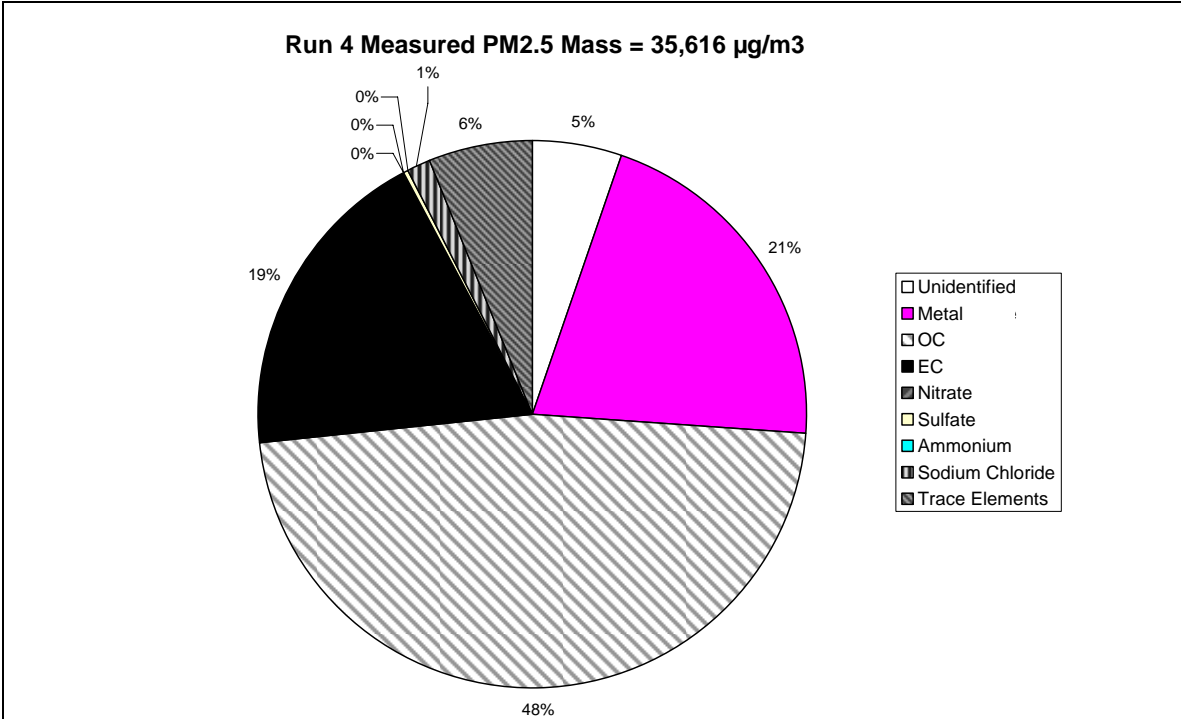
Run Number	Run 2	Run 3	Run 4	Run 5	Run 6
Carbon in Backup Filter by IMPROVE Protocol					
OC1 BK	1.02%	0.57%	1.13%	0.35%	1.07%
OC2 BK	1.00%	0.61%	1.18%	0.52%	1.08%
OC3 BK	1.00%	0.35%	0.70%	0.36%	0.73%
OC4 BK	0.20%	0.17%	0.31%	0.20%	0.45%
OP BK	0.00%	0.00%	0.00%	0.00%	0.00%
OC BK	4.19%	2.26%	4.42%	2.03%	4.76%
EC1 BK	0.13%	0.19%	0.36%	0.25%	0.56%
EC2 BK	0.10%	0.09%	0.25%	0.10%	0.32%
EC3 BK	0.00%	0.00%	0.00%	0.00%	0.04%
EC BK	0.24%	0.25%	0.53%	0.22%	0.60%
TC BK	4.43%	2.51%	4.95%	2.25%	5.36%
Inorganic Ions by IC/AC					
Chloride	0.15%	0.58%	0.65%	1.06%	1.19%
Nitrate	0.04%	0.03%	0.05%	0.03%	0.07%
Sulfate	0.36%	0.22%	0.20%	0.19%	0.21%
Ammonium	0.11%	0.10%	0.08%	0.39%	0.34%
Carbon in front filter by IMPROVE Protocol					
O1TC	1.96%	7.68%	4.95%	2.99%	4.80%
O2TC	3.16%	7.17%	5.44%	3.46%	4.48%
O3TC	3.26%	5.02%	3.62%	2.14%	2.98%
O4TC	1.82%	2.67%	4.15%	2.42%	3.82%
OPTC	0.00%	0.00%	0.00%	0.00%	0.00%
OCTC	15.29%	56.58%	47.15%	37.02%	66.70%
E1TC	21.34%	35.04%	33.34%	37.07%	37.37%
E2TC	3.87%	2.35%	3.58%	10.14%	20.47%
E3TC	0.45%	0.12%	0.19%	0.24%	0.20%
ECTC	24.09%	16.54%	18.99%	29.99%	22.81%
TCTC	39.38%	73.12%	66.14%	67.01%	89.51%
Elements By XRF					
Aluminum	0.00%	0.61%	0.66%	0.17%	0.44%
Silicon	10.68%	10.66%	15.36%	4.78%	7.84%
Phosphorus	0.00%	0.00%	0.01%	0.00%	0.05%
Sulfur	0.23%	0.09%	0.09%	0.02%	0.05%
Chlorine	0.20%	0.86%	0.84%	0.86%	0.89%
Potassium	0.05%	0.53%	0.68%	0.34%	0.52%
Calcium	0.17%	0.27%	0.34%	0.19%	0.25%
Titanium	0.00%	0.01%	0.02%	0.00%	0.00%
Vanadium	0.00%	0.00%	0.00%	0.00%	0.00%
Chromium	0.05%	0.02%	0.02%	0.01%	0.01%
Manganese	11.46%	3.05%	4.81%	3.84%	1.77%
Iron	17.95%	5.54%	4.34%	3.58%	3.27%
Cobalt	0.02%	0.01%	0.01%	0.00%	0.00%
Nickel	0.04%	0.01%	0.01%	0.00%	0.00%
Copper	1.05%	0.20%	0.24%	0.22%	0.12%
Zinc	1.00%	0.27%	0.21%	0.28%	0.11%
Gallium	0.00%	0.00%	0.00%	0.00%	0.00%
Arsenic	0.01%	0.00%	0.00%	0.00%	0.00%
Selenium	0.00%	0.00%	0.00%	0.00%	0.00%
Bromine	0.00%	0.00%	0.00%	0.00%	0.00%
Rubidium	0.00%	0.00%	0.00%	0.00%	0.00%
Strontium	0.00%	0.00%	0.00%	0.00%	0.00%
Yttrium	0.00%	0.00%	0.00%	0.00%	0.00%
Zirconium	0.00%	0.00%	0.00%	0.00%	0.00%
Molybdenum	0.01%	0.00%	0.00%	0.00%	0.00%
Palladium	0.00%	0.00%	0.00%	0.00%	0.00%
Silver	0.03%	0.01%	0.01%	0.00%	0.00%
Cadmium	0.00%	0.00%	0.00%	0.00%	0.00%
Indium	0.00%	0.00%	0.00%	0.00%	0.00%
Tin	0.09%	0.02%	0.02%	0.01%	0.01%
Antimony	0.03%	0.00%	0.02%	0.00%	0.02%
Barium	0.05%	0.01%	0.00%	0.01%	0.02%
Lanthanum	0.00%	0.00%	0.02%	0.01%	0.02%
Gold	0.00%	0.00%	0.00%	0.00%	0.00%
Mercury	0.01%	0.00%	0.00%	0.00%	0.00%
Thallium	0.00%	0.00%	0.00%	0.00%	0.00%
Lead	0.13%	0.02%	0.01%	0.01%	0.00%
Uranium	0.00%	0.00%	0.00%	0.00%	0.00%
Reconstructed Mass*	83.05%	96.12%	94.65%	82.53%	106.08%



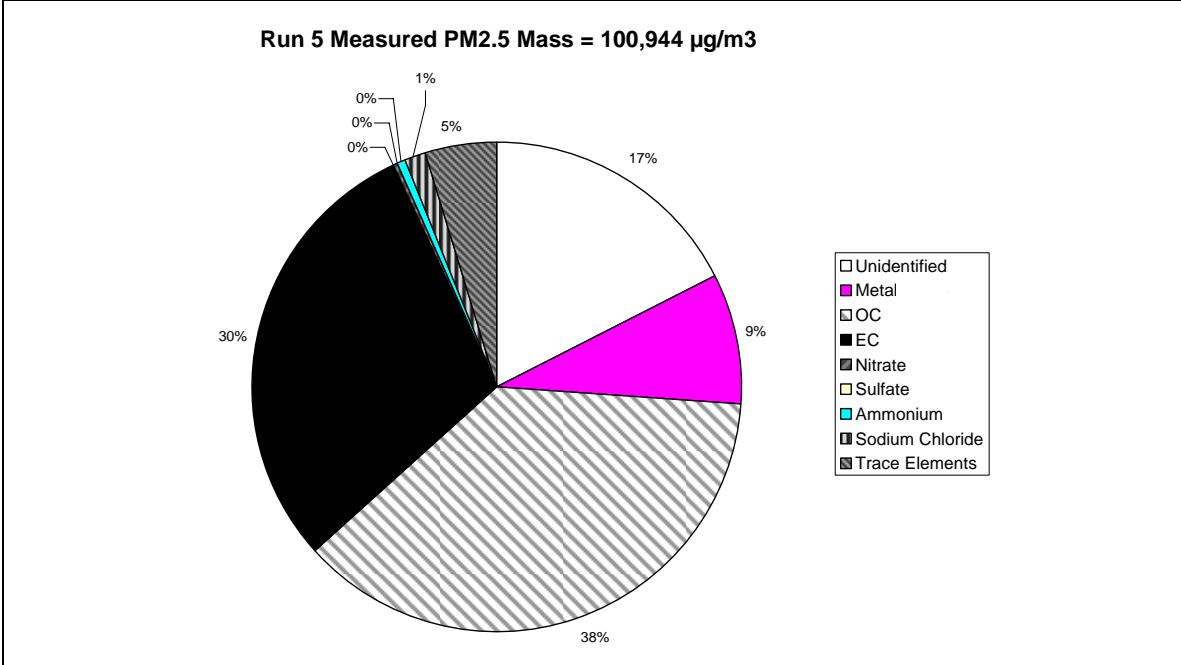
(a) Reconstructed mass balance for the sample collected from Run 2 using the DRI Source Dilution Sampling System



(b) Reconstructed mass balance for the sample collected from Run 3 using the DRI Source Dilution Sampling System.

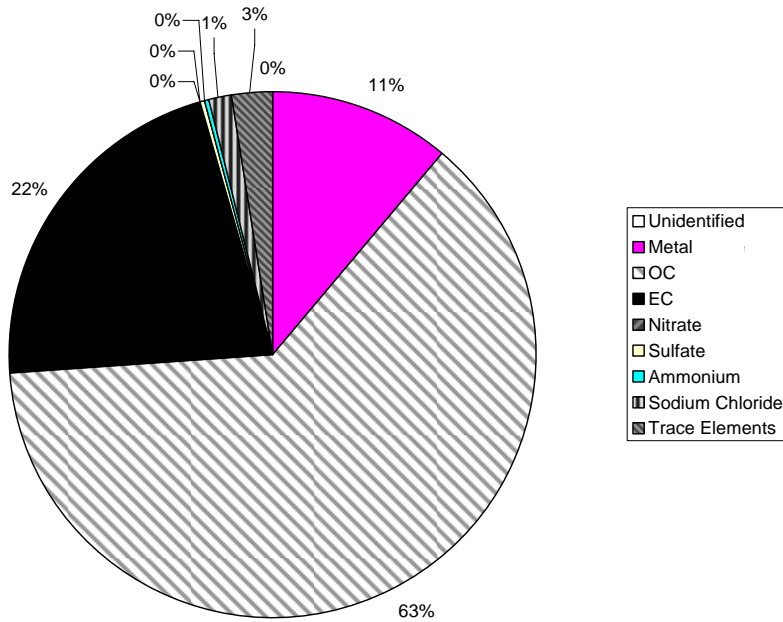


(c) Reconstructed mass balance for the sample collected from Run 4 using the DRI Source Dilution Sampling System



(d) Reconstructed mass balance for the sample collected from Run 5 using the DRI Source Dilution Sampling System

Run 6 Measured PM2.5 Mass = 66,884 µg/m3



(e) Reconstructed mass balance for the sample collected from Run 6 using the DRI Source Dilution Sampling System.

APPENDIX B-3

Calculation of Reconstructed Mass with Results from Chemical Analyses.

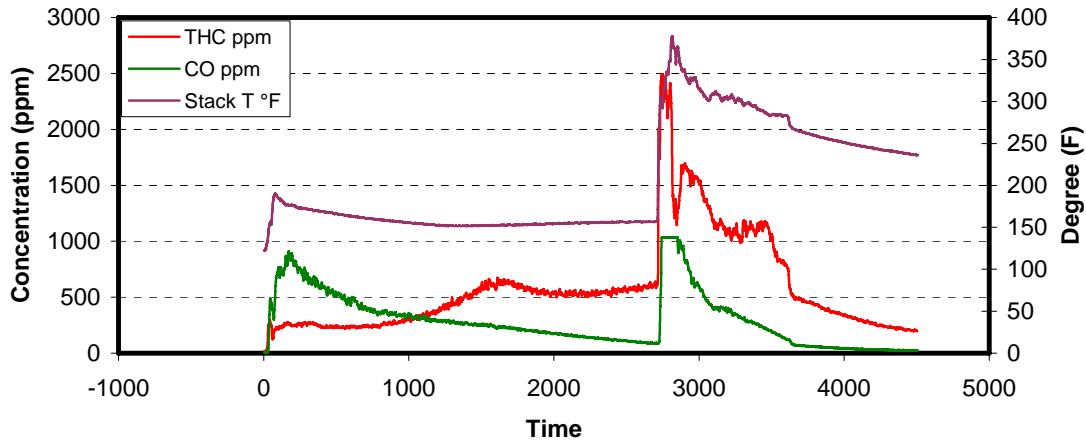
The reconstructed PM_{2.5} mass is the total of chemical species quantified by different analysis and is calculated by considering inorganic material and organic carbon as:

$$\begin{aligned} \text{Metal} &= 1.89 * \text{Al} + 2.14 * \text{Si} + 1.4 * \text{Ca} + 1.43 * \text{Fe} \\ \text{Organic Carbon Matter} &= 1.3 * \text{carbon in organic fraction determined by IMPROVE protocol} \\ \text{Sodium Chloride} &= 1.65 \times \text{Cl} \end{aligned}$$

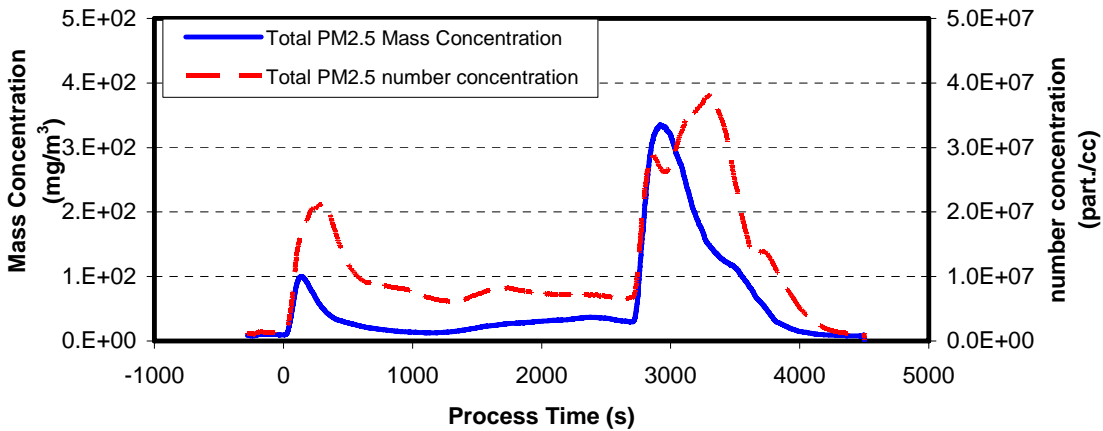
Trace elements are sum of elements (from X-ray fluorescence), excluding Al, Si, Ca, Fe, Cl, and S. Therefore, the unidentified fraction is the difference between reconstructed PM_{2.5} mass and PM_{2.5} mass determined by weighing.

APPENDIX C

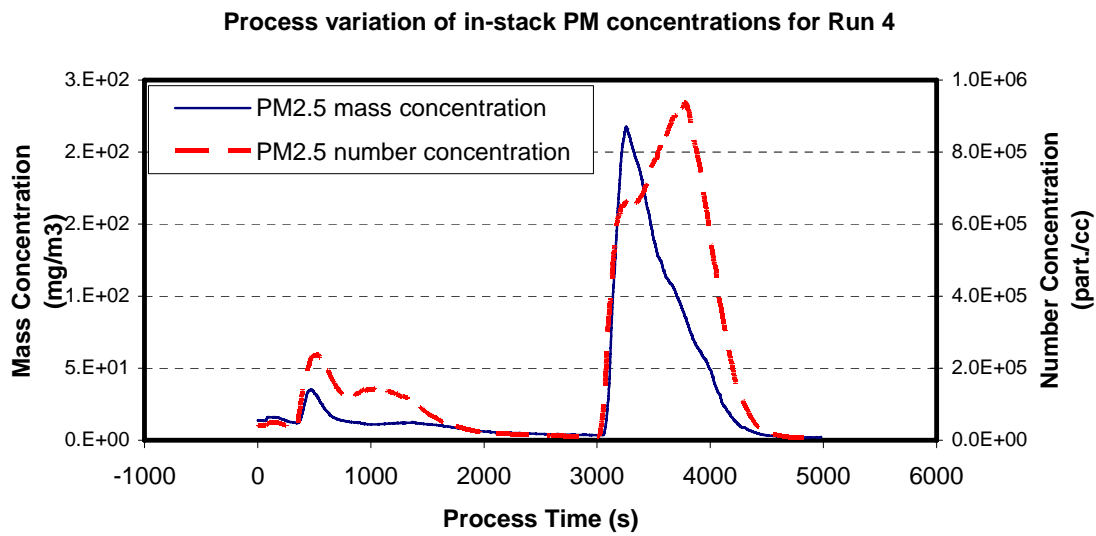
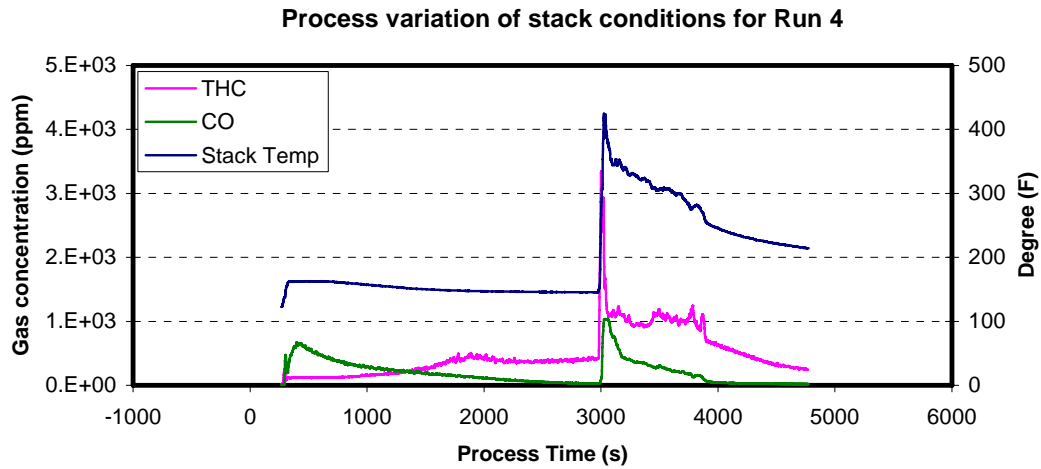
Process variation of stack conditions for Run 3



Process variation of in-stack PM concentrations for Run 3

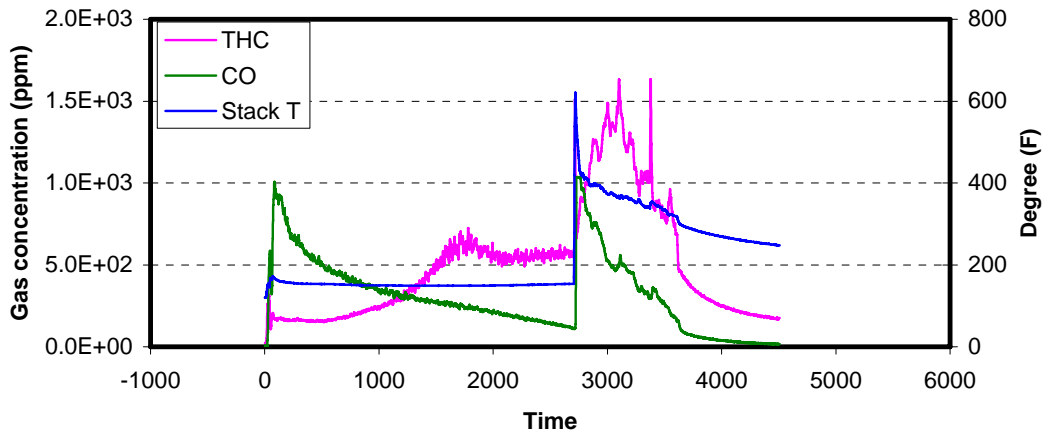


(a) Process variation of total PM_{2.5} mass concentration, total PM_{2.5} number concentration, and stack conditions for Run 3.

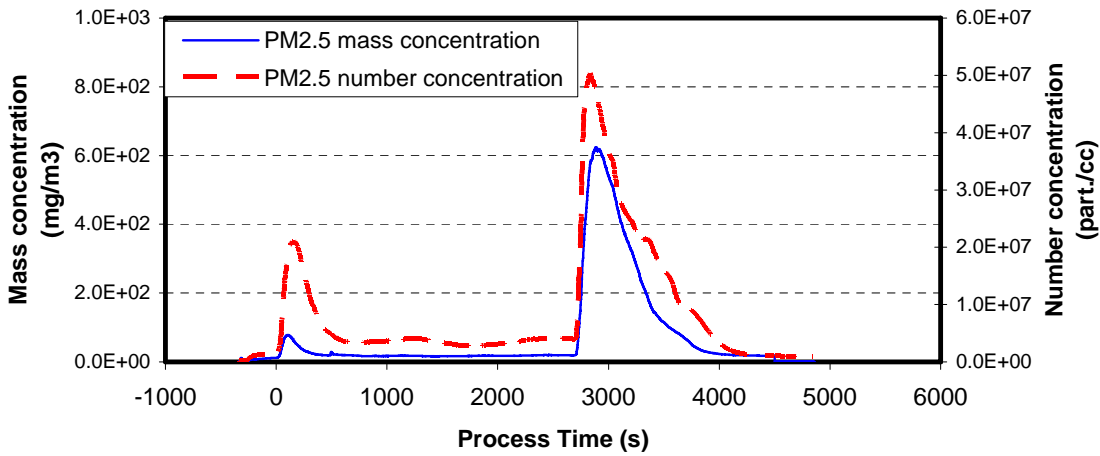


(b) Process variation of total PM_{2.5} mass concentration, total PM_{2.5} number concentration, and stack conditions for Run 4.

Process variation of stack condition for Run 5

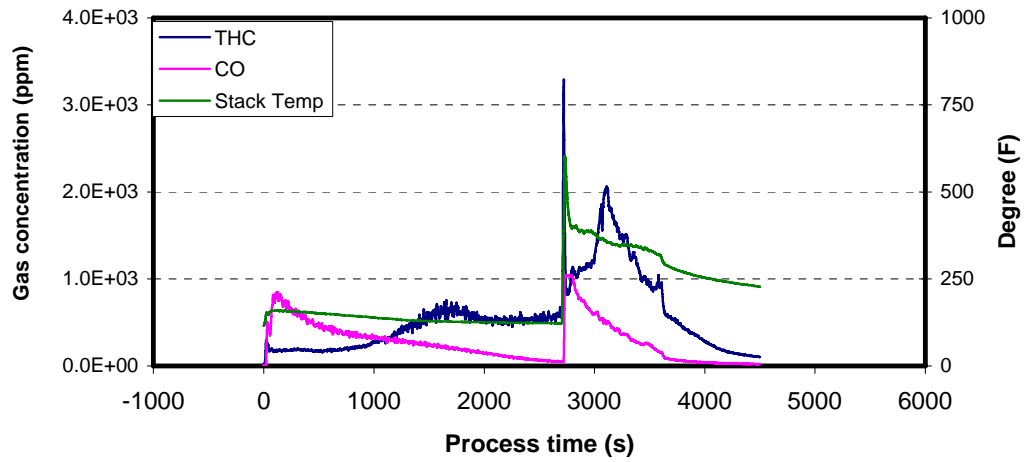


Process variaion of in-stack PM concentrations for Run 5

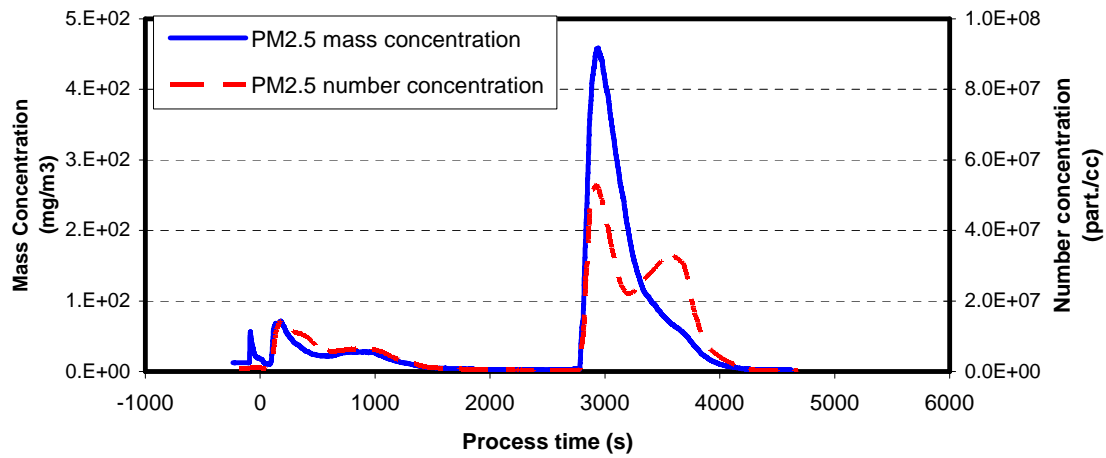


(c) Process variation of total PM_{2.5} mass concentration, total PM_{2.5} number concentration, and stack conditions for Run 5.

Process variation of stack conditions for Run 6



Process variation of PM_{2.5} concentrations for Run 6



(d) Process variation of total PM_{2.5} mass concentration, total PM_{2.5} number concentration, and stack conditions for Run 6.