ENVIRONMENT

Environmental Assurance
Monitoring, Reporting and
Innovation

McInytre Centre
4946 – 89 Street
Edmonton, Alberta T6E 5K1
Canada

Telephone: (780) 427-7888
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September 25, 2009

File No(s). 2009 – 292A / 314A

Dawn Ewan
Peace Airshed Zone Association
P.O. Box 21135
Grande Prairie, Alberta
T8V 6W7

Dear Dawn

Re: Peace Airshed Zone Association (Pasza) Ambient Air Monitoring Station Audits

Please see attached audit summary for all audit findings from the September 2009 audits conducted in the Pasza air shed

Please address the issues by October 23, 2009, in writing indicating what corrective actions have been taken. If you have any questions please contact the undersigned at 780-427-7888.

Yours truly,

Al Clark
Monitoring Systems Auditor
Environmental Assurance

Attachment(s): None

cc: Gary Sasseville: District Approvals Manager
Greg Smith: District Compliance Manager
Marilyn Albert: Industrial Monitoring Assessment Technologist
Janine Ross: Ambient Air Support Tech
Jennifer Keturakis: Industrial Approvals Engineer

Audit Summary

Facility / Zone	Pasza
Total # of parameters that passed	19
Total # of parameters audited in the network	23
Date(s) of the audit	September 14 - 17, 2009

Station Name	Valleyview		
Auditor	Al Clark		
Audit Date	September 14, 2009		
Critical	**Pass**	**Fail**	
H2S	√		
SO2	√		
TRS			
NOx			
O3			
CO			
HC			
C3H8			
NH3			
Teom/BAM PM 2.5			
WS/WD	√		
Wind head Orientation			
Manifold Fan			
Precipitation Sampler			
Partisol PM 2.5			
Partisol PM 10			
Partisol TSP			
Zero/Span Systems Operational	√		
Inspection Items	**OK**	**Need for Improvement**	
Sample pump venting/scrubbing		X	Not vented
HV/AC	√		
Manifold			
Sample Lines		X	Dirty
Particulate PM 2.5			
Partisol PM 10			
Partisol TSP			
Safety	√		
Site Conditions	√		
Non-critical	**OK**	**Opportunity for Improvement**	
RH	√		
Station Temperature			
Ambient Temperature	√		
Solar Radiation			
Barometric Pressure			
Tipping bucket			
Station Condition	√		
Station Documentation		X	Needs review / or missing

Not monitored at this location

Audit Summary

Facility / Zone	Pasza
Total # of parameters that passed	19
Total # of parameters audited in the network	23
Date(s) of the audit	September 14 - 17, 2009

Station Name	Smokey Heights		
Auditor	Al Clark		
Audit Date	September 14, 2009		
Critical	**Pass**	**Fail**	
H2S			
SO2	√		
TRS	√		
NOx			
O3			
CO			
HC			
C3H8			
NH3			
Teom/BAM PM 2.5		**X**	Excessive dirt in head
		X	Flow
WS/WD	√		
Wind head Orientation	√		
Manifold Fan	√		
Precipitation Sampler			
Partisol PM 2.5			
Partisol PM 10			
Partisol TSP			
Zero/Span Systems Operational	√		
Inspection Items	**OK**	**Need for Improvement**	
Sample pump venting/scrubbing	√		
HV/AC	√		
Manifold		**X**	Dirty
Sample Lines		**X**	Dirty
Particulate PM 2.5			
Partisol PM 10			
Partisol TSP			
Safety	√		
Site Conditions	√		
Non-critical	**OK**	**Opportunity for Improvement**	
RH			
Station Temperature			
Ambient Temperature	√		
Solar Radiation			
Barometric Pressure			
Tipping bucket			
Station Condition	√		
Station Documentation		**X**	Needs review / or missing

Not monitored at this location

Audit Summary

Facility / Zone	Pasza
Total # of parameters that passed	19
Total # of parameters audited in the network	23
Date(s) of the audit	September 14 - 17, 2009

Station Name	Beaverlodge		
Auditor	Al Clark		
Audit Date	September 15, 2009		
Critical	**Pass**	**Fail**	
H2S			
SO2	√		
TRS			
NOx	√		
O3	√		
CO			
HC			
C3H8			
NH3			
Teom/BAM PM 2.5		**X**	Excessive dirt in head
WS/WD	√		
Wind head Orientation	√		
Manifold Fan	√		
Precipitation Sampler			
Partisol PM 2.5			
Partisol PM 10			
Partisol TSP			
Zero/Span Systems Operational	√		
Inspection Items	**OK**	**Need for Improvement**	
Sample pump venting/scrubbing	√		
HV/AC	√		
Manifold	√		
Sample Lines	√		
Particulate PM 2.5			
Partisol PM 10			
Partisol TSP			
Safety	√		
Site Conditions	√		
Non-critical	**OK**	**Opportunity for Improvement**	
RH	√		
Station Temperature			
Ambient Temperature		**X**	+/- 1˚C
Solar Radiation			
Barometric Pressure			
Tipping bucket			
Station Condition	√		
Station Documentation		**X**	Needs review / or missing

Not monitored at this location

Audit Summary

Facility / Zone	Pasza
Total # of parameters that passed	19
Total # of parameters audited in the network	23
Date(s) of the audit	September 14 - 17, 2009

Station Name	Evergreen		
Auditor	Al Clark		
Audit Date	September 15, 2009		
Critical	**Pass**	**Fail**	
H2S			
SO2	√		
TRS	√		
NOx			
O3			
CO			
HC			
C3H8			
NH3			
Teom/BAM PM 2.5		X	Excessive dirt in head
WS/WD	√		
Wind head Orientation	√		
Manifold Fan	√		
Precipitation Sampler			
Partisol PM 2.5			
Partisol PM 10			
Partisol TSP			
Zero/Span Systems Operational	√		
Inspection Items	**OK**	**Need for Improvement**	
Sample pump venting/scrubbing		X	Not vented
HV/AC	√		
Manifold		X	Dirty
Sample Lines		X	Dirty
Particulate PM 2.5		X	Dirty Bypass Filter
Partisol PM 10			
Partisol TSP			
Safety	√		
Site Conditions	√		
Non-critical	**OK**	**Opportunity for Improvement**	
RH	√		
Station Temperature			
Ambient Temperature	√		
Solar Radiation			
Barometric Pressure			
Tipping bucket			
Station Condition	√		
Station Documentation		X	Needs review / or missing

Not monitored at this location

Audit Summary

Facility / Zone	Pasza
Total # of parameters that passed	19
Total # of parameters audited in the network	23
Date(s) of the audit	September 14 - 17, 2009

Station Name	Henry Pirker
Auditor	Al Clark
Audit Date	September 16, 2009

Critical	**Pass**	**Fail**	
H2S			
SO2	√		
TRS	√		
NOx	√		
O3	√		
CO	√		
HC	√		
C3H8			
NH3			
Teom/BAM PM 2.5		X	Excessive dirt in head
WS/WD	√		
Wind head Orientation	√		
Manifold Fan	√		
Precipitation Sampler			
Partisol PM 2.5			
Partisol PM 10			
Partisol TSP			
Zero/Span Systems Operational	√		

Inspection Items	**OK**	**Need for Improvement**	
Sample pump venting/scrubbing		X	Not vented
HV/AC	√		
Manifold		X	Dirty
Sample Lines		X	Dirty
Particulate PM 2.5		X	Dirty Bypass Filter
Partisol PM 10			
Partisol TSP			
Safety	√		
Site Conditions	√		

Non-critical	**OK**	**Opportunity for Improvement**	
RH	√		
Station Temperature			
Ambient Temperature	√		
Solar Radiation	√		
Barometric Pressure			
Tipping bucket			
Station Condition	√		
Station Documentation		X	Needs review / or missing

Not monitored at this location

Audit Summary

Facility / Zone	Pasza
Total # of parameters that passed	19
Total # of parameters audited in the network	23
Date(s) of the audit	September 14 - 17, 2009

Station Name	Rover		
Auditor	Al Clark		
Audit Date	September 17, 2009		
Critical	**Pass**	**Fail**	
H2S			
SO2	√		
TRS	√		
NOx	√		
O3	√		
CO			
HC			
C3H8			
NH3			
Teom/BAM PM 2.5			
WS/WD	√		
Wind head Orientation		X	Not True North
Manifold Fan	√		
Precipitation Sampler			
Partisol PM 2.5			
Partisol PM 10			
Partisol TSP			
Zero/Span Systems Operational	√		
Inspection Items	**OK**	**Need for Improvement**	
Sample pump venting/scrubbing		X	Not vented
HV/AC	√		
Manifold		X	Dirty
Sample Lines		X	Dirty
Particulate PM 2.5			
Partisol PM 10			
Partisol TSP			
Safety	√		
Site Conditions	√		
Non-critical	**OK**	**Opportunity for Improvement**	
RH			
Station Temperature			
Ambient Temperature	√		
Solar Radiation			
Barometric Pressure			
Tipping bucket			
Station Condition	√		
Station Documentation		X	Needs review / or missing

Not monitored at this location

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September 25, 2009

File No(s). 2009 – 292A / 314A

Dawn Ewan
Peace Airshed Zone Association (Pasza)
P.O. Box 21135
Grande Prairie, Alberta
T8V 6W7

Dear Dawn

Re: Pasza Ambient Air Monitoring Station Audits

This letter is address some concerns noted during the recent audits conducted in the Pasza network.

- All locations that contained a continuous particulate monitor had sampling heads that were excessively dirty. Both the PM10 sampling head and the PM2.5 sharp cut cyclone sampling head are not functioning properly. A review of station logs must be completed to determine when the last cleaning of the sampling heads was completed. Also a review of when the internal sampling filter was changed as well. This is necessary to determine downtime due to improper maintenance being done. Please forward all documentation to Alberta Environment for review.

- During one of the particulate audits a leak was found. This leak was identified as being from the installation of a bypass filter and not putting Teflon tape around the ends of the filter. The date of that bypass filter install is required. The leak tolerance of +/- 0.15 lpm was exceeded as per the audit criteria for that generation of sampler. Since those criteria would have been exceeded from the date of install downtime has been incurred. A new filter with Teflon taped ends was installed and the leak test then met the audit criteria of +/- 0.15 lpm.

- More frequent cleaning of the sample manifolds and sample lines is required. All stations that have manifolds were dirty and some of the lines had layered dirt around the ports and on the lines. At the Rover station there were even excessive amounts of plant material on the sample lines.

- Several of the stations had the pumps venting into the station and not outside. At the Rover station the smell of ozone was evident due to the scrubber being depleted. At most locations the pumps are loosely placed on the floors outside existing pump cabinets. This will cause damage to the floors, the lines attached to the pumps and any power cords that come in contact with the vibrating pumps. The noise level inside the stations is also quite high as a result of not being secured inside the existing cabinets. The Rover station was the most notably noisy.

- Interviews with the contractor's representative indicated that the TRS / H_2S analyzers are not having their SO_2 scrubbers challenged at a minimum of monthly as per the AMD. The contractor stated they might be done every 3 – 4 months which does not meet AMD guidelines.

- The wind head cross-arm at the Rover station was misaligned when installed. It was oriented approximately 20 degrees too far north. It was corrected during the audit to the proper east – west orientation.

- The locations that contain the ultra sonic wind heads have no visible marking to indicate north. Also the units contain the temperature and relative humidity sensors which are co-located with the wind sensor. This does not allow proper verification with the audit sensors. Typically the temperature and relative humidity sensors should be located at the 2 meter level.

- Please note that after research of the TEOMS for different generations of samplers, there has been 2 changes made to the specifications. The temperature sensor is now at +/- 2 degrees celcius tolerance and the main flow leak test is <0.65 lpm. Audits that fall under these different tolerances and were deemed as not meeting the original audit specification have been corrected to reflect the proper specifications.

Please forward all relevant documents for review. If you have any questions please contact the undersigned at 780-427-7888.

Yours truly,

Al Clark
Monitoring Systems Auditor
Environmental Assurance

Attachment(s): none

cc: Gary Sasseville: District Approvals Manager
Greg Smith: District Compliance Manager
Marilyn Albert: Industrial Monitoring Assessment Technologist
Janine Ross: Ambient Air Specialist
Jennifer Keturakis: Air Monitoring Report Coordinator

PASZA
Peace Air Shed Zone Association

P.O. Box 21135
Grande Prairie, Alberta
T8V 6W7
(780) 833-4343

December 10, 2009

Al Clark
Monitoring Systems Auditor
Environmental Assurance
Alberta Environment
McIntyre Centre
4946 89 Street
Edmonton, Alberta
T6E 5K1

Dear Mr. Clark

SUBJECT: Peace Airshed Zone Association Ambient Air Monitoring Station(s) Audit
File No. 2009 – 292A / 314A

Further to the Alberta Environment (AENV) audit correspondence dated September 25, 2009 and the teleconference between AENV, Focus and Peace Airshed Zone Association (PASZA) on October 30, 2009, PASZA provides the following response.

AENV noted that challenging SO_2 scrubbers on H_2S/TRS analyzers is a requirement of the AMD where SO_2 exists and following this procedure is an opportunity for improvement for the operation of the analyzers in PASZA network. PASZA has confirmed these analyzers will be challenged more frequently with SO_2 and this will be documented.

Data for temperature, relative humidity, wind speed and direction sensors at the Evergreen Park and Valleyview stations has historically been reported at the 2 metre height. The AENV audit identified these sensors are positioned closer to 10 metres as result, this data in now being reported at the 10 metre height. Further as an opportunity for improvement, the small orientation markings on the sensors will be supplemented with larger marking visible from the ground during the next scheduled sensor maintenance.

The Rover station wind direction data has been corrected and resubmitted.

The AENV audit identified the particulate heads in the network were “excessively dirty” at the time of the audit and as a result, may not have been functioning properly to achieve the proper cut point. AENV concluded in the conference call on October 30 that the condition of the particulate heads, at the time of audit, warranted removal of the data back to July 13, 2009 the date the audit was announced to PASZA.

PASZA
Peace Air Shed Zone Association

P.O. Box 21135
Grande Prairie, Alberta
T8V 6W7
(780) 833-4343

PASZA's October 23 response provided a study of the effects loading on the performance of the particulate monitor heads that was completed for the manufacture, BGI Incorporated. The study concludes that the VSCC $PM_{2.5}$ sample heads were able to operate at an equivalent concentration of 150 micrograms per cubic metre for a period of at least 90 days with little effect on the d50 cut point and only a small increase in the sharpness of cut. Following the phone conference there was also some confusion as to the exact model of particulate monitor heads used in the PASZA network.

PASZA has under gone the following steps to determine the validity of the particulate data in question:

- Confirmed the particulate monitor heads used in the PASZA network are the $PM_{2.5}$ sharp cut cyclone (SCC) samples heads
- Conducted additional research with the manufacture to determine:
    - the differences between the VSCC and the SCC,
    - if there is a measurable way to assess the point at which loading of a particulate head affects the data, and
    - if there is an impact on the data from a particulate head that appears to have heavy loading
- Focus conducted a review of the data from April until November 2009 to determine if there are any observable data quality changes
- Researched options and costs for addition third party data review

PASZA concludes the following from the additional research conducted:

- The physical design of the SCC and the VSCC are the same, where the design of the head will have the most impact on the effect of loading
- All studies indicate that the effect of loading on the SCC and the VSCC do not affect the cut point of the head enough to affect the data collected by the monitor (in this case TEOMs)
- The first set of data plots do not show any shift in trend of the data from period before the heads were cleaned to after
- Based on the findings in the studies there currently is no measurable way to assess whether data will be affected by loading of particulate heads.

Based on all the information provided above and the attached supporting documentation provided in Focus' response the indication is that there is not enough evidence to conclude loading of the particulate heads has affected the data.

Since there are no measurable criteria, no scientific data support and no observable data quality changes, PASZA feels the data in question is valid and should not be removed. As a result, PASZA is not willing to forgo the cost of additional third party data review without specified measurable criteria.

PASZA
Peace Air Shed Zone Association

P.O. Box 21135
Grande Prairie, Alberta
T8V 6W7
(780) 833-4343

If this response provided is not acceptable to AENV, PASZA requests a response in writing outlining the basis for data invalidation and a meeting with AENV to develop a written action plan, as per the current draft Audit.

I will be away from the office until January 4, 2010. If you have any questions or concerns during this time period, please contact Dawn Ewan at 780.833.4343. After January 4, 2010 please contact me at 780.882.4071.

Yours Truly,

Shelly Pruden
PASZA Program Manager

Cc: Gary Cross, Focus Corporation
Greg Smith, Alberta Environment
Jennifer Keturkis, Alberta Environment

Attachment: Focus letter response to PASZA dated December 2, 2009 and supporting documentation

December 2, 2009

Peace Airshed Zone Association
PO Box 21135
Grande Prairie, Alberta T8V 6W7

ATTENTION: Shelly Pruden

RE: PASZA Network Ambient Air Monitoring Station(s) Audit

Reference: File No. 2009 – 292A / 314A

AENV audited the continuous monitoring stations of the Peace Airshed Zone Association's (PASZA) ambient air quality monitoring network from September 14 to 17, 2009 and provided comments to the PASZA in a letter dated September 25, 2009. All points in this letter have been resolved with the exception of the first one. The AENV comment is included below followed initially by the first response to AENV and then by our second response.

AENV Comment #1
All locations that contained a continuous particulate monitor had sampling heads that were excessively dirty. Both the PM10 sampling head and the PM2.5 sharp cut cyclone sampling head are not functioning properly. A review of station logs must be completed to determine when the last cleaning of the sampling heads was completed. Also a review of when the internal sampling filter was changed as well. This is necessary to determine downtime due to improper maintenance being done. Please forward all documentation to Alberta Environment for review.

First Response from PASZA
The cleaning of the particulate heads in the PASZA network was last completed between June 9 and July 21, 2009 as outlined in the attached service and calibration reports. As per the manufacture maintenance specifications outlined in Section 4.0 of the enclosed BGI manual, for use on fine particulate continuous monitors i.e., TEOM the operator can clean the device on a 90 day continuous operation basis.

In addition, PASZA has included for your review a study of the effects loading on the performance of the particulate monitor heads that was completed for the manufacture, BGI Incorporated. The study concludes that the PM2.5 sample heads used in the PASZA network were able to operate at an equivalent concentration of 150 micrograms per cubic metre for a period of at least 90 days with little effect on the d50 cut point and only a small increase in the sharpness of cut.

A review of the data from June to September did not indicate any unusual step changes in the PM2.5 concentrations measured at the stations, except for elevated readings measured during the forest fires at the end of August and the Canada Day celebration fireworks on July 1, 2009. Based on the manufacturer's operating limits and our data review, data was not invalidated. However PASZA will look at increasing the particulate head cleaning frequency.

Introduction

From the audit findings presented by AENV, our interpretation of those findings is as follows:
The heads were excessively dirty (heavy loading) and because of that were not functioning properly (not achieving the proper cutpoint). As the cutpoint was not achieved, the data must be removed for the period back to the previous cleaning.

The issues that we feel are important to the interpretations above and need to be resolved to make a proper assessment of the data collected over the period in question are:

1. Is there an impact on the data from a particulate head that appears to have heavy loading?
2. Is there a measureable way to assess the point at which loading of a particulate head affects the data?

Answers to these two questions will resolve the current outstanding issue with the findings from the September audit. The remainder of this document will summarize the information gathered while researching this issue and provide our conclusion at the end.

Background

To start, an understanding of the history and evolution of the particulate fractioning heads is required. This history is restricted to the PM2.5 head as this is the one in question and the last cut prior to reaching the monitor's detector. To start, I would like to present an email from Bob Gussman of BGI, which helps to summarize the history of the development of these types of heads

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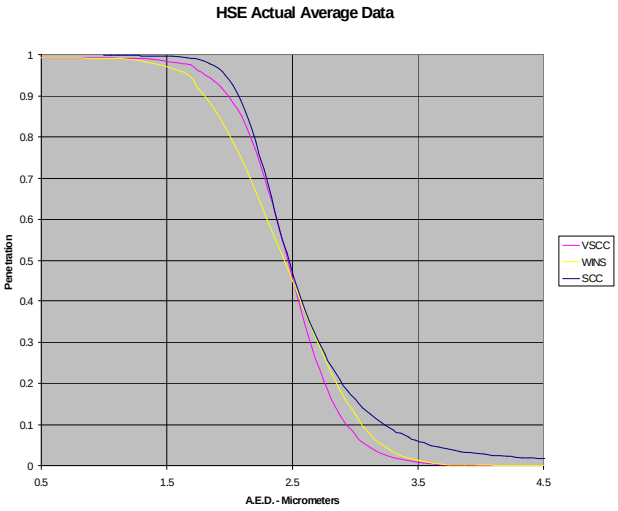
From: R. Gussman [mailto:g@bgiusa.com]
Sent: Wednesday, November 18, 2009 11:54 AM
To: Grover Christiansen
Cc: Brian
Subject: Re: PM2.5 details

Grover,
Bob Gussman here. I am aware of this situation. I will answer you with a thread of factual events, all of which I was a leading part of.

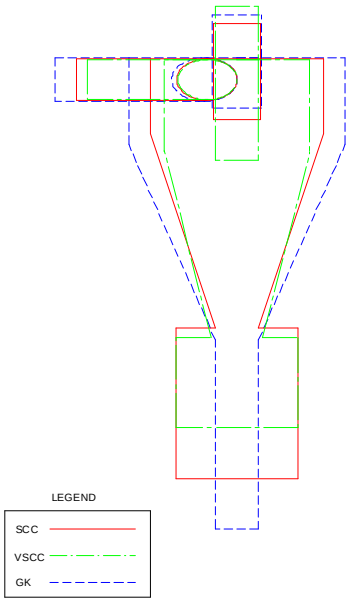
1. The WINS sampler for PM 2.5 was barely adequate.
2. BGI and R&P financed the development of the SCC http://www.bgiusa.com/aam/hse_pdf.pdf
3. EPA refused to accept it as a replacement for the WINS because the curve was not as sharp.
4. BGI developed the VSCC, tested it and Designation followed as an Equivalent Standard (Now at Reference Level).
5. As part of the Designation procedure we tested it for loading effect http://www.bgiusa.com/aam/vsccref7.pdf This proved that it required cleaning once every 90 days. EPA decided to limit the cleaning cycle to 30 days. No explanation was furnished.
6. R&P followed by TFS manufacture their own SCC, as they are quite entitled to do. Met One buys it from BGI.
7. Both Met One and Thermo buy the VSCC from BGI as they are not permitted to manufacture it.
1. They make a few hundred dollars more on the SCC than the VSCC, so they only furnish the VSCC in the US. For export sales of all PM2.5 equipment they furnish the SCC. This means that the instruments can not carry a PM 2.5 designation sticker.
8. I have attached a presentation showing the difference between the WINS, SCC and VSCC.
9. Because EPA refused to consider the SCC for designation we did not spend the requisite large sum of money to do a loading study.
10. The VSCC is now the proven PM2.5, EPA approved device. We invested between $200 and $250 K on its development.

Best regards,
Bob

For reference from Bob's comment #8 on the presentation, the three slides are attached below.



Slide 1 – cutpoint curve



Slide 2 - dimension differences

Sharpness is defined as (D84/D50)^0.5

VSCC	**1.156**
SCC	**1.19**
WINS	**1.23**

Slide 3 – sharpness definition

To confirm the key points from Bob's email:

- The SCC head was jointly developed to improve the cut point from the WINS impactor
- The studies indicate that the SCC is a better cut point than the WINS impactor and that the cutpoint improves with loading
- The VSCC was developed exclusively by BGI to improve the cutpoint further
- From slide 2 it can be seen that the difference between the SCC and VSCC are negligible
- BGI only invested in studies on the VSCC as that is the one they developed exclusively.
- The SCC head used throughout Canada, does not have a designation with the EPA as traceable to a reference method.

Reference to Loading Studies Conducted.

The first link in Bob's email is to a comparative study (Kenny PM2.5 head comparative study.pdf) that was completed after the development of the SCC and two other head designs from different manufacturers. The conclusions of the study indicate that the SCC outperformed the WINS impactor and the cutpoint was minimally impacted by loading.

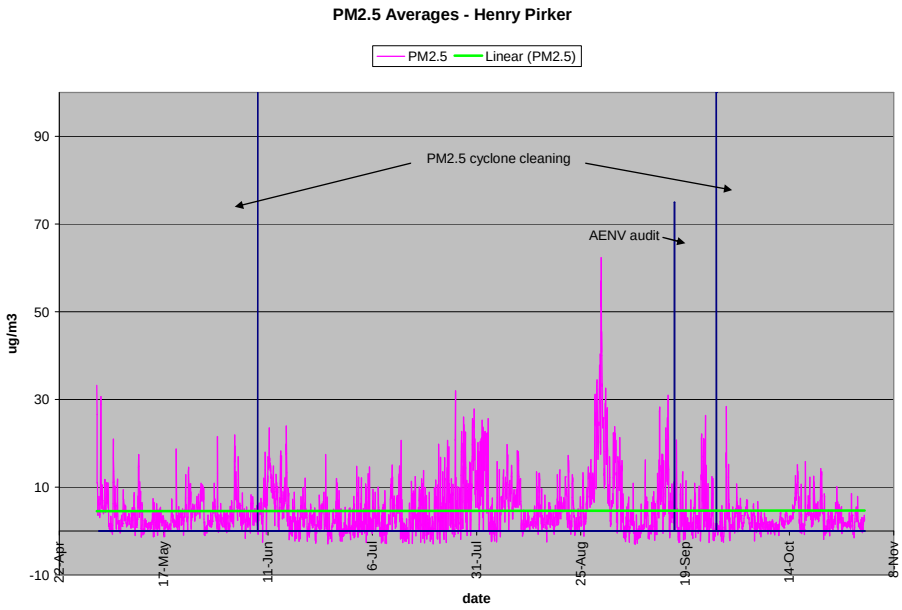
Another paper published in the "*2007 American Society of Agricultural and Biological Engineers ISSN 0001−2351*" and included as attachment (PM sampler errors.pdf) stated the following:

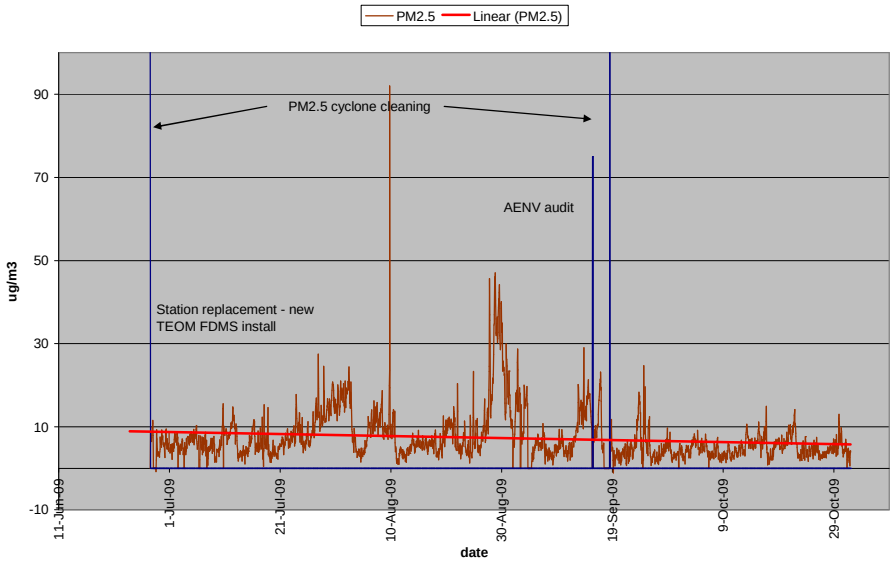
- Kenny et al. (2000) evaluated the WINS and SCC when loaded with Aloxite dust (and no PM_{10} inlet) and determined that the WINS cutpoint shifted steadily downwards to 2.15 _m, whereas the SCC cutpoint did not exhibit a significant downward shift.
- Kenny et al. (2000) concluded that cyclonic separators become more efficient with increased loading (i.e., the cutpoint shifts to the left with increased loading).

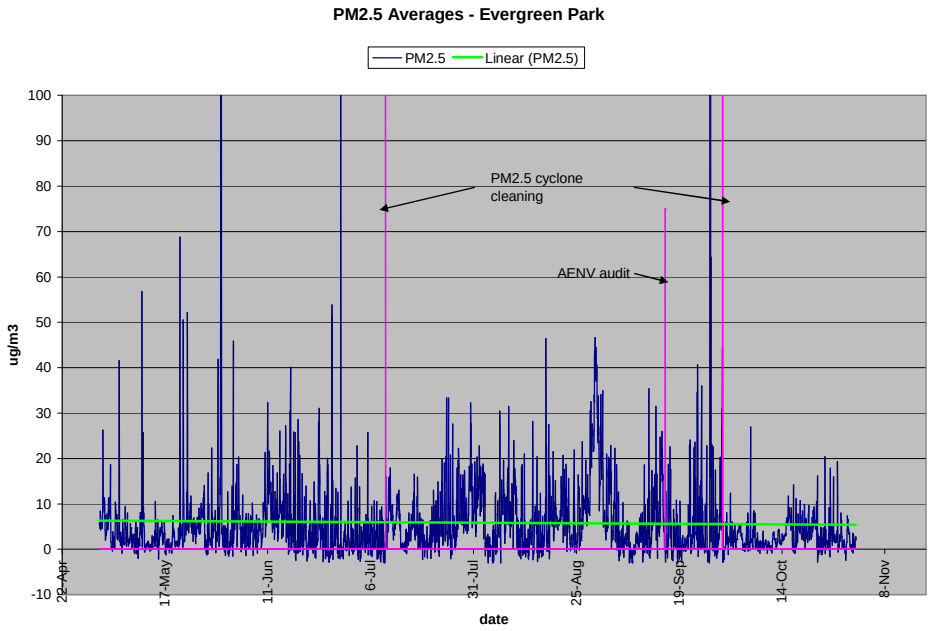
The final published study is the *"Effects of dust loading on the performance of the VSCC cyclone.pdf"*, which was presented in the initial response to AENV on the results of the September audit. AENV's response was that this study does not apply as the heads used in the PASZA network are the SCC design. We feel that the results of this study should be considered in this issue as the difference in the design of the SCC to VSCC are negligible and amount to only a slight difference in dimension to achieve a higher cut point. Because the physical shape of the cyclones is the same, the characteristics of the head under loading would also be the same. The difference is the cutpoint is slightly better with the VSCC whether either were clean or loaded.

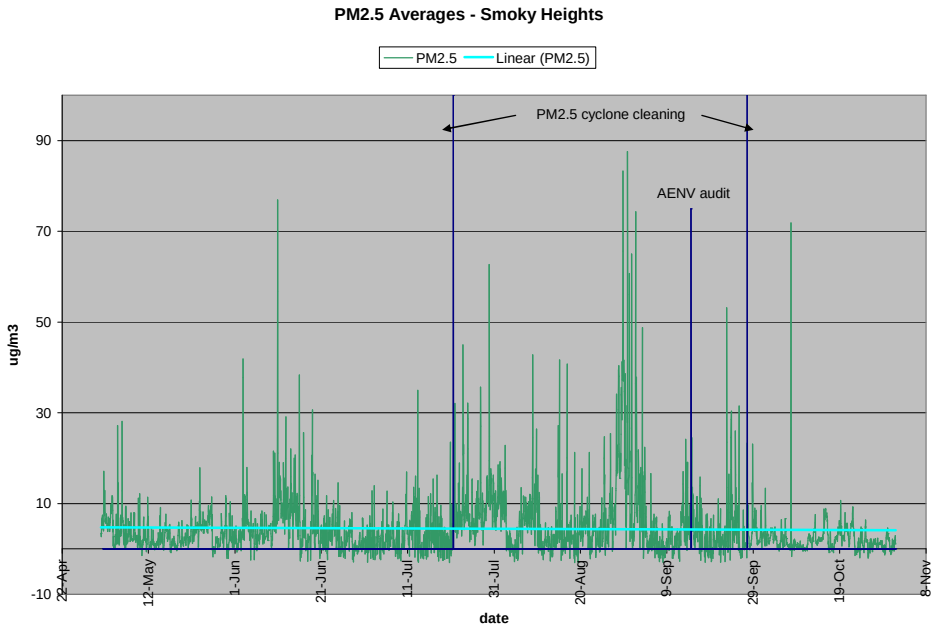
Data Review
Included below are two sets of data plots.

The first set of plots included below, show the final data over the period from spring to fall 2009 for each site that monitors PM2.5. The times when the heads were cleaned are indicated on the plots as well as the time of the AENV audit. When viewing these plots, it should be considered that the particulate data during the summer months is typically higher than spring fall and winter months and that precipitation plays a large roll in the increase and decrease of particulate levels. The trend lines on three of the four plots indicate no shifts or changing trends over the entire period. The only trend line that does show downward trend is the Beaverlodge FDMS unit as it was just installed when the station replacement took place.

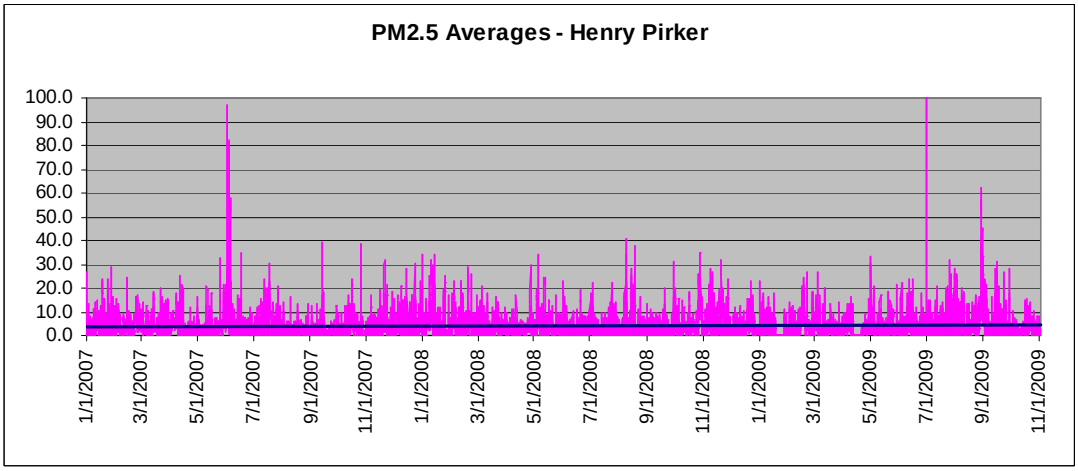








The second set of plots were generated from the final data collected over the period from January 2007 to October 2009. These plots show that there have been consistent trends that align with the trend values from the first set of plots at approximately 5μg/m^3.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100.0
90.0
80.0
70.0
60.0
50.0
40.0
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20.0
10.0
0.0
1/1/2007
3/1/2007
5/1/2007
7/1/2007
9/1/2007
11/1/2007
1/1/2008
3/1/2008
5/1/2008
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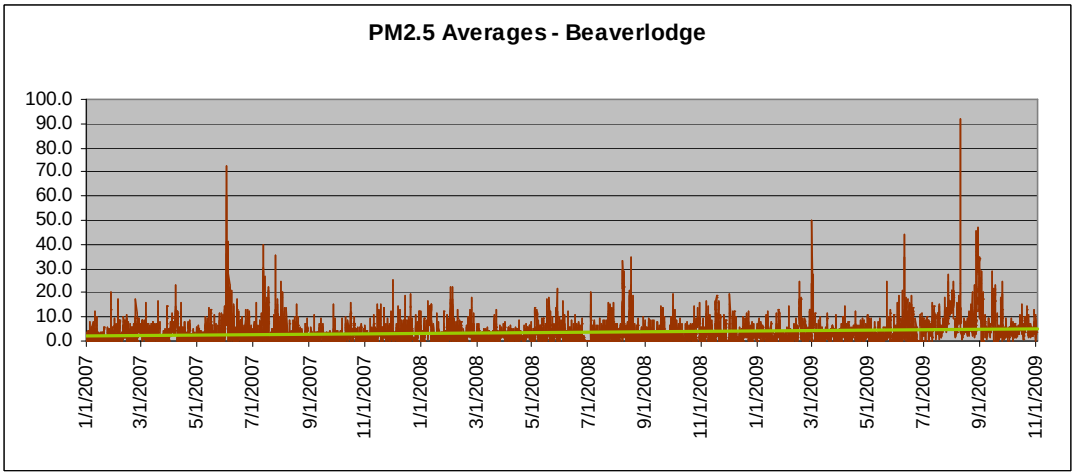
11/1/2009


PM2.5 Averages - Beaverlodge
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50.0
40.0
30.0
20.0
10.0
0.0
1/1/2007
3/1/2007
5/1/2007
7/1/2007
9/1/2007
11/1/2007
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3/1/2008
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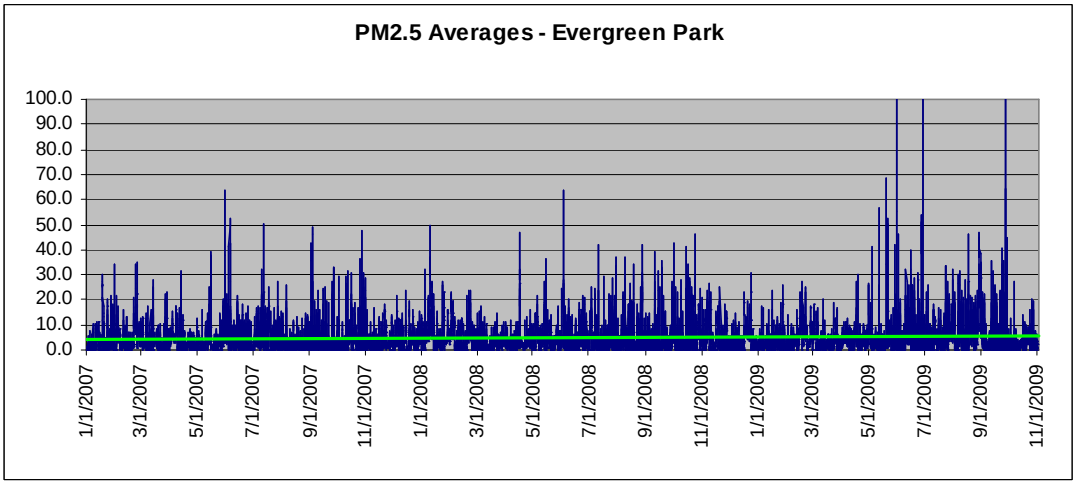
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3/1/2007
5/1/2007
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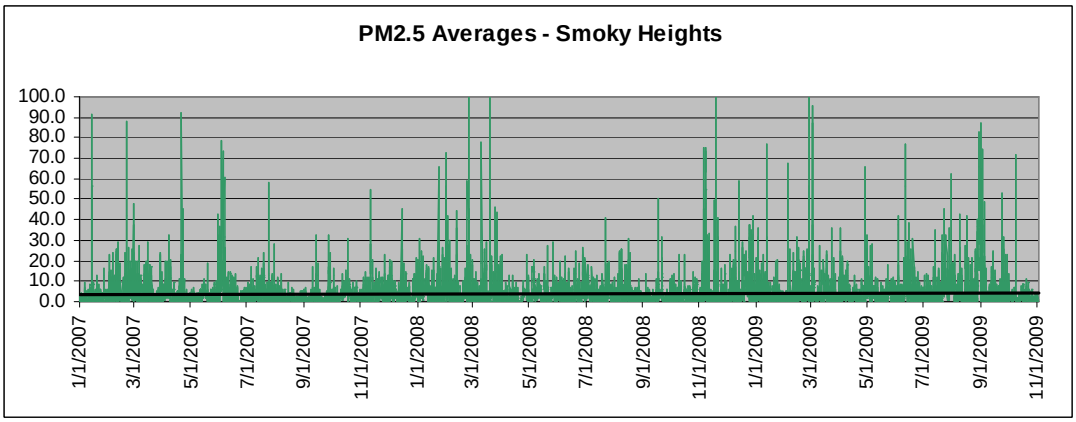

Conclusion

To answer the first point identified in the introduction, *"Is there an impact on the data from a particulate head that appears to have heavy loading?"* consider the following points:

- The physical design of the SCC and the VSCC are the same, where the design of the head will have the most impact on the effect of loading
- All study's indicate that the effect of loading on the SCC and the VSCC do not effect the cut point of the head enough to affect the data collected by the monitor (in this case TEOMs)
- The first set of data plots do not show any shift in trend of the data from period before the heads were cleaned to after

Based on all the information provided in the above points the indication is that there is not enough evidence to conclude that loading of the heads will affect the data. As this is the case, PASZA feels the data collected over the period in question is valid.

To answer the second point identified in the introduction, *"Is there a measureable way to assess the point at which loading of a particulate head affects the data?"* consider the following point:

- Based on the findings in the studies described in this document, there currently is no measurable way to assess whether data will be affected by loading of particulate heads.

Please contact me if you have any questions or concerns.

Sincerely,

THE FOCUS CORPORATION

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HEALTH & SAFETY LABORATORY

INVESTIGATION OF THE EFFECTS OF LOADING ON PM2.5 SELECTORS

L C Kenny

IR/L/A/98/13

Project Leader: L C Kenny
Biomedical Sciences Group

HEALTH AND SAFETY LABORATORY
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SUMMARY

Four different PM2.5 selectors were tested to determine their aerodynamic size-selection characteristics, both before and after loading with dust, under laboratory and field conditions. The aerosol penetration curves were measured using an Aerodynamic Particle Sizer. Many repeat tests were performed on two specimens of the Well Impactor Ninety Six (WINS), two specimens of a novel sharp cut cyclone (SCC), one member of the GK cyclone family (GK4.39) and one University Research Glass (URG) cyclone.

Four loadings of the WINS and SCC were made in the laboratory using a narrow-fraction alumina dust. The penetration curves were measured after each loading. Five cumulative outdoor loadings were made by setting up four PM2.5 samplers, two with WINS and two with SCC's, in a suburban garden during the summer months. The penetration curves were measured at weekly intervals after sampling times ranging from 96 to 132 hours. Three further cumulative loadings were tested in a similar experiment in a city-centre underground car park.

When clean, all three PM2.5 size selectors have 50% penetration (D_{50}) values close to 2.5 µm, although the penetration curve shape differs for the three selector designs. Under loading the D_{50} value for both the WINS and SCC fell, with the decrease being largest for the WINS. With high loadings the SCC D_{50} fell to 2.35 µm and the WINS D_{50} fell to 2.15 µm. The WINS deviation is large enough to possibly lead to undersampling of PM2.5.

The SCC cyclone provides a sharp cut for ambient air sampling applications and is less affected than the WINS by loading. Additionally, the SCC is a dry system whereas the WINS uses an oiled substrate. While the WINS cut point is unlikely to shift to an unacceptable degree during 24 or 96 hour sampling periods, it would perform less well than the SCC over extended sampling periods.

CONTENTS

1. INTRODUCTION

Aerosol samplers for ambient PM2.5 typically utilise either impactors or cyclones to effect the aerodynamic particle size selection. In this work, Rupprecht and Patashnick Co. Inc. (R&P) asked the Health and Safety Laboratory (HSL) to determine the feasibility of developing a lower maintenance, higher loading sharp cut point selector for use with continuous PM monitors. This was to be accomplished by testing four different PM2.5 selectors, two pre-existing commercial designs and two novel cyclone prototypes developed by BGI Inc. The purpose of the work was to assess the characteristics of the novel cyclones, finalise the design, and to assess the effects of dust loading on the different types of selector. The work was carried out collaboratively by HSL, R&P and BGI.

The EPA requirements for an ideal PM2.5 selector are contained in the US Federal Register (USEPA, 1997. The Federal Register tabulates the desired aerodynamic size selection curve and requires that any PM2.5 sampling device should have a 50% penetration value (or cut-point) of 2.5+0.2 µm, and sampling bias for PM2.5 concentrations less than 5%. The sampling bias is calculated numerically for three specified ambient aerosol size distributions, designated 'fine', 'typical' and 'coarse', details of which are also given in the Federal Register. Hence the characteristics of any real sampling device can be tested against these criteria to determine whether it's performance meets the required standard.

2. DESCRIPTION OF PM 2.5 SELECTORS TESTED

2.1 WINS impactor

The Well Impactor Ninety Six (WINS) impactor is described in the Federal Register and forms part of the designated PM2.5 Federal Reference Method (FRM). The design of the WINS Impactor is shown in cut away view in Figure 1. One of the principal features of the WINS Impactor is that it contains a well into which is placed a 37mm disc of fiberglass filter media and 1 ml of a low vapor pressure mineral oil, both of which are specified in the FRM. Concerns have been expressed as to the maximum interval between cleanings of the impactor well before a shift in the D_{50} cut will occur. The time factor is of concern because sequential PM2.5 samplers are intended to run without maintenance for 4 (USA) to 16 days (EUROPE); if the D_{50} shifts a false concentration will be indicated. The presence of the oil

may also effect speciation sampling, in which the major chemical species present in the PM2.5 aerosol are separated and quantified. Whilst there is no proven deleterious effect that is proven to occur when passing an aerosol over a pool of low volatility oil prior to subjecting the particles to chemical analysis, the concern does exist.

The WINS impactor was tested during its development by EPA contractors (Peters and Vanderpool, 1996) who measured it's aerodynamic size selection characteristics both before and after loading. The cut point or D_{50} was shown to shift downwards under load to 2.25 µm, but the effect of the shift on PM2.5 sampling bias was just within the acceptable limits.

2.2 GK cyclone

The most logical alternative to an impactor as a size selective collection device is a cyclone. Indeed two cyclone designs were considered by EPA during the development of the WINS Impactor (Peters et al., 1996). Both of these designs were rejected by the investigators as being unsuitable for EPA purposes, due to either a cut point shift when loaded, or an insufficiently sharp cut.

These findings notwithstanding, it was felt that cyclones deserved further investigation. Early work for EPA on stack sampling produced a series of round entry cyclones of intriguing characteristics with regards to the steepness of their efficiency curves (Smith et al., 1979). Several of these round entry designs were evaluated by Kenny and Gussman (1997) and a model describing a family of cyclones - GK cyclones - was derived and successfully applied to the design of several cyclones for various air sampling applications. A prototype GK cyclone, designed to fit within a PM2.5 FRM sampler as a direct replacement for the WINS, was manufactured for testing within this project. The dimensions of this cyclone are given in Table 1.

2.3 SCC cyclone

The Sharp-Cut Cyclone developed within this project was based on the design of the SRI-III cyclone described by Smith et al. (1979). Two differently-sized cyclones based on the SRI-III geometry were tested previously by Kenny and Gussman (1997). For PM2.5 sampling applications, the dimensions of the SRI-III were scaled up as suggested by the previous results in order to achieve the required cut point (D_{50}=2.5 µm) at a flow rate of 16.7 $l.min^{-1}$.

Following initial favourable test results, prototype SCC cyclones were fabricated that could be fitted within FRM samplers as an exact mechanical replacement for the WINS impactor. A cut-away drawing of the SCC is shown in Figure 2, and its dimensions are given in Table 1.

2.4 URG cyclone

The URG cyclone is based on the Stairmand design described and evaluated by Moore and Mc Farland (1993), and its dimensions are listed in Table 1. The cyclone is commercially available as an attachment for R&P's Tapered Element Oscillating Microbalance (TEOM) sampling system. One difference in the way the URG cyclone is used is that it is fitted as a replacement for the usual TEOM PM10 inlet, whereas the WINS impactor (and the SCC cyclones) are designed to be fitted downstream of the PM10 inlet. In principle this should have no effect provided that particles in the sub-2.5 µm range are aspirated with unit efficiency by both systems. However this assumption has not yet been validated by either wind tunnel or outdoor comparisons of the two systems.

3. EXPERIMENTAL METHODS

3.1 Determination of aerosol penetration curves

The experimental methods used to test the PM2.5 selectors were similar to those described in detail by Maynard and Kenny (1994). The tests were carried out in an aerosol chamber with working section 1 m^2. The test aerosol consisted of solid, spherical glass microspheres (Whitehouse Scientific) with physical diameters up to 25 µm, and density 2.95 g/cm^3. The aerosol was dispersed using a rotating brush generator into the separate mixing section at the top of the chamber. An aluminium honeycomb layer was used to remove eddies from the aerosol which was transferred into the working section by a slow (<2 $cm.sec^{-1}$) steady downflow of air. The generated aerosol typically had a number median diameter around 2 µm and a mass median diameter around 8 µm. The number concentration was typically 100-200 particles per cubic centimetre, and was very stable over the time scales necessary for the test (10 minutes per selector).

The test sampling lines were situated close to the centre of the chamber's working section, connected to an Aerodynamic Particle Sizer (APS) via two 15mm diameter vertical metal tubes. The APS was situated directly below the working section, outside the chamber. Access to the working section was gained through sealed glove ports in the side of the chamber, which allowed the flow through each test selector to be measured accurately using a Gillibrator bubble flowmeter placed inside the chamber. The flow through the system was maintained using a mass flow controller, calibrated and set before and after each test using the Gillibrator.

The test procedure involved placing a PM2.5 selector on one of the two sampling lines. Both sampling lines to the APS shared identical geometry and switching from one to the other was accomplished by means of ball valves. The size selection characteristics were measured by taking five 60-second samples of the polydisperse aerosol alternately from the two sampling lines. Hence the ratio of the aerosol size distributions measured through each line gives the size selective aerosol penetration through the selector alone, all other effects (including any aspiration and transfer losses) being identical in both lines.

Accumulator data files from the APS were stored and transferred to a separate PC for processing. A dedicated Pascal programme was used to reconfigure the particle counts in the 1024 APS accumulator channels into a histogram with selected aerodynamic diameter bin limits. The calibration function relating APS accumulator channel to particle aerodynamic diameter was derived using the calibration data file for the APS, taking into account the appropriate corrections for particle density. At the start of each working day the APS calibration was checked at three particle diameters, (3, 5 and 10 µm) using latex spheres traceable to Community Bureau of Reference (BCR) standards. The APS operating parameters were adjusted using the methodology described by Radar *et al.* (1990) to ensure that the actual calibration was in close agreement with the calibration data file.

For each aerodynamic diameter range, the average particle number counted with the selector present was divided by the average number counted without the selector present to determine the aerosol penetration for that diameter. The penetration values were analysed using the software package 'Tablecurve' (Jandel Scientific) in order to locate the D_{50} by interpolation.

The raw data were normalised so that the penetration values tended to unity for d_{ae}=0. Normalisation is necessary with this test system as the pressure drop across the selector causes the flow rates through the two sampling lines to differ slightly when the valve system is switched. In all cases it was assumed that any departures from unity were anomalous, and a suitable scaling factor for the penetration axis was used to eliminate them. Very little correction was required when testing the cyclones, which have a much lower pressure drop than the WINS impactor.

3.2 Laboratory loading experiment

Controlled loadings of the WINS and SCC size selectors only were made in a separate aerosol chamber. The dust used for loading was an aluminium oxide grinding powder, Aloxite F1200, which is known to have a MMAD around 6 µm and GSD of around 1.4 (Mark and Witherspoon, 1985). Hence almost all the particle mass is contained within an aerodynamic particle size range of 3 to 9 µm. For each loading test a single WINS impactor, a single SCC cyclone and a reference sharp-edged probe with 37mm glass fibre filter were set up within the chamber. Teflo filters were used downstream of the selectors to capture any under-size particles. The SCC and WINS flow rates were set to 16.7 lpm using a calibrated bubble flow meter, whereas the reference probe was operated at 10 lpm. The aloxite dust was generated into the chamber using a rotating table generator and mixed to produce a homogenous aerosol at the sampling positions.

The quantities of dust collected within the PM2.5 selectors were estimated by weighing all filters, plus blanks of each type, before and after sampling. The weight changes on the SCC and WINS filters were indistinguishable from the blank weight changes, indicating that all the aspirated particles were retained within the selectors. The best estimate of mass loading within the PM2.5 selectors was therefore calculated by scaling the reference filter loading for the difference in flow rates.

After each loading the PM2.5 selectors were re-tested using the APS system to re-measure the particle size selection curve. The cycle of loading and testing was repeated for four different dust loadings, ranging from 0.4 to 4.5 mg.

3.3 Garden loading experiment

Five cumulative outdoor loadings were made by setting up four PM2.5 samplers, two R&P Partisol samplers and two BGI PQ200 samplers, in a suburban garden during the summer months. One of the Partisol samplers contained a WINS impactor, and one contained an SCC cyclone. Likewise, one WINS and one SCC were used in the PQ200 samplers. Both the Partisol and PQ 200, when used with the WINS, are US EPA designated, single channel refrence samplers. A schematic diagram of the sampling site is shown in Figure 3.

Clean pre-weighed 2 µm Teflo filters were used in the samplers for each run. The instruments were set up to sample continuously for periods ranging from 96 to 132 hours. At the end of each sampling period the filters were conditioned and re-weighed to assess the PM2.5 concentration. The PM2.5 selectors were carefully transported to the laboratory for re-measurement of their aerosol penetration curves, and then replaced in the samplers without cleaning. Hence over a five week period the change in D_{50} was monitored with cumulative loading of the selectors. At the end of the experiment, the selectors were cleaned and the aerosol penetration curves re-measured.

3.4 Car park loading experiment

Three further cumulative loadings were made by setting up the four PM2.5 samplers in a city-centre underground car park, open to the atmosphere during the day via large doors, but sheltered from winds. Clean pre-weighed 2 µm Teflo filters were used in the samplers for each run. At the end of each sampling period were conditioned and re-weighed to assess the PM2.5 concentration. The PM2.5 selectors were carefully transported to the laboratory for re-measurement of their aerosol penetration curves, and then replaced in the samplers without cleaning. The first week of this experiment showed very low PM2.5 concentrations, and it was continued in the second and third weeks with only two samplers, operated without their PM10 inlets. One sampler used the WINS and one was fitted with the SCC. This would subject the PM2.5 selectors to higher concentrations of large particles, normally removed by the PM10 inlet. At the end of the experiment, the selectors were cleaned and the aerosol penetration curves re-measured.

As a final test, the two samplers were run for one further week with one PM10 inlet in place and one removed, to check whether this had any effect on the apparent PM2.5 concentration.

4. RESULTS

4.1 Penetration curves for clean selectors

Table 2 summarises the number of penetration curve measurements obtained for each clean selector type during this project. The mean and standard deviation of the D_{50} values for each clean selector is shown. The averaged penetration curve for each selector is shown in Figure 4, along with the 'ideal' WINS curve as published in the FRM.

The large number of replicate measurements allows the precision of the test method to be assessed. Table 2 shows that the method allows determination of the D_{50} to within ± 0.07 µm. Obviously the precision of results obtained on the same test day is better, but this figure is a realistic estimate of the true repeatability of the method. Any systematic differences between individual selector specimens are too small to be detected.

4.2 Shifts in aerosol penetration after laboratory loadings

The results of the laboratory loading experiment are shown in Figure 5, which plots the selector D_{50} as a function of loading within the selector (as determined from the separate reference filter sample). Only one selector penetration curve was measured at each loading, which means that the D_{50} values can be measured to ± 0.07 µm. D_{50} values below 2.4 µm may be considered to represent a significant decrease from the 'clean' value.

The loading was seen to cause a hummock-like deposit to build on the WINS substrate. With the SCC cyclone, a diffuse deposit was spread over the whole interior of the cyclone, with only small amounts of material reaching the grit pot.

4.3 Shifts in aerosol penetration after outdoor loadings

The results from the garden experiment are summarised in Table 3, and plotted as D_{50} versus cumulative PM2.5 sampled mass in Figure 5. Again, only one selector penetration curve was measured at each loading, which means that the D_{50} values can be determined to ± 0.07 µm.

The actual loading of dust inside the PM2.5 selectors is not known for this experiment. However, it can be assumed that since the sampling location is remote from pollution sources, the aerosol is likely to be very fine, and hence most of the PM10 will also be PM2.5. Observation of the WINS substrates after five weeks of sampling suggested that the loading was not greater than the mid-range of the laboratory experiment. The WINS deposit was also more diffuse during the garden loading experiment, and the SCC deposit concentrated more towards the lower part of the cyclone. These observations support the assumption of a very fine aerosol.

The results from the car park experiment are summarised in Table 4, and plotted as D_{50} versus cumulative PM2.5 sampled mass in Figure 6. The PM2.5 concentrations showed a very large increase in the second and third weeks, which was continued in the fourth week of the supplementary experiment. This was probably due to the normal users of the underground car park (mainly motorcyclists) changing their parking habits in week 1 in response to the appearance of the four PM2.5 samplers. Over the course of the experiment the users returned to parking their vehicles close to the sampling site.

4.4 Calculations of expected bias in PM2.5 concentrations

In order to assess the impact of downward shifts in the particle size selection curves on apparent PM2.5 concentrations, the three ambient aerosol size distributions cited in the Federal Register can be utilised. The bias in PM2.5 concentrations that results from numerically ‘sampling’ these aerosols with selectors whose characteristics differ from the ‘ideal’ PM2.5 curve specified as the Federal Reference Method is shown in Table 5. Bias values in the range -5% to +5% are permissible for FRM-equivalent samplers.

5. DISCUSSION

The measurements on the clean PM2.5 selectors show that all four instruments have D_{50} values close to the ideal value (2.5 µm). However, the shapes of the selection curves are very different. The URG cyclone curve falls off very gradually at large particle diameters. The GK cyclone curve also has a significant large-diameter ‘tail’, although it is lower than that of the URG cyclone. The SCC curve is slightly less sharp than the WINS impactor at large particle aerodynamic diameters, but sharper at small diameters than the WINS. The WINS curve

shown here, which is the averaged result from eight independent tests, is slightly less sharp than the 'ideal' WINS curve obtained by Peters and Vanderpool (1996).

If the 'sharpness' of the selectors is defined as $(D16/D84)^{0.5}$ as suggested by Peters and Vanderpool (1996), the mean values obtained are: WINS = 1.23; SCC = 1.19; GK = 1.28; URG = 1.45. For comparison, Peters and Vanderpool obtained a value of 1.18 for the current version of the WINS, and values ranging from 1.14 to 1.3 for other WINS variants they investigated. Hence overall, the SCC cyclone is as sharp as the WINS impactor.

When loaded in the laboratory with Aloxite dust, the WINS D_{50} shifted steadily downwards, whereas the SCC did not show a significant shift. The results obtained can be compared to those in a similar experiment by Peters and Vanderpool (1996), in which the WINS was cumulatively loaded with Arizona Road Dust. Their data indicate a shift to D_{50}=2.25 µm after apparently sampling a total of 24 mg of dust. Their report does not state the proportion of sampled dust retained within the WINS, but the quoted size distribution (MMAD 5 µm, GSD 2) would imply that around 60% of the sampled dust was between 2.5 and 10 µm. Hence the loading required to shift the cut-point to 2.25 µm would be in the range 14 mg, or eight times the amount of Aloxite apparently required to have the same effect in this experiment. The discrepancy between these two results cannot be explained.

The garden experiment did not show such a large shift in the WINS D_{50} as the laboratory experiment, although the shift (to D_{50} ~2.3 µm) after five weeks of sampling was significant. The SCC D_{50} also shifted, although to a lesser extent. The upturn in D_{50} towards the end of the experiment may have been caused by the deposits shifting during transport (by road) of the selectors to and from the laboratory. Given that that sampled aerosol was fine it is likely that the mass of particulate retained within the selectors was not more than around one quarter of the PM2.5 mass, i.e. less than ~1.5 mg.

In the car park experiment the main source of airborne particulate was again vehicle exhaust but the concentrations were much higher. With a fine aerosol, removing the inlets from the samplers would not have had much effect, and it is likely that the large concentration increases in weeks 2 and 3 simply reflect increased use of the car park. Assuming that the

particulate retained within the selectors is between one quarter and one half of the PM2.5 mass, the maximum loading can be estimated as being less than 2 - 4 mg. The fall in D_{50} is approximately the same as for the laboratory loading experiment, reaching a minimum value of D_{50} = 2.15 µm. The SCC D_{50} also decreases, but by a lesser amount, to D_{50}=2.35 µm.

For loadings of this magnitude, Table 5 indicates significant under sampling of the coarse aerosol by the dirty WINS impactor (i.e. when D_{50} = 2.15 µm). The clean URG cyclone is calculated to overestimate the PM2.5 concentration of the 'coarse' aerosol by around 10%, and all other calculated concentration values are within the acceptable error band.

It is important therefore to estimate how long sampling can take place with the WINS impactor before the loading causes an unacceptable shift in the D_{50}. The results from this project suggest that WINS loadings greater than 3 mg are probably sufficient to cause significant undersampling. Table 6 shows the number of hours required to build up a loading of this magnitude for different (extreme) concentrations of the three suggested aerosol size distributions. This table implies that in rare instances of high concentrations of coarse aerosol, there may be problems with the WINS impactor over four-day (96 hour) sampling periods. For longer sampling periods, e.g. the 16-day (384 hour) periods suggested for air quality monitoring in Europe, the WINS impactor is likely to become overloaded even at moderate concentrations.

6. CONCLUSIONS

- The SCC cyclone has been shown to provide a sharp cut for ambient air sampling applications, although the shape of it's selection curve differs somewhat from that of the WINS impactor.
- When loaded with dust the cut-point of the WINS impactor shifts downwards. The loading required to produce a significant deterioration in the WINS performance was shown to be in the region of 3mg.
- The SCC cut point also shifts under loading, however not enough to cause a significant deterioration in performance for any of the loadings tested in this project. Additionally, the SCC is a dry system whereas the WINS uses an oiled substrate.

- The URG cyclone has a very shallow particle size selection curve and is likely to overestimate PM2.5 concentrations when the aerosol being sampled is coarse.
- The WINS cut point is unlikely to shift to an unacceptable degree during 24 hour sampling periods, or even for 96 hour sampling periods under typical circumstances. However the WINS would perform less well than the SCC over extended sampling periods.

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Table 1. Dimensions (in cm) of Cyclones Tested Based Upon Body Diameter

	D	Din	De	B	H	h	Z	S	Hcup	Dcup
URG Relative dimensions										
GK 4.39	4.39	0.878	1.01	0.878	5.707	1.756	3.951	1.01	3.819	0.878
Relative dimensions		0.2D	0.23D	0.2D	1.3D	0.4D	0.9D	0.23D	0.87D	0.2D
SCC Relative dimensions										

Table 2: Summary of penetration curve measurements for clean PM2.5 selectors

Selector	Number of tests	Number of test days	Mean D_{50} µm	D_{50} standard deviation
WINS	8	5	2.44	0.034
SCC	5	3	2.46	0.035
GK	4	4	2.37	0.029
URG	3	3	2.46	0.015

Table 3: Summary of results from the garden experiment

week	sampling time hours	result	PQ WINS	PQ SCC	Partisol WINS	Partisol SCC	Mean PM2.5 (st.dev)
1	96	PM2.5 D_{50}	8.94 2.52	9.07 2.45	9.82 2.45	8.74 2.49	9.14 (0.47)
2	108	PM2.5 D_{50}	5.73 2.45	6 2.4	6.05 2.4	6.47 2.5	6.06 (0.31)
3	108	PM2.5 D_{50}	7.98 2.45	9.53 2.4	dropped 2.4	7.63 2.49	8.38 (1.01)
4	132	PM2.5 D_{50}	6.77 2.39	7.86 2.34	6.77 2.34	7.07 2.45	7.11 (0.51)
5	132	PM2.5 D_{50}	8.97 2.38	9.51 2.42	8.47 2.28	9.24 2.43	9.05 (0.44)
After	cleaning	D_{50}	2.47	2.45	2.45	2.5	

PM2.5 concentrations are in µg/m3; D_{50} values are in µm.

Table 4: Summary of results from the car park experiment

week	sampling time hours	result	PQ WINS	PQ SCC	Partisol WINS	Partisol SCC	Mean PM2.5 (st.dev)
1	168	PM2.5 D_{50}	5.4 2.43	6.73 2.48	6.57 2.49	6.74 2.5	6.36 (0.64)
2	168	PM2.5 D_{50}		18.14 2.34	18.93 2.26		18.54
3	118	PM2.5 D_{50}		15.49 2.36	15.69 2.15		15.59
4	166	PM2.5		37.9	36.4		37.15
After	cleaning	D_{50}		2.48	2.45		

PM2.5 concentrations are in µg/m3; D_{50} values are in µm.

Table 5: Bias in PM 2.5 concentrations for three ambient aerosol size distributions

Selector	'Fine' aerosol	'Typical' aerosol	'Coarse' aerosol
Clean WINS	-1%	0%	0%
Clean SCC	0	+1%	+2%
Clean GK	+1%	+2%	+5%
Clean URG	0	+3%	+10%
Dirty WINS[1]	-3%	-2%	-4%
Dirty WINS[2]	-4%	-3%	-6%

1: WINS D_{50} = 2.25 µm; 2: WINS D_{50} = 2.15 µm

Table 6: Number of hours of sampling required in order to build up a loading of 3 mg within a WINS impactor

Idealised distribution	PM2.5/PM10 ratio	Hours sampling at 10µg/m^3 PM2.5	Hours sampling at 50µg/m^3 PM2.5
'Coarse'	0.27	411	82
'Typical'	0.55	667	133
'Fine'	0.94	5000	1000

FIGURE 4: Penetration curves of PM2.5 selectors

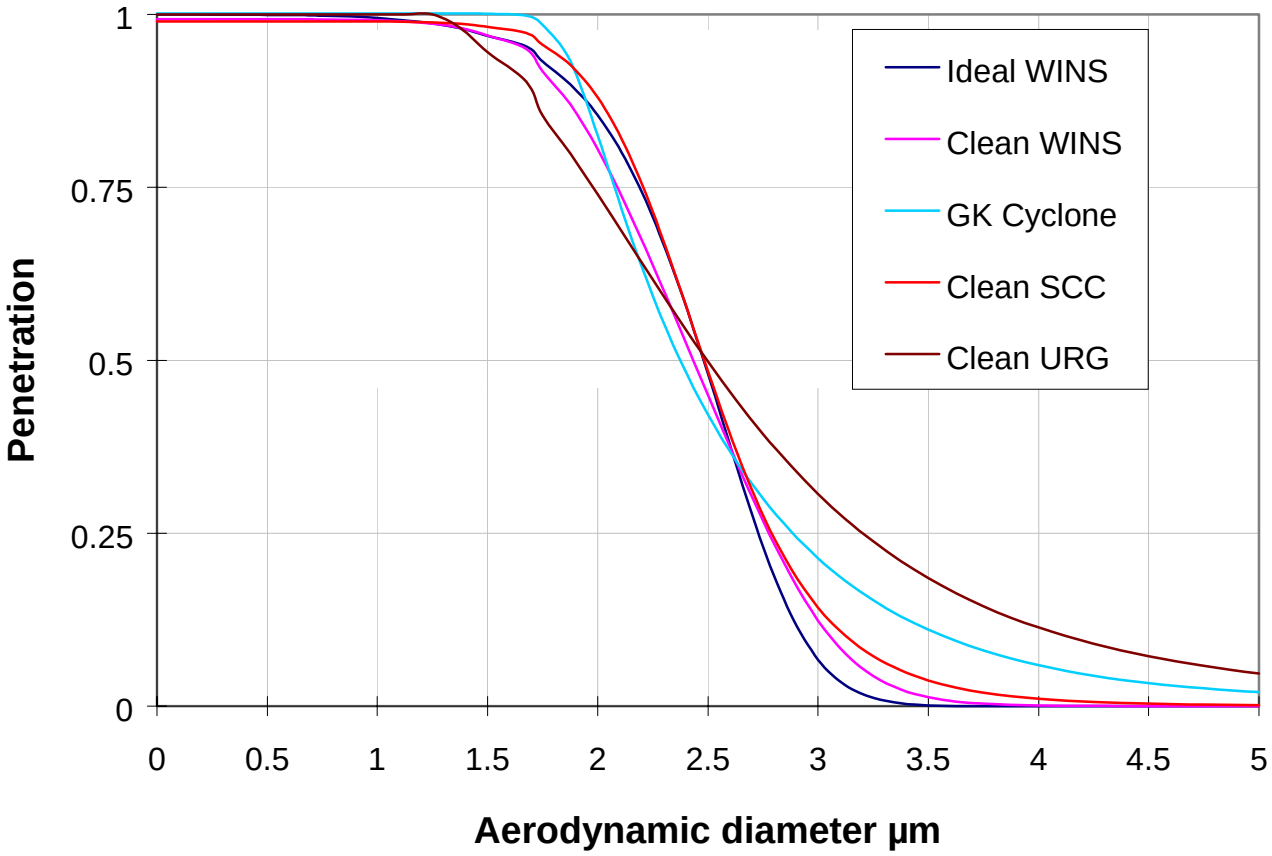


FIGURE 5: Results of laboratory loading experiment

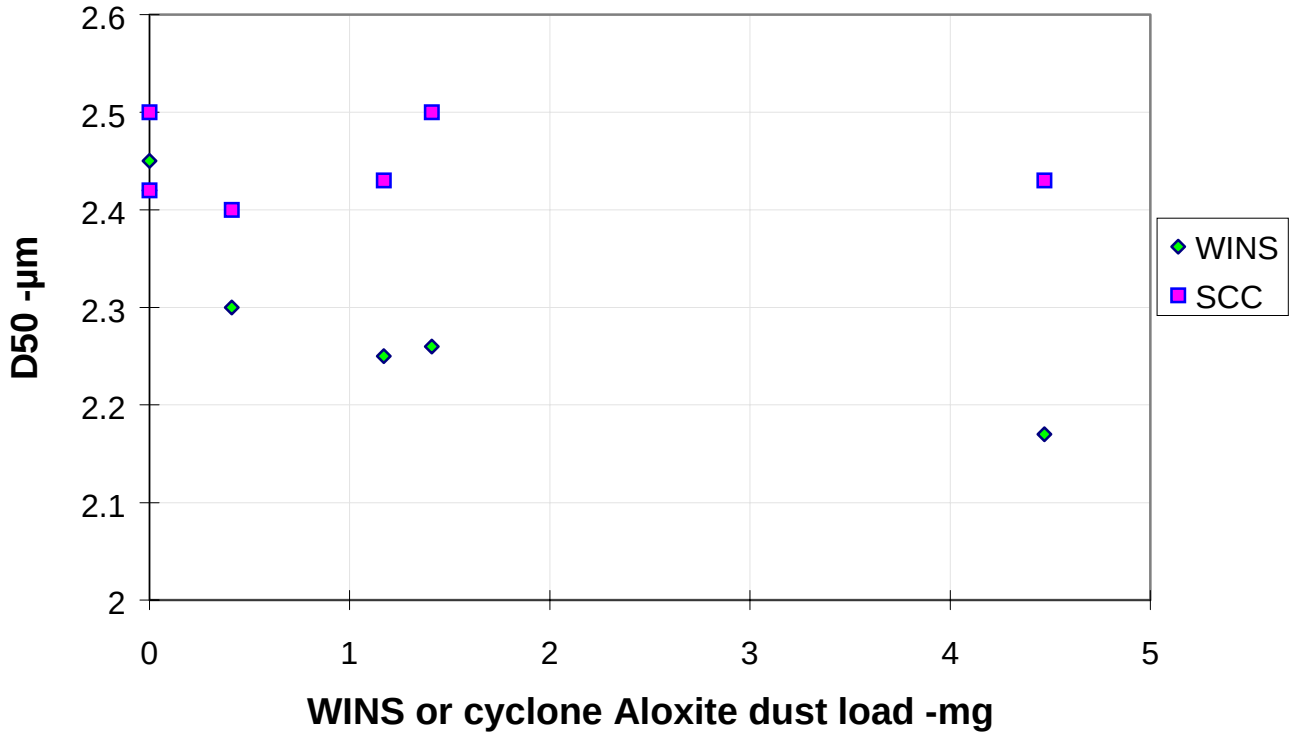


FIGURE 6: Results from garden loading experiment

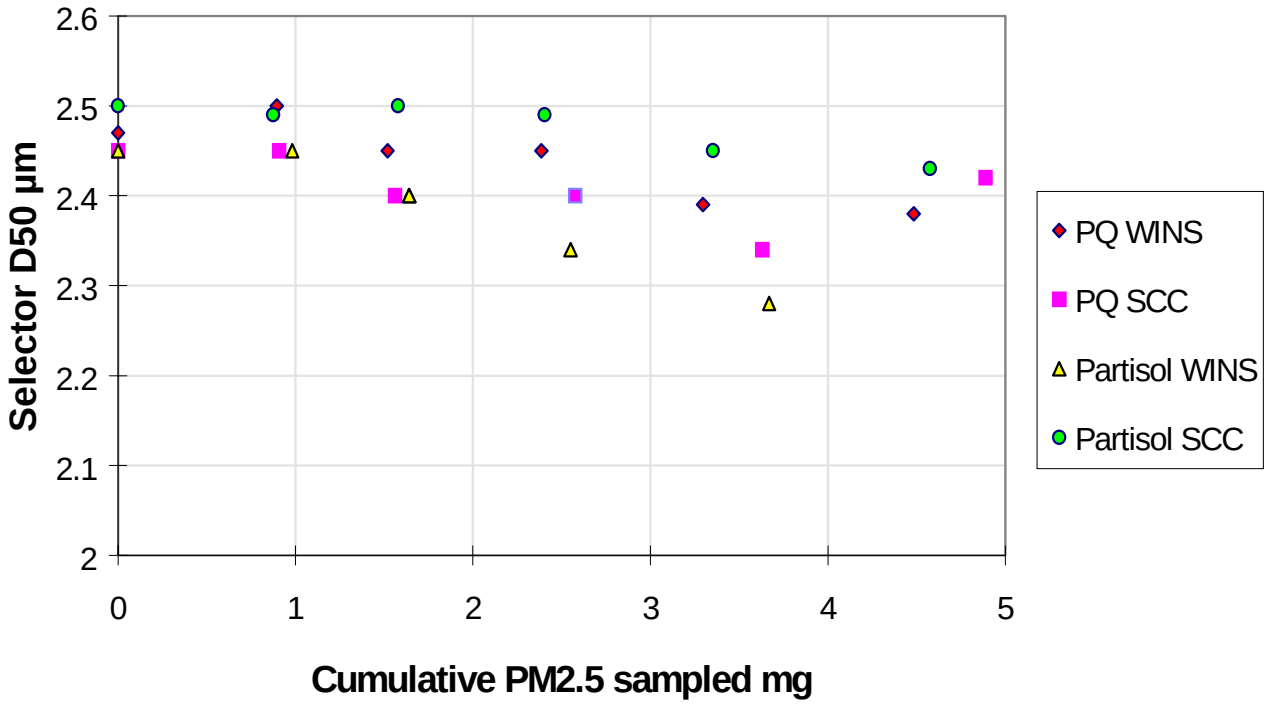
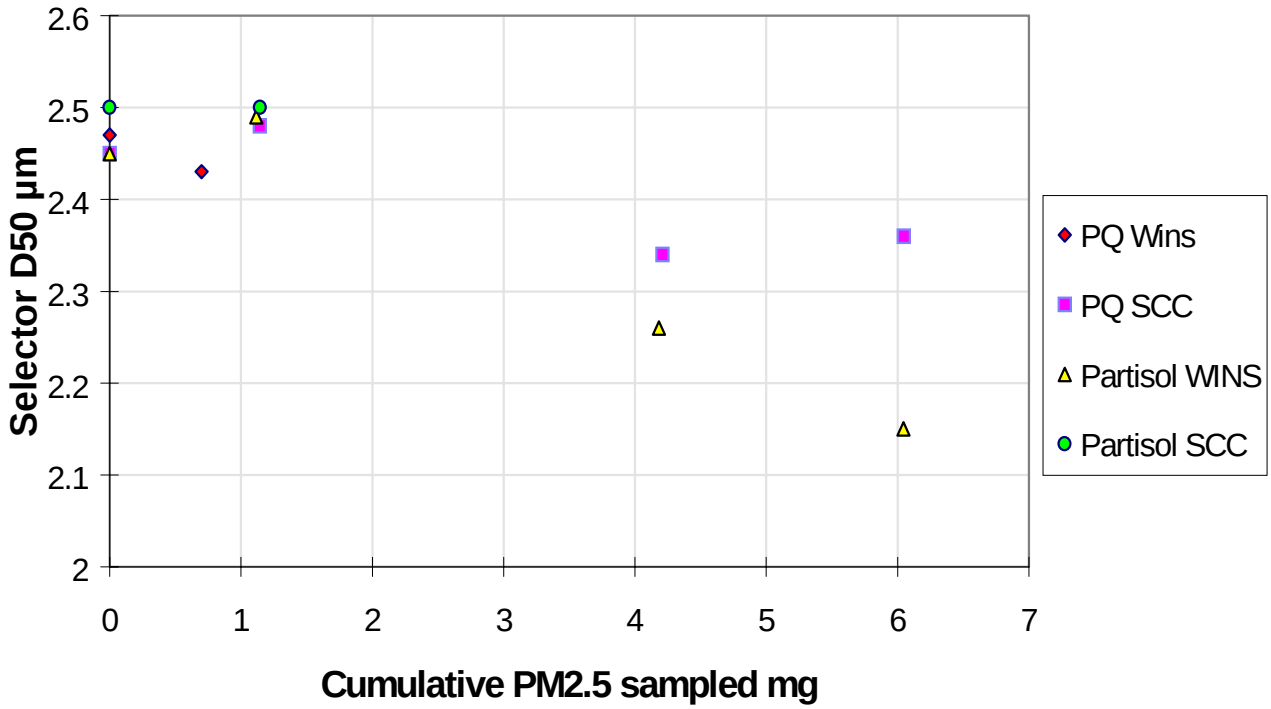


FIGURE 7: Results from car park loading experiment



PARTICULATE MATTER SAMPLER ERRORS DUE TO THE INTERACTION OF PARTICLE SIZE AND SAMPLER PERFORMANCE CHARACTERISTICS: AMBIENT $PM_{2.5}$ SAMPLERS

M. D. Buser, C. B. Parnell, Jr., B. W. Shaw, R. E. Lacey

ABSTRACT. *The National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) in terms of $PM_{2.5}$ are ambient air concentration limits set by the EPA to protect public health and well-being. Further, some state air pollution regulatory agencies (SAPRAs) utilize the NAAQS to regulate criteria pollutants emitted by industries by applying the NAAQS as property-line concentration limits. Prior to and since the inclusion of the $PM_{2.5}$ standard, numerous journal articles and technical references have been written to discuss the epidemiological effects, trends, regulation, and methods of determining $PM_{2.5}$. A common trend among many of these publications is the use of samplers to collect $PM_{2.5}$ concentration data. Often, the sampler data are assumed to be accurate concentration measures of $PM_{2.5}$. The fact is that issues such as sampler uncertainties, environmental conditions, and characteristics of the material that the sampler is measuring must be incorporated for accurate sampler measurements. The focus of this article is on the errors associated with particle size distribution (PSD) characteristics of the material in the air that is being sampled, the $PM_{2.5}$ sampler performance characteristics, the interaction between these two characteristics, and the effect of this interaction on the regulatory process. Theoretical simulations were conducted to determine the range of errors associated with this interaction for the $PM_{2.5}$ ambient air samplers. Results from the $PM_{2.5}$ simulations indicated that a source emitting PM characterized by a mass median diameter (MMD) of 20 μm and a geometric standard deviation (GSD) of 1.5 could be forced to comply with a $PM_{2.5}$ standard that is 14 times more stringent than that required for a source emitting PM characterized by an MMD of 10 μm and a GSD of 1.5, and 59 times more stringent than that required for a source emitting PM characterized by an MMD of 5.7 μm and a GSD of 1.5. Therefore, in order to achieve equal regulation among differing industries, $PM_{2.5}$ measurements must be based on true concentration measurements.*

Keywords. *Air, Environmental impact, Legislation, Mathematical models, Particle size distribution, PM, $PM_{2.5}$, PM_{10}, Pollution, Samplers.*

The Federal Reference Method (FRM) $PM_{2.5}$ samplers are specified by design, unlike the performance-based FRM criteria for the PM_{10} samplers. $PM_{2.5}$ refers to particles with an aerodynamic equivalent diameter (AED) less than or equal to a nominal 2.5 μm. PM_{10} refers to particles with an AED less than or equal to a nominal 10 μm. An update published by the EPA (USEPA, 2000) states: "The requirement that these instruments rely on specific design elements, rather than performance criteria alone, is structured to produce greater measurement reproducibility and to avoid the data measurement uncertainties experienced in the PM_{10} monitoring program."

In addition to the FRM $PM_{2.5}$ sampler designation, the EPA also provides a Federal Equivalent Method (FEM) $PM_{2.5}$ sampler designation. The EPA defined three FEM classes (Class I, Class II, and Class III) based on the degree of dissimilarity between a candidate sampler and the FRM requirements (CFR, 2001e). An increase in equivalency designation, from Class I to Class II to Class III, indicates a greater deviation from the FRM, requiring more extensive testing for equivalency verification. Class I equivalent methods correspond to candidate samplers that have only minor deviations from the reference method, usually relating to sample transmission component modifications incorporated to accommodate a sequential sampling mechanism. A Class I FEM candidate sampler must undergo the same testing as the FRM candidate sampler, with the addition of an internal aerosol transport test.

Class II equivalent methods are 24-hour integrated filter collection techniques that rely on gravimetric analysis, but have significant design or performance deviations from the reference method. For example, substituting a cyclone separator for the Well-Type Impactor Ninety Six (WINS) (Thermo Electron Corp., Waltham, Mass.) is a deviation from the FRM that could be designated as a Class II FEM. A

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Class II FEM candidate sampler must undergo more extensive testing than the FRM or Class I FEM, with the tests being specific to the nature of the modifications in the candidate method. Additional testing may include all, or some subset, of the following tests: full wind tunnel test, wind tunnel aspiration test, static fractionator test, loading test, and volatility test.

Class III equivalent methods do not fall under Class I or Class II designations because of further deviations from the FRM, but still provide mass concentration measurements of $PM_{2.5}$ comparable to the reference method. The two primary sampling categories that fall into this class are non-filter-based techniques and continuous (or semi-continuous) analyzers. Specific requirements for Class III FEM are not defined because of the wide range of technologies that might be employed for $PM_{2.5}$ mass measurement. As a result, the EPA develops specific Class III FEM testing and other requirements on a case-by-case basis. Class III FEMs may be required to undergo any or all of the testing required for validation as an FRM, Class I FEM, or Class II FEM, as well as additional testing specific to the sampling technology.

The basic design of the FRM $PM_{2.5}$ sampler is given in the Federal Register (1997) and 40 CFR Part 50, Appendix L (CFR, 2001e). Performance specifications for FRM $PM_{2.5}$ samplers are listed in 40 CFR Parts 53 and 58 (CFR, 2001a, 2001b). According to the EPA's criteria, the accuracy of FRM $PM_{2.5}$ samplers is determined through collocated sampler evaluation tests. The performance specifications for FEM $PM_{2.5}$ Class I samplers are very similar to those required for the FRM sampler. Detailed performance specifications are listed in 40 CFR Part 53.

A candidate $PM_{2.5}$ sampler classified as a Class II FEM is required to meet a more rigorous set of performance criteria, as defined in 40 CFR Part 53. Specifically, 40 CFR Part 53, Subpart F, describes the procedures for testing the performance characteristics of Class II FEM candidate $PM_{2.5}$ ambient air samplers. In the full wind tunnel test, the candidate sampler's collection efficiency is determined for several mono-disperse particle sizes (i.e., solid particle target diameters of 1.5, 2.0, 2.2, 2.5, 2.8, 3.5, and 4.0 μm AED) at wind speeds of 2 and 24 km/h (CFR, 2001a). A smooth collection efficiency curve is then generated using the individual collection efficiencies determined in the wind tunnel tests. The candidate sampler's collection efficiency curve, along with the three idealized ambient particle size distributions, i.e., coarse, "typical" coarse, and fine, as defined by the EPA (CFR, 2001e), is then used to determine the expected mass concentration for the candidate sampler. The candidate sampler passes the full wind tunnel evaluation if the expected mass concentration calculated for the candidate sampler, at each wind speed and for each idealized distribution, differs by no more than ±5% from that predicted for the "ideal" sampler. The candidate method passes the 50% cutpoint test if the test result at each wind speed falls within 2.5 ±0.2 μm. The candidate sampler must also pass the wind tunnel aspiration, static fractionator, loading, and volatility tests listed in 40 CFR Part 53, Subpart F; however, the full wind tunnel test is the primary test for evaluating the samplers collection efficiency curve.

Vanderpool et al. (2001b) listed several factors that influence the mass concentration measured by the FRM WINS sampler including: PM concentration and size distribution; chemical composition of the collected aerosol; sampler volumetric flow rate (affected by the accuracy of the sampler's ambient temperature, ambient pressure, and flow sensors); sampling time; sampler inlet geometry; performance of the sampler's internal size-selective separator; sampler internal particle losses; pre-sampling and post-sampling filter conditioning; and all other associated sampling and analysis procedures. In addition, relatively small changes in a sampler's cutpoint can produce significant and hard to predict mass concentration errors (USEPA, 1996a). Therefore, factors that affect sampler concentration errors should be identified and the corresponding influences determined as a function of particle size.

According to Vanderpool et al. (2001b), "Regardless of the inertial fractionation mechanism (conventional impaction, virtual impaction, or cyclonic separation) and the separator design, all separators overload to some degree if continuously exposed to particle-laden airstreams." One method of determining the sampler uncertainty attributed to overloading is to evaluate the elemental composition of $PM_{2.5}$ and PM_{10}, or the coarse fraction of PM_{10} (Vanderpool, 2001b). Using this method, elements relating to soil-type materials have been found in the $PM_{2.5}$ fraction. In a study using dichotomous samplers, the soil-type material found in the $PM_{2.5}$ fraction was equivalent to 5% of the coarse mode fraction of PM_{10} (Dzubay et al., 1988). Similar results were reported from the IMPROVE network, which suggested that the soil-derived material found in the $PM_{2.5}$ sample was equivalent to 20% of the coarse fraction of PM_{10} (Eldred et al., 1994).

Pitchford (1997) stated that an early concern with the WINS impactor was cleaning to avoid the possibility of having part of the impactor deposit break off and make its way to the filter, resulting in an over-sampling of $PM_{2.5}$. Pitchford (1997) also reported that sampling with a dirty WINS impactor could result in an under-sampling of $PM_{2.5}$. This under-sampling was attributed to deposits building up on the impaction surface, in effect changing the critical dimensions of the WINS, resulting in a low cutpoint. Vanderpool et al. (2001a) evaluated the loading characteristics of the WINS separator by monitoring the sampler's performance after repeated operation in an artificially generated, high concentration, coarse mode aerosol composed of Arizona Test Dust, as well as in field tests. In the wind tunnel experiments, the WINS performance was found to be a monotonic function of loading. A negative 5% error in the $PM_{2.5}$ measurement resulted from a coarse particulate loading of approximately 16 mg because of a slight reduction in the separator's cutpoint. It was also determined that the results from the laboratory experiments could not be extrapolated to the field settings and that the performance of the WINS was more sensitive to impactor loading in the field tests than in experiments with the single-component aerosol.

Kenny et al. (2000) evaluated a clean WINS Sharp-Cut Cyclone (SCC) (Thermo Electron Corp., Waltham, Mass.), GK cyclone (BGI, Inc., Waltham, Mass.), and University Research Glassware (URG) cyclone (University Research Glassware, Chapel Hill, N.C.) using EPA procedures for testing the performance characteristics of Class II equivalent $PM_{2.5}$ methods. They reported that the SCC could over-sample "coarse" aerosols by 4% to 5%. The URG cyclone could overestimate "coarse" aerosols by more than 13%, and the GK could overestimate "coarse" aerosols by more than 9%. The clean WINS impactor was within 1% of the ideal

concentration, which was expected since the ideal penetration curve is a sigmoid model fit to the WINS impactor data.

The WINS impactor was designed to be deployed downstream of the Graseby-Anderson 246A PM_{10} inlet and operate at a flow rate of 16.7 L/min. Peters and Vanderpool (1996), under contract with the EPA to evaluate the WINS sampler, characterized the WINS penetration curve as a lognormal distribution with a cutpoint of 2.48 µm AED and a slope of 1.18. Peters et al. (2001b) evaluated the WINS using mono-disperse aerosols and reported that the WINS cutpoint ranged from 2.44 to 2.48 µm and the slope of the sampler's penetration curve ranged from 1.17 to 1.22. Vanderpool et al. (2001b) stated that "unlike conventional greased flat-plate impactors, the general effect of loading in the WINS separator is to reduce the cutpoint rather than to increase it." Vanderpool et al. (2001b) reported that the cutpoint for 13 archived WINS samplers from the various field sites after five days of loading ranged from 2.32 to 2.51 µm.

Kenny (1998) conducted an evaluation study on the WINS impactor, the SCC, the GK4.39 cyclone, and the URG. The SCC was based on the design of the SRI Cyclone III described by Smith et al. (1979) and the URG cyclone was based on the Stairmand design evaluated by Moore and McFarland (1993). Kenny (1998) reported cutpoints (slopes) of 2.44 µm (1.23), 2.46 µm (1.19), 2.37 µm (1.28), and 2.46 µm (1.45) for the WINS, SCC, GK4.39, and URG samplers, respectively, using mono-disperse particles. Kenny et al. (2000) evaluated the WINS and SCC when loaded with Aloxite dust (and no PM_{10} inlet) and determined that the WINS cutpoint shifted steadily downwards to 2.15 µm, whereas the SCC cutpoint did not exhibit a significant downward shift.

Buch (1999) evaluated the WINS and the Interagency Monitoring of Protected Visual Environments (IMPROVE) $PM_{2.5}$ samplers in a dust chamber using poly-disperse particles. Buch (1999) determine that the WINS cutpoint was 2.7 ±0.41 µm and the slope was 1.32 ±0.03 when exposed to a dust consisting of 67% $PM_{2.5}$. The IMPROVE $PM_{2.5}$ sampler was reported to have an average cutpoint of 3.8 µm and an average slope of 1.23 (Buch, 1999). Pargmann (2001) conducted a similar study that evaluated the WINS, the SCC, and the hi-vol $PM_{2.5}$ sampler (Thermo Electron Corp., Waltham, Mass.) in a dust chamber using poly-disperse particles (i.e., alumina, corn starch, and wheat flour). No cutpoints or slopes were reported for the SCC or hi-vol $PM_{2.5}$ samplers; however, the WINS fractional efficiency curve was defined by a cutpoint of 1.95 ±0.10 µm and a slope of 1.31 ±0.04 when exposed to a dust consisting of 5.34% $PM_{2.5}$. Pargmann (2001) also reported the percent error between the sampler measurements and actual $PM_{2.5}$ concentrations. The WINS sampler over-sampled by 51%, 211%, and 444% when sampling alumina, corn starch, and wheat flour, respectively. The SCC sampler over-sampled by 119%, 585%, and 1771% when sampling alumina, corn starch, and wheat flour, respectively. The hi-vol $PM_{2.5}$ sampler over-sampled by 111%, 467%, and 632% when sampling alumina, corn starch, and wheat flour, respectively. Pargmann (2001) stated that over-sampling increased as the mass median diameter (MMD) of the dust being sampled increased.

BGI Incorporated (Waltham, Mass.) developed the Very Sharp-Cut Cyclone (VSCC), which was based on the design of the SCC described by Kenny et al. (2000). The VSCC differs from the SCC in that it has a longer cone, wider base diameter, and decreased inlet and outlet tube diameters. The evaluation study conducted by Kenny (2000) consisted of testing the VSCC and the WINS impactor in a wind tunnel using solid, spherical glass microspheres (density = 2.45 g/cm^3) with physical diameters up to 25 µm (MMD = 4 µm) at a loading rate of 100 to 200 particles/cm^3. Kenny (2000) reported cutpoints (slopes) of 2.48 µm (1.22) and 2.5 µm (1.16) for the WINS impactor and VSCC (operated at 16.67 L/min), respectively.

Peters et al. (2001a) evaluated the SCC 1.829 (BGI, Inc., Waltham, Mass.), the SCC 2.141 (Met One Instruments, Inc, Grants Pass, Ore.), and the AN 3.68 (Andersen Instruments, Inc., Smyrna, Ga.) $PM_{2.5}$ cyclones and a Spiral impactor using EPA procedures for testing the performance characteristics of Class II equivalent $PM_{2.5}$ samplers. Each of these cyclone separators is based on the SRI designs described by Smith et al. (1979). Peters et al. (2001a) reported a cutpoint of 2.44 µm and a slope of 1.23 for the SCC 1.829. The SCC 2.141 was reported to have a cutpoint of 2.52 µm and 2.35 µm for flow rates of 6.7 and 7.0 L/min, respectively. The slope associated with the SCC 2.141 was reported as 1.24 for both flow rates tested. Peters et al. (2001a) reported that the SCC 2.141 overestimated the idealized "coarse" mass concentration by as much as 6.1% at a flow rate of 6.7 L/min. The AN 3.68 was reported to have a cutpoint of 2.72 µm and a slope of 1.15 when operated at the design flow rate of 24.0 L/min. Peters et al. (2001a) reported that the AN 3.68 overestimated the idealized "coarse" mass concentration by 7.4%, which was attributed to the sampler's larger cutpoint. Peters et al. (2001a) reported that the cutpoint associated with the Spiral impactor was highly variable and ranged from 1.9 to 2.7 µm for three separate tests when operated at the design flow rate of 7.0 L/min. Peters et al. (2001a) characterized the performance of the ungreased Spiral impactor by a cutpoint of 2.69 µm and a slope of 1.30. Kenny et al. (2000) concluded that cyclonic separators become more efficient with increased loading (i.e., the cutpoint shifts to the left with increased loading).

The MiniVol (Airmetrics, Eugene, Ore.), which is designed to have a 2.5 µm AED cutpoint at a flow rate of 5 L/min, does not meet the design specifications required for designation as a $PM_{2.5}$ regulatory monitor (Hill et al., 1999). Based on the data provided by Hill et al. (1999) the MiniVol 2.5 µm impactor appeared to have a cutpoint of 2.7 µm and a slope of 1.4 when wind tunnel tested using mono-disperse particles. Hill et al. (1999) also evaluated a MiniVol $PM_{2.5}$ impactor with various impactor plate grease loadings. The MiniVol impactor appeared to have a cutpoint ranging from 2.66 to 2.82 µm with a slope ranging from 1.25 to 1.37 based on data provided by Hill et al. (1999) for a wind tunnel study using mono-disperse particles and various application rates (defined as light, heavy, and very heavy) of grease on the impactor plate. Hill et al. (1999) also noted that recent modifications of the MiniVol $PM_{2.5}$ impactor design required the use of a PM_{10} impactor upstream of the $PM_{2.5}$ impactor (i.e., cascade or tandem impactor configuration). Hill et al. (1999) provided data that were used to estimate the cutpoint (and slopes) associated with the MiniVol $PM_{2.5}$ impactor using a flat plate, cup plate, flat plate following a PM_{10} impactor, and a cup plate following a PM_{10} impactor, which were determined to be 2.7 µm (1.48), 2.97 µm (1.29), 2.7 µm (1.65), and 3.1 µm (1.29), respectively.

The EPA recommended the use of a sharp 2.5 μm cutpoint for a fine-particle indicator (USEPA, 1996a). However, $PM_{2.5}$ samplers have some potential for an intrusion of the "tail" of the coarse mode during episodes of fugitive dust concentrations. The EPA recommends a sharp inlet for the FRM to minimize this potential intrusion of coarse-mode particles. According to the EPA, "Such intrusions into $PM_{2.5}$ measurement are not anticipated to be significant in most situations. Nevertheless, if subsequent data reveal problems in this regard, this issue can, and should be, addressed on a case-by-case basis in the monitoring and implementation programs. Because the purpose of a $PM_{2.5}$ standard is to direct controls toward sources of fine-mode particles, it would be appropriate to develop analytical procedures for identifying those cases where a $PM_{2.5}$ standard violation would not have occurred in the absence of coarse-mode particle intrusion. Consideration should be given to a policy similar to the natural events policy for addressing such cases" (USEPA, 1996a).

The available data show that typically only 5% to 15% (on the order of 1 to 5 $\mu g/m^3$) of the $PM_{2.5}$ mass is attributable to soil-type sources, even in dusty areas such as the San Joaquin Valley, California, and Phoenix, Arizona (USEPA, 1996a). However, this percentage may increase during events such as high winds. According to the EPA, "A sharper inlet for the Federal Reference Method may help to minimize the intrusion of coarse-mode particles into the $PM_{2.5}$ measurement" (USEPA, 1996a).

The ultimate goal of a PM sampler is to accurately measure the concentration of specific ranges of particle sizes that exist in the atmosphere. However, it is not currently possible to accurately characterize the material that exists as particles in the atmosphere because of difficulties in creating a reference standard for particles suspended in the atmosphere. No calibration standards for suspended particle mass exist. As a result, the EPA defines accuracy for PM measurements in terms of the agreement between a candidate sampler and a reference sampler under standardized conditions for sample collection, storage, and analysis (USEPA, 1996a, 2001). Therefore, sampler comparisons become very important in determining the reproducibility of sampler measurements (measurement precision, as defined by the EPA) and how the sampler design influences accuracy (USEPA, 2001).

The National Ambient Air Quality Standards (NAAQS) for PM, in terms of $PM_{2.5}$, are the concentration limits set by the EPA that should not be exceeded (CFR, 2001c). Further, some state air pollution regulatory agencies (SAPRAs) utilize the NAAQS to regulate criteria pollutants emitted by industries by applying the NAAQS as property-line concentration limits. The regional or area consequences for multiple exceedances of the NAAQS are having an area designated as non-attainment, with a corresponding reduction in the permit-allowable emission rates for all sources of PM in the area. The source-specific consequence of an exceedance of the NAAQS at the property line is the SAPRA denying an operating permit. The current $PM_{2.5}$ primary 24-hour NAAQS is 65 micrograms per actual cubic meter (μg/acm) (CFR, 2001c).

Buser et al. (2006a) briefly discussed the evolution of the $PM_{2.5}$ regulation. Prior to and since the inclusion of the $PM_{2.5}$ standard, numerous journal articles and technical references have been written to discuss the epidemiological effects, trends, regulation, and methods of determining $PM_{2.5}$. A common trend among many of these publications is the use of samplers to collect information on $PM_{2.5}$. The data collected from these samplers are commonly used in statistical correlations and statistical comparisons to draw conclusions about $PM_{2.5}$ emission concentrations. All too often, the sampler data are assumed to be accurate measures of $PM_{2.5}$. The fact is that issues such as sampler uncertainties, concentration reporting basis (dry standard versus actual conditions), and characteristics of the material that the sampler is measuring must be incorporated for accurate sampler measurements. The focus of this article is on the particle size distribution (PSD) characteristics of the material in the air that is being sampled, the sampler performance characteristics, the interaction between these two characteristics for $PM_{2.5}$ ambient air samplers, and the effect of these interactions on the regulatory process.

METHODS AND PROCEDURES

Buser et al. (2006a) provided background information on mathematically defining PSDs and sampler and true penetration curves. The equation for the lognormal mass density function most commonly used to describe dust particles in the ambient air or emitted from urban or agricultural operations, was defined as:

$$f(d_p, MMD, GSD) = \frac{1}{d_p \ln GSD\sqrt{2\pi}} \exp\left[\frac{-(\ln d_p - \ln MMD)^2}{2(\ln GSD)^2}\right] \quad (1)$$

where MMD, GSD, and d_p are the mass median diameter, geometric standard deviation, and particle diameter of the distribution, respectively (Hinds, 1982). The cumulative sampler penetration efficiency was defined as:

$$P_m(d_{50}, slope) = 1 - \int_0^{\infty} \left(\frac{1}{d_p \ln(slope)\sqrt{2\pi}} \times \exp\left[\frac{-(\ln d_p - \ln d_{50})^2}{2[\ln(slope)]^2}\right] \right) dd_p \quad (2)$$

where d_{50} is the particle size at which 50% of the particulate matter (PM) is captured by the pre-separator and 50% of the PM penetrates to the filter, and *slope* is the slope of the cumulative penetration curve. A complete definition of slope is provided by Buser et al. (2006a). In addition, Buser et al. (2006a) defined a true cumulative penetration curve or cut as a step function, which was defined as:

$$P_t(d_p, d_{50}) = \begin{cases} 1 & if\ d_p \le d_{50} \\ 0 & if\ d_p > d_{50} \end{cases} \quad (3)$$

In order to solve equation 2, additional information is needed to define the d_{50} and slope associated with the $PM_{2.5}$ ambient air sampler's PM_{10} and $PM_{2.5}$ pre-separators. The $PM_{2.5}$

ambient air sampler's PM_{10} pre-separator d_{50} and slope were defined as 10.0 ±0.5 μm and 1.5 ±0.1, respectively. Additional information on the selection of these PM_{10} performance characteristics is discussed by Buser et al. (2006b). The EPA essentially defines the d_{50} and slope associated with the $PM_{2.5}$ pre-separator in 40 CFR Part 53 in the discussion of tests required for a candidate sampler to receive EPA approval. The d_{50} for the $PM_{2.5}$ pre-separator is explicitly stated in the EPA standards as 2.5 ±0.2 μm AED. No slope values for the sampler are listed in 40 CFR Part 53, nor in any other current EPA standard; however, penetration data are presented in 40 CFR Part 53. Ideally, the penetration data could be fit to a cumulative lognormal distribution to determine the characteristic d_{50} and slope for the $PM_{2.5}$ samplers; however, it was found that no single cumulative lognormal curve adequately represented the EPA dataset in 40 CFR Part 53. It should be noted that these penetration data, along with EPA-defined interval mass concentrations and mass penetration tolerances, are used to determine if proposed samplers meet the EPA's PM_{10} performance criteria.

It appears from the literature that the EPA intended for the $PM_{2.5}$ sampler to have a "sharp cut" or represent a true concentration of $PM_{2.5}$, which would mean that, ideally, the slope would be equal to 1.0 (USEPA, 1996b). However, from an engineering standpoint, it is not possible to design a sampler with a true cut. Work by Peters and Vanderpool (1996) suggested that a slope of 1.18 could be achieved with the WINS Impactor, an EPA-approved ambient air sampler. Further work by Buch (1999) suggested that the WINS Impactor slopes were not as sharp as previously reported and that a more appropriate estimation of the sampler slopes would be 1.3 ± 0.03. Based on Buch's (1999) work, the primary performance characteristics for ambient $PM_{2.5}$ sampler used in this research were a d_{50} of 2.5 ±0.2 μm and a slope of 1.3 ±0.03. These performance characteristic ranges were divided into nine d_{50} and slope combinations, i.e., all combinations for d_{50} values of 2.3, 2.5, and 2.7 μm and slope values of 1.27, 1.30, and 1.33. These sampler performance characteristics were evaluated using the EPA criteria defined in 40 CFR Part 53 to determine if these performance criteria fall within the EPA's ambient $PM_{2.5}$ sampler criteria. Further, these performance criteria were evaluated to determine the uncertainty associated with these performance characteristic tolerances and were used to estimate sampler and true concentrations for an array of various PSD characteristics.

Estimating Sampler and True Concentrations

Sampler and true concentrations can be theoretically estimated using PSD and sampler performance characteristics defined in equations 1 through 3. The method of determining sampler concentrations depends on whether the sampler uses a single or multi-stage pre-separator. For instance, most PM_{10} ambient air samplers are single stage; however, an EPA-approved $PM_{2.5}$ ambient air sampler consists of a PM_{10} pre-separator and a $PM_{2.5}$ pre-separator. Some $PM_{2.5}$ samplers do not include the PM_{10} pre-separator. Sampler concentrations for single-stage samplers can be estimated by:

$$C_m(\mathrm{MMD}, \mathrm{GSD}, d_{50}, slope) = C_a \int_0^{\infty} f(d_p, \mathrm{MMD}, \mathrm{GSD}) P_m(d_p, d_{50}, slope)\, dd_p \quad (4)$$

Sampler concentrations for a two-stage sampler can be estimated by:

$$C_{m_2}(\mathrm{MMD}, \mathrm{GSD}, d_{50_1}, slope_1, d_{50_2}, slope_2) = C_a \int_0^{\infty} f(d_p, \mathrm{MMD}, \mathrm{GSD}) P_{m1}(d_p, d_{50_1}, slope_1) P_{m2}(d_p, d_{50_2}, slope_2)\, dd_p \quad (5)$$

For true concentrations, the cumulative penetration efficiency distribution function is assumed to be equal to 1 for all particle sizes less than or equal to the size of interest, and zero for all other particle sizes, as defined in equation 3. Therefore, using equations 1 and 3, the true concentration can be estimated by:

$$C_t(\mathrm{MMD}, \mathrm{GSD}, d_{50}) = C_a \int_0^{d_{50}} f(d_p, \mathrm{MMD}, \mathrm{GSD})\, dd_p \quad (6)$$

Relative Differences Between Sampler and True Concentrations

Sampler and true concentrations are not always equal. An estimate of the differences, $E(x)$, between these two concentrations can be defined as:

$$E(x) = \frac{(Sampler - True)}{True} = \left(\frac{Sampler}{True}\right) - 1 \quad (7)$$

where *Sampler* and *True* are the estimated sampler and true concentrations, respectively. Substituting equations 4 and 6 into equation 7 and canceling like terms yields:

$$E(\mathrm{MMD}, \mathrm{GSD}, d_{50}, slope) + 1 = \left[\frac{\int_0^{\infty} f(d_p, \mathrm{MMD}, \mathrm{GSD}) P_m(d_p, d_{50}, slope)\, dd_p}{\int_0^{d_{50}} f(d_p, \mathrm{MMD}, \mathrm{GSD})\, dd_p}\right] \quad (8)$$

for a sampler with a single pre-separator. Equation 8 can be further expanded for a multistage pre-separator. Throughout the remaining sections of this article, E(MMD, GSD, d_{50}, *slope*) + 1 will be referred to as the ratio of the sampler to true concentration.

Mathcad 2000 (Mathsoft, Natick, Mass.) was used for the mathematical analyses. Equation 8 was solved for various PSD and sampler performance characteristics in order to obtain an initial concept of how the interaction of these characteristics impacts the concentration ratio. The PSD characteristics included in the evaluation were MMDs of 5 and 10 μm with a GSD of 1.5, and MMDs of 15 and 20 μm with a GSD of 2.0. The sampler performance characteristics included the nine combinations of d_{50} and slope values for the ambient $PM_{2.5}$ sampler, as previously described. In order to further define the differences between the simulated sampler measurements and true PM_{10} concentrations, equations 4 and 6 were solved for a d_{50} equal to 2.7 μm, slope of 1.33, GSD of 2.0, and MMDs ranging from 1 to 40 μm.

To further describe how the interaction of the PSD and sampler performance characteristics affects the acceptable PM concentrations, a series of calculations was performed to solve equation 8 over a range of parameters. These PSD parameters included MMD values ranging from 1 to 40 μm (in increments of 1 μm) and GSD values ranging from 1.3 to 2.5 (in increments of 0.1). The sampler performance characteristics corresponded to the $PM_{2.5}$ ambient air sampler with no PM_{10} inlet and the $PM_{2.5}$ ambient air sampler with a PM_{10} inlet. The sampler performance characteristics also corresponded to the parameters defining the boundary tolerance ranges for the individual samplers. For example, d_{50} values of 9.5 and 10.5 μm with slopes of 1.6 and 1.4 were used for the PM_{10} ambient air sampler, as specified by the EPA. Graphs of the results were created to demonstrate how each of the parameters affects the sampler to true concentration ratio.

Results and Discussion

According to the literature, the EPA's emphasis on the 2.5 μm cutpoint was more closely associated with separating the fine and coarse atmospheric aerosol modes than mimicking a respiratory deposition convention (USEPA, 1996b). This emphasis is apparent when the penetration curve associated with the $PM_{2.5}$ ambient air sampler is compared to the American Conference of Governmental Industrial Hygienists (ACGIH) respirable fraction of PM, as shown in figure 1. The EPA's $PM_{2.5}$ cumulative penetration data set for Class II $PM_{2.5}$ candidate samplers produced a relatively smooth curve; however, the curve appeared to have a larger slope associated with particle sizes less than 2.5 μm AED than the slope associated with particle sizes larger than 2.5 μm AED.

According to 40 CFR Part 53, a candidate sampler passes the sampling effectiveness test if the expected mass concentration calculated for the candidate sampler differs by no more than ±5% from that predicted for the ideal sampler when using the idealized coarse aerosol, idealized "typical" coarse aerosol, and idealized fine coarse aerosol size distributions (CFR, 2001e). The results of the comparison of the nine sampler performance criteria used in this research to that of the EPA's ideal sampler are shown in table 1. All the penetration curves evaluated passed the sampler effectiveness tests for the "typical" coarse and fine coarse aerosol size distributions; however, not all curves passed the test for the coarse aerosol size distribution. The penetration curve defined by a d_{50} of 2.5 μm and a slope of 1.33 and all curves defined by a d_{50} of 2.7 μm failed the sampler effectiveness test for the coarse aerosol size distribution (i.e., deviated from the EPA idealized sampler by more than 5%). Although some of the penetration curves generated from d_{50} values of 2.5 ±0.2 μm and slope values of 1.3 ±0.03 failed the sampler effectiveness tests, these performance criteria ranges were used throughout the remainder of this research effort since these ranges have been observed in the actual evaluation of EPA-approved $PM_{2.5}$ samplers.

Based on the ambient $PM_{2.5}$ sampler performance criteria used in this article, four combinations of d_{50} and slope values were used to define boundary penetration efficiency curves. These penetration curves were defined with d_{50} values of 2.3 and 2.7 μm and slope values of 1.27 and 1.33. Figure 2 illustrates the comparison of the boundary penetration curves and the EPA ideal $PM_{2.5}$ sampler penetration efficiency curve. The ideal penetration curve was encompassed by the boundary penetration curves for particle diameters less than about 2.7 μm and was outside of the boundary curves for particle diameters greater than 2.7 μm.

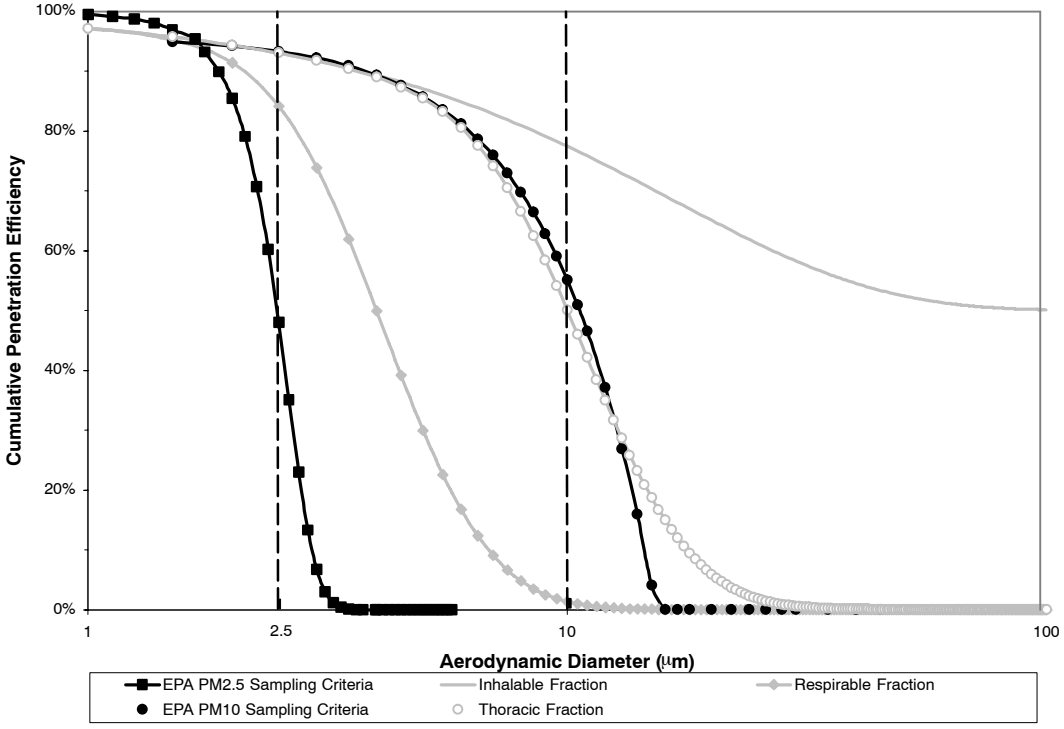

Figure 1. EPA ideal PM_{10} and $PM_{2.5}$ sampler penetration curves overlaid on the ACGIH sampling criteria for inhalable, thoracic, and respirable fractions of PM (ACGIH, 1997; CFR, 2001d, 2001e).

Table 1. Estimated $PM_{2.5}$ mass concentration ratios between sampler performance characteristics and the EPA idealized sampler.

Coarse Aerosol			"Typical" Coarse Aerosol			Fine Aerosol		
Cutpoint (μm)	Slope	Ratio (%)	Cutpoint (μm)	Slope	Ratio (%)	Cutpoint (μm)	Slope	Ratio (%)
2.3	1.27	100	2.3	1.27	100	2.3	1.27	99
2.3	1.30	100	2.3	1.30	100	2.3	1.30	99
2.3	1.33	101	2.3	1.33	100	2.3	1.33	98
2.5	1.27	104	2.5	1.27	101	2.5	1.27	101
2.5	1.30	105	2.5	1.30	101	2.5	1.30	100
2.5	1.33	106	2.5	1.33	102	2.5	1.33	100
2.7	1.27	109	2.7	1.27	103	2.7	1.27	102
2.7	1.30	110	2.7	1.30	103	2.7	1.30	102
2.7	1.33	111	2.7	1.33	103	2.7	1.33	102

When comparing the boundary penetration efficiency curves in figure 2, it is apparent that there is an acceptable range of penetration efficiencies for the $PM_{2.5}$ ambient air sampler. The acceptable range of penetration efficiencies for a particle size of 2.5 μm AED is 36% to 63%. In other words, the uncertainty associated with the performance characteristics of a $PM_{2.5}$ ambient air sampler when sampling 2.5 μm particles is ±16.5%. These ranges are considered one form of inherent error associated with $PM_{2.5}$ ambient air samplers.

Table 2 shows estimates of the ratios of sampler to true concentrations for the ambient $PM_{2.5}$ sampler, based on equation 8. In addition, table 2 shows estimates for sampler concentrations under the assumption that the current regulated limit is based on a sampler concentration and that the regulation should be based on a true concentration. In other words, the NAAQS are based on sampler concentrations; however, the NAAQS should be based on true concentrations so that all industries are equally regulated. The mathematical definition for this assumption is:

$$C_{Acceptable} = Ratio * C_{NAAQS} \qquad (9)$$

where C_{NAAQS} is the current concentrations associated with the NAAQS, and $C_{acceptable}$ is the acceptable concentrations if the NAAQS were based on true concentrations. Table 2 shows that: (1) the range of $PM_{2.5}$ sampler performance characteristics used (from d_{50} of 2.3 μm with slope of 1.27 to d_{50} of 2.7 μm with slope of 1.33) define the range of acceptable concentrations for the PSDs characterized by MMDs greater than 2.5 μm, and (2) the ratios of sampler to true concentrations ranged from 108% to 1314%. This initial evaluation was expanded to incorporate a larger range of MMDs and GSDs for the $PM_{2.5}$ ambient air sampler.

Results of the expanded simulation for the wider range of MMDs (ranging from 1 to 40 μm) are illustrated in figure 3. In figure 3, three MMDs are highlighted. The first (5.7 μm) corresponds to the MMD associated with urban dust as defined by the EPA, and the other two (15 to 25 μm) correspond to MMDs encompassing the range expected from agricultural-type dusts. When comparing the sampler to true concentrations for the urban dust, the sampler concentration is about 33% [i.e., (true percent less than 5.7 μm – sampler percent less than 5.7 μm) / (true percent less than 5.7 μm)] higher than the true concentration. Further, when comparing the sampler to true concentrations for the range of agricultural-type dusts, the sampler concentrations were 120% to 2400% higher than the true concentrations.

Figure 4 shows the sampler to true concentration ratios for the two sets of $PM_{2.5}$ sampler (no PM_{10} inlet) performance

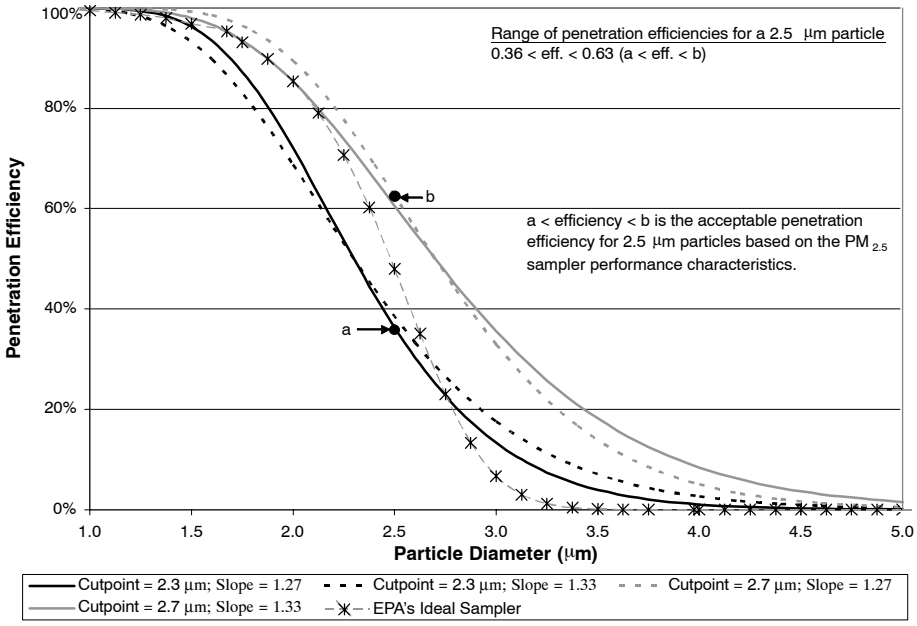

Figure 2. $PM_{2.5}$ sampler penetration curves based on the defining performance characteristics.

Table 2. Concentration ratios of the theoretical sampler to true concentrations for various particle size distributions and sampler performance characteristics.

Sampler Characteristics		Particle Size Distribution Characteristics							
		GSD = 1.5				GSD = 2.0			
		MMD = 5 μm		MMD = 10 μm		MMD = 15 μm		MMD = 20 μm	
Cutpoint (μm)	Slope	Ratio (%)[a]	$PM_{2.5}$ Conc. (μg/m³)[b]	Ratio (%)[a]	$PM_{2.5}$ Conc. (μg/m³)[b]	Ratio (%)[a]	$PM_{2.5}$ Conc. (μg/m³)[b]	Ratio (%)[a]	$PM_{2.5}$ Conc. (μg/m³)[b]
2.3	1.27	113.3	73.65	285.3	185.45	108.3	70.40	117.8	76.57
2.3	1.30	123.5	80.28	372.6	242.19	117.1	76.12	130.4	84.76
2.3	1.33	134.2	87.23	482.0	313.30	126.9	82.49	144.7	94.06
2.5	1.27	161.2	104.78	531.3	345.35	149.3	97.05	169.1	109.92
2.5	1.30	173.1	112.52	652.1	423.87	160.4	104.26	186.0	120.90
2.5	1.33	185.5	120.58	821.8	534.17	172.7	112.26	204.9	133.19
2.7	1.27	218.1	141.77	860.1	559.07	198.7	129.16	233.8	151.97
2.7	1.30	231.2	150.28	1066.9	693.49	212.4	138.06	255.4	166.01
2.7	1.33	244.8	159.12	1314.0	854.10	227.4	147.81	279.6	181.74

[a] Values are based on the assumption that true concentrations are the correct estimates of the corresponding PM concentrations.
[b] Concentrations are based on the corresponding regulations and adjusted by the ratio. Sampler concentrations for $PM_{2.5}$ are 65 μg/m³.

characteristics that define the acceptable concentrations for $PM_{2.5}$, GSD = 2.0, and PSD MMDs ranging from 1 to 40 μm. To aid in the interpretation of the graph, an average concentration ratio is defined as the average of the largest and smallest ratios for a particular MMD. The information presented in figure 4 shows that: (1) the average ratio is equal to 1.0 when the MMD is equal to the d_{50}, (2) the average ratio is greater than 1.0 when the MMD is greater than the d_{50}, and (3) the ratio range increases as the MMD increases. In general terms, when the ratio is equal to 1.0, the current method of regulating $PM_{2.5}$ results in an exact concentration measurement of PM less than or equal to 2.5 μm AED, and when the ratio is greater than 1.0, the current method overestimates the concentration of PM less than 2.5 μm AED. For example, if a PSD were characterized by an MMD of 5.7 μm and a GSD of 2.0, then the acceptable range of $PM_{2.5}$ sampler concentrations to be in compliance with the property-line concentration limits would be 60 to 87 μg/m³ (i.e., ratios of 0.92 and 1.34 obtained from figure 4 and multiplied by 65 μg/m³, the proposed NAAQS for $PM_{2.5}$). In this scenario, the $PM_{2.5}$ sampler uncertainty is ±13.5 μg/m³, and since the EPA essentially states that the $PM_{2.5}$ NAAQS should correspond to a true concentration, the $PM_{2.5}$ sampler bias is 8.5 μg/m³. If the PSD were characterized by an MMD of 10 μm and a GSD of 2.0, then the acceptable range of $PM_{2.5}$ sampler concentrations would be 64 to 115 μg/m³, with a corresponding $PM_{2.5}$ sampler uncertainty of ±25.5 μg/m³ and a bias of 24.5 μg/m³. Further, if the PSD were characterized by an MMD of 20 μm and a GSD of 2.0, then the acceptable range of $PM_{2.5}$ sampler concentrations would be 77 to 182 μg/m³, corresponding to a $PM_{2.5}$ sampler uncertainty of ±52.5 μg/m³ and a bias of 64.5 μg/m³.

The data presented in figure 5 are based on the same assumptions as figure 4, except the data are based on a GSD of 1.5. When comparing figures 4 and 5, it is obvious that the ratios increase much more rapidly as the MMD increases when the GSD is 1.5 as compared to a GSD of 2.0. For example, if a PSD were characterized by an MMD of 5.7 μm AED and a GSD of 1.5, then the acceptable range of $PM_{2.5}$ sampler concentrations would be 81 to 193 μg/m³ (i.e., ratios of 1.24 and 2.96 obtained from figure 6 and multiplied by 65 μg/m³, the proposed NAAQS for $PM_{2.5}$), corresponding to a $PM_{2.5}$ sampler uncertainty of ±56 μg/m³ and a bias of 72 μg/m³. If the PSD were characterized by an MMD of

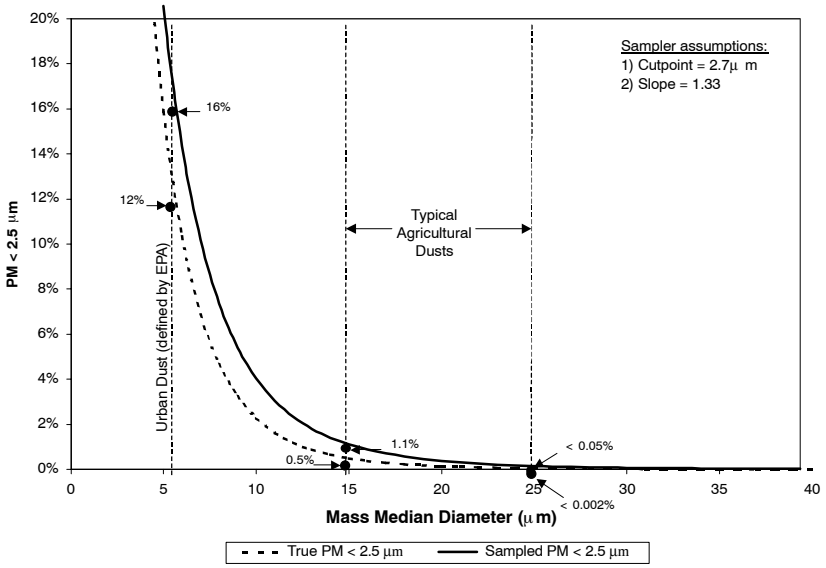

Figure 3. Comparison of sampler and true $PM_{2.5}$ percentages for a range of PSD MMDs and GSD = 2.0.

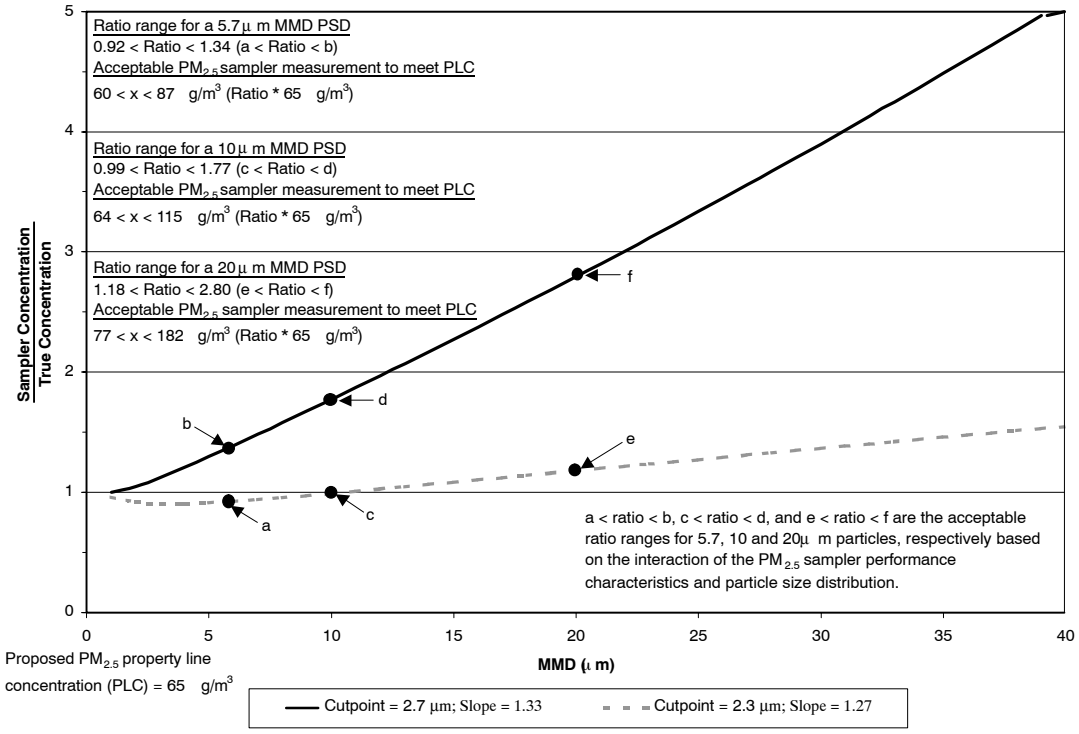

Figure 4. Theoretical ratios of $PM_{2.5}$ sampler to true PSD concentrations for a range of MMDs and a GSD = 2.0.

10 μm AED and a GSD of 1.5, then the acceptable range of $PM_{2.5}$ sampler concentrations would be 185 to 854 μg/m^3, corresponding to a $PM_{2.5}$ sampler uncertainty of ±334.5 μg/m^3 and a bias of 454.5 μg/m^3. Further, if the PSD were characterized by an MMD of 20 μm AED and a GSD of 1.5, then the acceptable range of $PM_{2.5}$ sampler concentrations would be 963 to 11,929 μg/m^3, corresponding to a $PM_{2.5}$ sampler uncertainty of ±5,483 μg/m^3 and a bias of 6,381 μg/m^3. Thus, the data presented in figures 4 and 5 indicate that the range of acceptable concentrations increases as the GSD increases.

The data presented in figure 6 are based on the same assumptions as figure 4, except the sampler performance characteristics of a PM_{10} inlet are incorporated into the

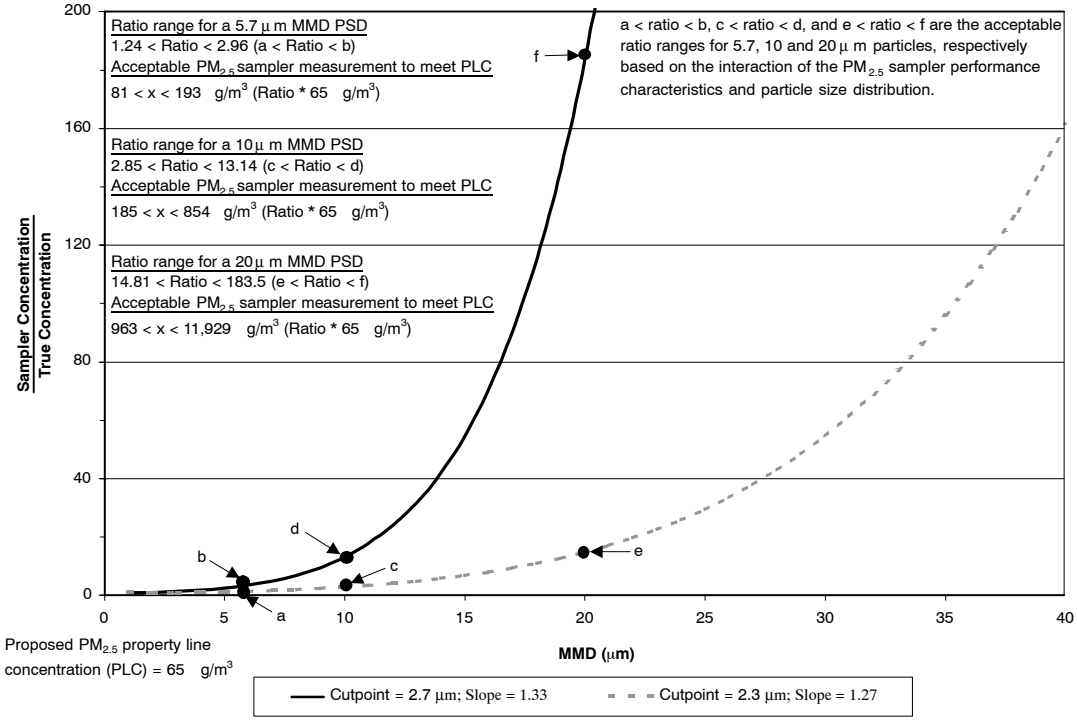

Figure 5. Theoretical ratios of $PM_{2.5}$ sampler to true PSD concentrations for a range of MMDs and a GSD = 1.5.

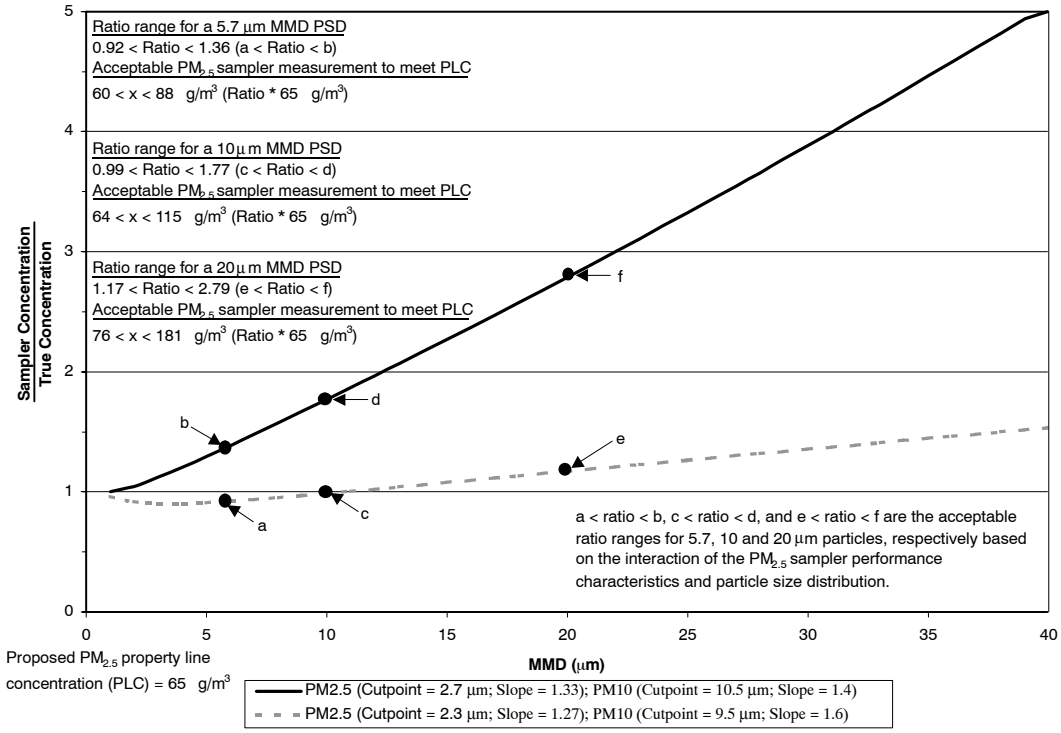

Figure 6. Theoretical ratios of $PM_{2.5}$ sampler, with PM_{10} inlet, to true PSD concentrations for a range of MMDs and a GSD = 2.0.

simulation. The d_{50} and slope values for the PM_{10} inlet used in the simulation were based on EPA guidelines and were refined through a trial and error process (i.e., determining which PM_{10} d_{50} and slope values coupled with the $PM_{2.5}$ boundary performance characteristic generated the $PM_{2.5}$ sampler with PM_{10} inlet boundary performance characteristics). The resulting PM_{10} performance characteristics were defined as a d_{50} of 9.5 µm with a slope of 1.6, and a d_{50} of 10.5 µm with a slope of 1.4. In general, the inclusion of the PM_{10} inlet on the $PM_{2.5}$ sampler had very little effect on the sampler to true concentration ratio. For example, if the PSD were characterized by an MMD of 5.7 µm AED and a GSD of 2.0, then the acceptable concentration range for a $PM_{2.5}$ sampler with a PM_{10} inlet would be 60 to 88 µg/m^3 (fig. 6),

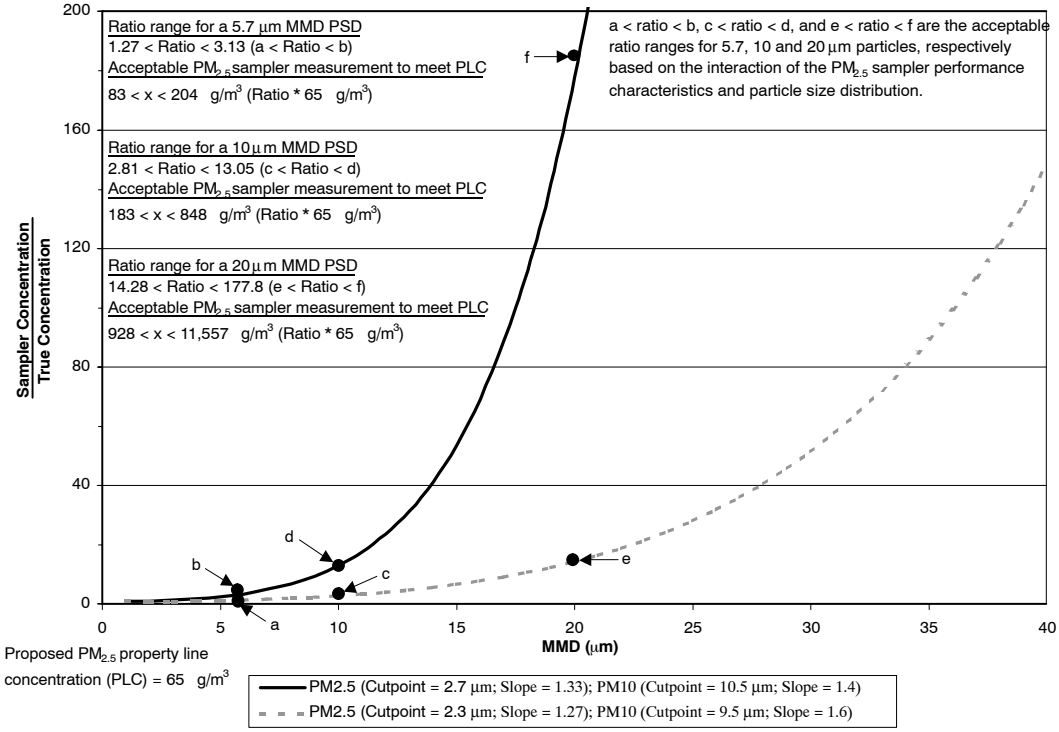

Figure 7. Theoretical ratios of $PM_{2.5}$ sampler, with PM_{10} inlet, to true PSD concentrations for a range of MMDs and a GSD = 1.5.

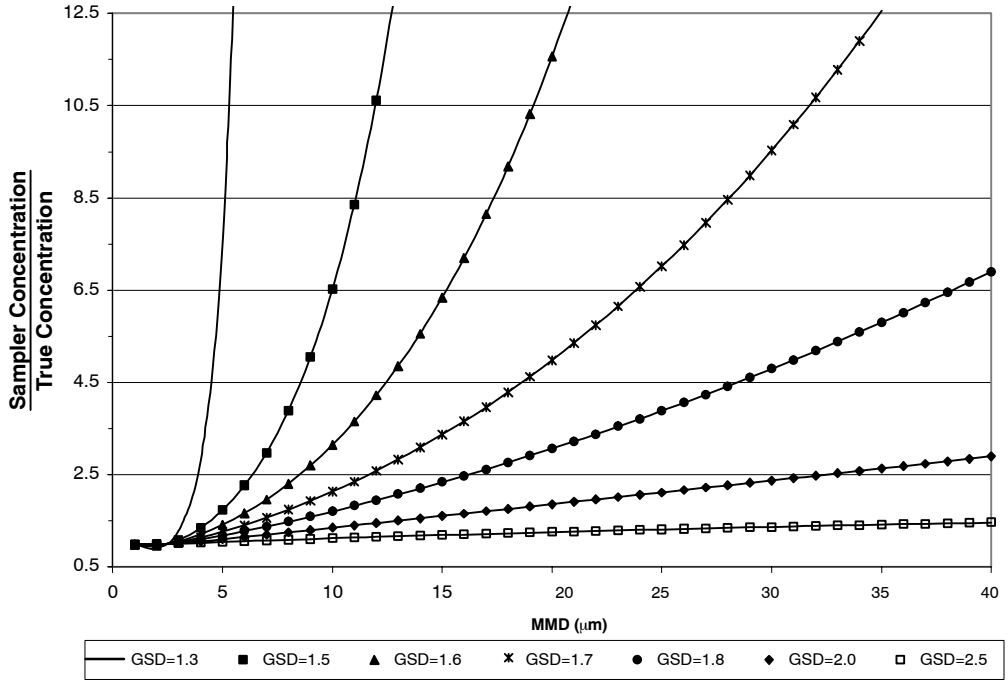

Figure 8. Theoretical ratios of $PM_{2.5}$ sampler measured to true PSD concentrations ($PM_{2.5}$ sampler characteristics: cutpoint = 2.5 μm and slope = 1.3).

as compared to 60 to 87 μg/m^3 for a $PM_{2.5}$ sampler with no PM_{10} inlet (fig. 4). If the PSD were characterized by an MMD of 20 μm AED and a GSD of 2.0, then the acceptable concentration range for a $PM_{2.5}$ sampler with a PM_{10} inlet would be 76 to 181 μg/m^3, as compared to 77 to 182 μg/m^3 for a $PM_{2.5}$ sampler with no PM_{10} inlet.

The data presented in figure 7 are based on the same assumptions as figure 6, except the GSD = 1.5. Comparison of figures 4 and 6 shows that the inclusion of the PM_{10} inlet on the $PM_{2.5}$ sampler had very little relative effect on the sampler to true concentration ratio. For example, if the PSD were characterized by an MMD of 5.7 μm AED and a GSD of 1.5, then the acceptable concentration range for a $PM_{2.5}$ sampler with a PM_{10} inlet would be 83 to 204 μg/m^3 (fig. 7), as compared to 81 to 193 μg/m^3 for a $PM_{2.5}$ sampler with no PM_{10} inlet (fig. 5). If the PSD were characterized by an MMD of 20 μm AED and a GSD of 1.5, then the acceptable concentration range for a $PM_{2.5}$ sampler with a PM_{10} inlet

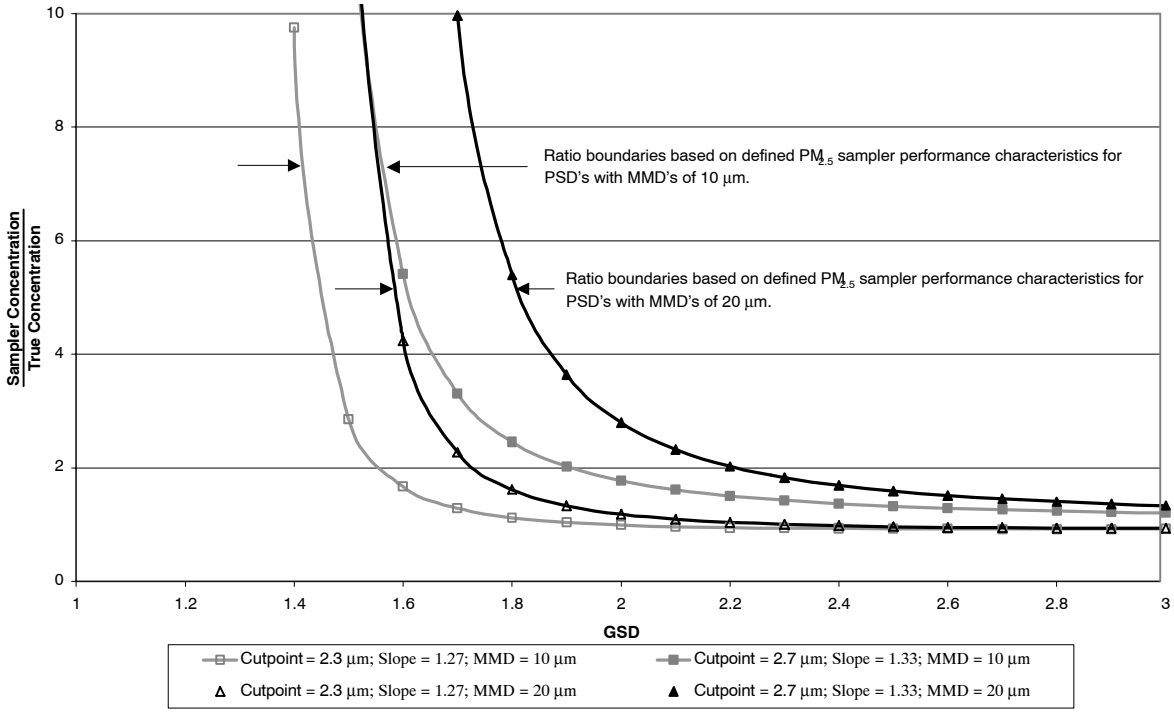

Figure 9. Theoretical $PM_{2.5}$ sampler measured to true concentration ratio boundaries for varying GSDs with MMDs of 10 and 20 μm.

would be 928 to 11,557 μg/m^3, as compared to 963 to 11,929 μg/m^3 for a $PM_{2.5}$ sampler with no PM_{10} inlet. Although a decrease of 372 μg/m^3, when comparing the $PM_{2.5}$ sampler with and without a PM_{10} inlet for a PSD characterized by an MMD of 20 μm and a GSD of 1.5, would seem significant, the relative difference is negligible (i.e., only about a 3% decrease). Therefore, only the $PM_{2.5}$ sampler performance characteristics without the PM_{10} inlet performance characteristics are used in the remainder of the inherent sampler errors discussion.

Figure 8 further illustrates the effect of MMD and GSD on the concentration ratios for a $PM_{2.5}$ sampler with a d_{50} of 2.5 μm and a slope of 1.3. In general, the concentration ratios decrease (ratio approaches 1.0) as the GSD increases and as MMD decreases. Figure 9 further expands on how the concentration ratios are impacted by GSD. The data presented in figure 9 are based on MMDs of 10 and 20 μm, sampler performance characteristic of a d_{50} equal to 2.3 μm with a slope of 1.27 and a d_{50} of 2.7 μm with a slope of 1.33, and variable GSDs ranging from 1.2 to 3.0. The figure shows that: (1) as the GSD increases, the concentration ratio decreases and approaches 1.0, and (2) as the GSD decreases, the concentration ratio increases and approaches infinity.

Summary and Conclusion

Several errors are associated with the current air pollution rules and regulations established by the EPA that should be minimized to ensure equal regulation of air pollutants between and within all industries. Potentially one of the most significant errors is attributed to the interaction of the industry-specific PSD and sampler performance characteristics. Currently, the regulation of PM is based on sampler measurements and not on true concentrations.

Sampler concentration refers to the concentration collected by a PM sampler. This concentration is dependent on the sampler's performance characteristics (i.e., d_{50} and slope of the sampler penetration curve). Since the concentration is based on the sampler's performance characteristics, there are two inherent errors associated with the measurement. For a $PM_{2.5}$ sampler, the first error corresponds to the mass of particles less than 2.5 μm that should have been captured on the filter but was removed from the air stream by the pre-separator. The second error (for a $PM_{2.5}$ sampler) corresponds to the mass of particles greater than 2.5 μm that should have been removed from the air stream by the pre-separator but was allowed to pass through the pre-separator and was captured on the filter. When the MMD of the dust being sampled is less than the sampler d_{50}, under-sampling of the mass of particles less than 2.5 μm occurs. When the MMD of the dust being sampled is equal to the d_{50} of the sampler, the sampler provides a measurement equivalent to the true mass of particles less than 2.5 μm. When the MMD of the dust being sampled is greater than the d_{50} of the sampler, over-sampling of the mass of particles less than 2.5 μm occurs.

True concentration refers to the mass of particles less than or equal to the size of interest. In order for a sampler to provide a true concentration, independent of the MMD of the dust being sampled, the sampler would have to maintain a slope of 1.0 (i.e., the sampler's penetration curve would be represented by a step function).

According to the literature, the EPA decided to regulate $PM_{2.5}$ based on the availability of the dichotomous sample. The $PM_{2.5}$ regulation was not based on determining the respirable fraction of PM. ACGIH, ISO, and others have defined the respirable fraction of PM as having a d_{50} between 3.5 and 5 μm. The final justification for using true $PM_{2.5}$ values as opposed to sampler-based concentration comes from the literature in the following direct quotation:

"Staff also recommended the use of a sharp 2.5 micron cutpoint for a fine particle indicator. $PM_{2.5}$ does have some potential for intrusion of the tail of the coarse mode during episodes of fugitive dust concentrations. Staff recommends a sharp inlet for the FRM to minimize this potential intrusion of coarse-mode particles. Such intrusion into $PM_{2.5}$ measurement is not anticipated to be significant in most situations; nevertheless, if subsequent data reveal problems in this regard, this issue can and should be addressed on a case-by-case basis in the monitoring and implementation programs. Because the purpose of a $PM_{2.5}$ standard is to direct controls toward sources of fine-mode particles, it would be appropriate to develop analytical procedures for identifying those cases where a $PM_{2.5}$ standard violation would not have occurred in the absence of coarse-mode particle intrusion. Consideration should be given to a policy similar to the natural events policy for addressing such cases" (USEPA, 1996b).

The NAAQS standards correspond to PM in the ambient air (i.e., not impacted by only one source). Therefore, the question becomes, "Is it appropriate to use an EPA-approved ambient $PM_{2.5}$ sampler to determine emission values from individual sources?" In all situations when the source is emitting PM with an MMD larger than 2.5 μm, the answer is "absolutely not."

So how is this a problem? If a state or air district finds itself in non-attainment with the $PM_{2.5}$ NAAQS, then the corresponding agencies will, most likely, be required to reduce $PM_{2.5}$ emissions within the air shed. In order to reduce emissions from individual sources, the amount of PM emitted by the sources must be known or estimated. This is typically accomplished through source sampling or the use of emission factors, which may have been determined from source sampling or interpreted by some other means. In order to illustrate why it is crucial that emission factors, emission rates, and/or emission concentrations from individual sources be based on true $PM_{2.5}$ and not $PM_{2.5}$ sampler measurements, the following example is provided.

Assume that EPA-approved $PM_{2.5}$ ambient air samplers were set up to monitor two commercial operations. Assume also that the samplers have performance characteristics described by a d_{50} of 2.3 μm and a slope of 1.3 (both parameters are within the performance criteria defined by the EPA). Now assume that one operation is a power plant and is emitting PM (sampled by the $PM_{2.5}$ sampler) that can be described by a lognormal distribution with an MMD of 5 μm and a GSD of 1.8. Assume that the second operation is an agricultural operation and is emitting PM (sampled by the $PM_{2.5}$ sampler) that can be described by a lognormal distribution with an MMD of 20 μm and a GSD of 1.8. Further, assume that the $PM_{2.5}$ sampler used to monitor each of the operations measures 50 μg/m^3. Now, based on the methods laid out in this article, the true PM (PM less than 2.5 μm) emitted from each industry would be defined as follows:

Based on a PSD analysis, the percent of PM mass less than 2.5 μm being emitted by the power plant is 11.9%. Based on the PSD and sampler performance characteristics, the percent of total suspended particulate (TSP) captured by the $PM_{2.5}$ sampler is 11.4%. The TSP concentration emitted by the power plant is 439 μg/m^3 (i.e., 50 μg/m^3 (PM measured by the $PM_{2.5}$ sampler) / 0.114 (% of TSP captured by the $PM_{2.5}$ sampler). By multiplying the TSP concentration by the true fraction of $PM_{2.5}$ (i.e., 439 μg/m^3 × 0.119), the true $PM_{2.5}$ concentration is determined to be 52 μg/m^3. Therefore, the $PM_{2.5}$ sampler underestimated the true $PM_{2.5}$ concentration by 3.8%.

For the agricultural operation, using the previous procedures, the true percent $PM_{2.5}$ is 0.02%, and based on the PSD and sampler performance characteristics, the percent of TSP captured by the $PM_{2.5}$ sampler is 0.039%. Therefore, the TSP concentration is 128,205 μg/m^3, resulting in the true $PM_{2.5}$ emitted by the operation being equal to 25.6 μg/m^3. In this case, the $PM_{2.5}$ sampler overestimated the true $PM_{2.5}$ by 95%. Based on this scenario, the two operations are not being equally regulated, and the $PM_{2.5}$ ambient air samplers are overestimating the concentration of particles less than 2.5 μm that are being emitted by the operations.

Looking at the issue from another viewpoint, assume that the two operations described previously are emitting 60 μg/m^3 true $PM_{2.5}$. If the percent of TSP measured by the $PM_{2.5}$ sampler (defined as measured $PM_{2.5}$) is divided by the percent of true $PM_{2.5}$, and this ratio is then multiplied by the true concentration of $PM_{2.5}$ being emitted, the $PM_{2.5}$ sampler concentrations can be determined. For the power plant, the $PM_{2.5}$ sampler would measure a concentration of 58 μg/m^3. For the agricultural operation, the PM_{10} sampler would measure a concentration of 116 μg/m^3. What this means for the agricultural operation is that 60 μg/m^3 of the PM being sampled is less than 2.5 μm and 56 μg/m^3 of the PM being sampled is larger than 2.5 μm. Therefore, regarding the question, "Is it appropriate to use $PM_{2.5}$ samplers to determine $PM_{2.5}$ emission values from industries that are emitting PM with an MMD larger than 2.5 μm?," the answer is "absolutely not."

Results of the analysis presented in this article show that all industries are not being equally regulated in terms of $PM_{2.5}$ and that all industries should be concerned with the current site-specific regulations implemented by the EPA and enforced by SAPRAs.

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EFFECTS OF DUST LOADING ON THE PERFORMANCE OF THE VSCC CYCLONE

for BGI Incorporated

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IR/L/EXCON/01/09

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SUMMARY

The Very Sharp Cut Cyclone (VSCC) is a tangential round-entry cyclone geometry that has been designed to offer size selectivity with sharpness on a par with the WINS impactor for $PM_{2.5}$ sampling.

This report details an experimental evaluation of the effect of dust loading on the particle size-selective performance of the VSCC cyclone. The dust loading tests were conducted in line with the criteria set out by EPA in part of 40 CFR part 53. This describes the loading periods at an exposure concentration of 150 µg m^{-3} after which the VSCC should show no significant signs of changes in cut-point or 'sharpness of cut' values. The critical loading interval is defined by EPA as the minimum exposure period up to which the VSCC should show no change in performance.

It would be difficult to generate a concentration as low as this and the tests would be too lengthy. Therefore, higher concentrations of ISO 12103-1 fine test dust (ATD) were generated for shorter intervals to give equivalent 1 day exposures of 150 µg m^{-3}.

BGI supplied HSL with a VSCC cyclone fitted with the EPA standard PM_{10} low-flow louvered inlet and a FRM cassette which fits at the outlet of the cyclone. The dust was generated inside a calm air chamber using a Wright dust feed (WDF) aerosol generator and the VSCC was exposed for 1,2,3,7,14, 30 and 90 days at an equivalent concentration of 150 µg m^{-3}.

After each exposure interval, the performance of the VSCC was measured using an Aerodynamic Particle Sizer system in the same calm air chamber, using methods previously developed and applied routinely by HSL in the characterisation of aerosol fractionators.

CONTENTS

1. INTRODUCTION

The VSCC (Very Sharp Cut Cyclone) is a designation for a novel cyclone geometry that should offer sharpness on a par with impactor systems. In order to realise this concept BGI Incorporated constructed a prototype VSCC cyclone with PM2.5 aerosol sampling applications in mind. BGI is applying to EPA for class II equivalency designation for FRM samplers using the VSCC as part of 40 CFR part 53 criteria. This criteria describes a dust loading protocol which will be followed during these tests. The device will be challenged with a concentration of ISO fine test dust which is at an equivalent to an ambient concentration of 150 $\mu g/m^3$ over a 24 hr period. It is the intention of this work to verify the ability of the VSCC to perform within the EPA criteria and as such the key exposure periods are two weeks, 30 days and 90 days.

2. EXPERIMENTAL METHODS

2.1 Loading of the VSCC with dust

The dust loading tests were carried out inside the same chamber used to carry out the VSCC penetration curves. This was so that the cyclone was moved as little as possible during the tests, since dust inside the VSCC collects on a dry deposition container rather than an oiled impactor plate and could possibly be disturbed. The test dust used to load the VSCC was ISO 12103-1 fine (commonly referred to as Arizona Road Dust or ATD, by EPA). The dust was generated inside the chamber using a Wright dust feed (WDF) which was serviced before use and was fitted with the Tungsten carbide tipped blade. The dust emitted from the WDF entered the chamber at the top where it was mixed and neutralised using an ioniser fan. It then passed through aluminium honeycomb into the working section. The WDF was set to the minimum speed at which it would operate consistently (0.05 rpm) and the dispersion air was set to 0.5 bar pressure. At this speed the WDF should run for around 60 hours before it requires re-filling. The air flow through the chamber was then adjusted using a butterfly valve situated at the base of the chamber to give a concentration of approximately 10 mg/m^3 inside the working region which simulated a 24 hour test at 150 $\mu g/m^3$ in approximately 20 minutes. The velocity through the chamber was less than 0.04 m

s^{-1}. The dust concentration inside the chamber was measured using two thin walled samplers set up according to the Lui and Agarwal (1980) criteria. These were fitted with 25 mm GF/A glass fibre filters and the dust laden air was pulled through at 4 l/min using Rotheroe and Mitchel sampling pumps. At the same time the temporal variation in concentration was monitored using the Microdust 880 nm direct reading dust monitor. This could then be calibrated using the gravimetric measurements. The Microdust 880 nm was very useful as a tool for checking that the dust generator was operating properly. However, its main use was as a predictor of exposure time at any given concentration to give the equivalent 150 µg/m^3 24 hour exposure. The Microdust 880 is calibrated with ATD.

An important consideration in producing valid test results during loading is producing the correct size distribution. If a very fine aerosol is being produced then the VSCC will collect very little material and the tests will overestimate the cyclones required cleaning interval. Similarly, if the aerosol is too coarse, then a large amount of the mass will be removed by the PM_{10} inlet and the interval may again be overestimated. For this reason the size distribution inside the chamber was measured using a Sierra 8 stage impactor which operates at a typical flow rate of 2 l/min. The impactor uses Mylar disks as the collection substrates which were greased in order to minimise losses due to particles bouncing off the surface. Fig 1. Shows a photograph of the experimental set-up.

Throughout the loading tests, the VSCC was fitted with the EPA standard PM_{10} low-flow louvered inlet, and was operated at 16.67 l/min using a high flow rate pump. The dust penetrating the cyclone was collected on a 47 mm GF/A filter mounted inside a FRM cassette at the outlet of the cyclone. The test protocol agreed with BGI was as follows.

a) Verify the penetration performance curve of the clean test object using standard glass microspheres (see 2.2).

b) Generate a concentration of approximately 10 mg m^{-3} ISO 12103-1 fine test dust into the chamber, measure the concentration using the thin wall samplers and calibrate the Microdust

880 nm dust monitor. Determine the mass median diameter and standard geometric standard deviation of the test dust using the cascade impactor.

c) During each loading test, determine the dust concentration measured by the VSCC, and the dust concentration inside the chamber using the calibrated Microdust 880 nm to predict the required sampling period.

d) Carry out the tests for the following intervals:

Test No	Equivalent days (nominal) (at 150 µg m^{-3})	Verify
1	1	Penetration
2	2	Penetration
3	3	Penetration
4	7 (1 week total)	Penetration
5	14 (2 weeks total)	Penetration
6	30 (4 weeks total)	Penetration and size distribution
7	90 (12 weeks total)	Penetration and size distribution

The intention of the above schedule is to verify the ability of the VSCC to perform within EPA criteria. The key tests are No. 5, which will verify a two-week cleaning interval, No. 6 to verify a 30 day cleaning interval and No. 7 for a 90 day interval.

All of the pumps used for gravimetric sampling were used with rotameters that were checked at the flow rate of interest using a calibrated Ametek bubble flowmeter.

2.2 Determination of aerosol penetration curves

The experimental methods used to test the cyclones were similar to those described in detail by Maynard and Kenny (1995). The tests were carried out in an aerosol chamber with a working section 1 m^2. The chamber was purged with clean air prior to a cyclone calibration test to remove

traces of the dust used during loading. The test aerosol consisted of solid, spherical glass microspheres (Whitehouse Scientific) with physical diameters up to 25 µm, and density 2.45 g/cm^3. The aerosol was dispersed using a rotating brush generator into the separate mixing section at the top of the chamber. An aluminium honeycomb layer was used to remove eddies from the aerosol which was transferred into the working section by a slow (< 2 cm.sec^{-1}) steady downflow of air. The generated aerosol typically had a number median diameter around 1.5 µm and a mass median diameter around 4 µm. The number concentration was typically 100-200 particles per cubic centimetre, and was generally stable over the time scales necessary for the test (10 minutes per cyclone).

The test sampling lines were situated close to the centre of the chamber's working section, connected to an Aerodynamic Particle Sizer (APS3310) via two 15mm diameter vertical metal tubes. The APS was situated directly below the working section, outside the chamber. Access to the working section was gained through sealed glove ports in the side of the chamber, which allowed the flow through each cyclone to be measured accurately using calibrated Ametek bubble flowmeter placed inside the chamber. The flow through the system was maintained using a mass flow controller, calibrated and set before and after each test using the Ametek.

The test procedure involved placing the cyclone on one of the two sampling lines. Both sampling lines to the APS shared identical geometry and switching from one to the other was accomplished by means of ball valves. The size selection characteristics were measured by taking five 60-second samples of the polydisperse aerosol alternately from the two sampling lines. Hence the ratio of the aerosol size distributions measured through each line gives the size selective aerosol penetration through the selector alone, all other effects (including any aspiration and transfer losses) being identical in both lines.

Files from the APS were exported and processed using an Excel spreadsheet in order to calculate the penetration curves, taking into account the appropriate corrections for particle density. At the start of each working day the APS calibration was checked at three particle diameters, (3, 5 and 10 µm), using latex spheres traceable to Community Bureau of Reference (BCR) standards.

2.3 Data Analysis

For each aerodynamic diameter range, the average particle number counted with the selector present was divided by the average number counted without the selector present to determine the aerosol penetration for that diameter. The penetration values were analysed using the software package 'Tablecurve' (Jandel Scientific) in order to locate the D_{50}, D_{16} and D_{84} diameters by interpolation. The sharpness values were calculated as:

$$Sharpness = \left(\frac{D_{16}}{D_{84}} \right)^{\frac{1}{2}}$$

Where necessary the raw data were normalised by scaling the penetration values so that they tended to unity for d_{ae}= 0. The APS 3310 flow control does not compensate for the additional pressure drop through the cyclone, and so the raw penetration values usually reached a maximum value of 0.95 to 1.0. The VSCC design has a relatively low pressure drop compared to a WINS impactor and so the adjustments required to re-normalise the data were generally small.

3. RESULTS

A summary of all experimental data, with interpolated D_{50}, D_{16}, D_{84} and sharpness values, is given in Table 1. Bias estimates are presented in Table 2. Penetration curves measured after the various loading intervals are shown in Fig 2.

Penetration curves for the VSCC cyclone after the various loading intervals were analysed and the relationship of D_{50} and sharpness of cut to exposure interval (at an equivalent concentration of 150 µg m^{-3}) is shown in Figure 3.

In order to assess the impact of differing size selection curves, with loading on apparent PM2.5 concentrations, the three ambient aerosol distributions cited in the Federal Register can be utilised. The bias in PM2.5 concentrations that results from numerically 'sampling' these aerosols with selectors whose characteristics differ from the 'ideal' PM2.5 curve specified as the Federal

Reference Method is shown in Table 2. Bias values in the range –5% to +5% are permissible for FRM equivalent samplers. These calculations have been performed for each time interval for which a penetration curve of the VSCC was determined (1, 2, 3, 7, 15, 30 and 90 days). A detailed discussion of how these calculations are performed has been presented by Kenny *et al* (2000).

4. DISCUSSION

The results shown in Fig 2 and Table 1 indicate that the VSCC can operate at an equivalent dust concentration of 150 µg m^{-3} for a minimum of 90 days without any significant change in the cyclone cut-point. A small increase in the sharpness of cut value was observed over the same period.

The size distribution of the challenge aerosol was measured on 3 occasions using the Sierra 8-stage cascade impactor and once using the APS at a reduced concentration to minimise coincidence effects within the instrument. Table 1 shows that there is good agreement between the individual cascade impactor results and also between the cascade impactor results and the APS results.

The Wright dust feed was able to generate and maintain a very constant dust concentration within the test chamber and ran without problems for the full duration of the tests.

The penetration results for the clean VSCC are comparable to those obtained at HSL on a previous occasion. (Kenny, L. C. & Thorpe, A, 2000)

The calculation of bias on observed mass concentrations for all of the test intervals up to 90 days was 1% for the 'typical' and 'fine' modes. The 'coarse' mode started at 4% and descended to 3% at day three, rising to 4% at day 90.

5. CONCLUSIONS

The VSCC was able to operate at an equivalent concentration of 150 µg m^{-3} for a period of at least 90 days with little effect on the d_{50} cut point and only a small increase in the sharpness of cut. Bias calculations demonstrated that the VSCC never exceeded the EPA '5%' criteria at any time, throughout the study.

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Table 1. Summary of loading results

Nominal exposure time at 150 µg m^{-3} (days)	Total concentration inside calm air chamber (mg m^{-3})	$PM_{2.5}$ conc (mg m^{-3})	Exposure time (mins)	Equivalent exposure time at a conc of 150 µg m^{-3} (days)	Cumulative exposure time at a conc of 150 µg m^{-3} (days)	d_{50}	d_{16}	d_{84}	Sharpness of cut	Aerosol particle size	
										Mass Median (um)	Geometric standard deviation (um)
0					0	2.54	2.86	2.22	1.135	* 5.1	1.67
1	8.33	2.46	23.1	0.89	0.89	2.59	2.9	2.22	1.143		
1	11.78	2.76	20.8	1.13	2.02	2.55	2.88	2.19	1.147		
1	11.1	2.52	19.25	0.99	3.01	2.55	2.9	2.2	1.148	# 5.75	2.29
4	10.23	2.18	88.43	4.19	7.20	2.51	2.86	2.12	1.161		
7	10.54	2.46	160.85	7.85	15.05	2.54	2.9	2.16	1.159		
16	10.7	2.41	320.67	15.89	30.94	2.52	2.9	2.12	1.17	5.81	1.62
60	13.3	3.1	979.2	60.29	91.23	2.54	2.98	2.11	1.19	6.01	1.62

* Size distribution carried out inside calm air chamber before dust loading tests commenced

\# Size distribution measured with Aerodynamic particle sizer (APS model 3310) at a reduced concentration to minimise coincidence errors

Table 2. % Bias in VSCC PM2.5 concentrations for three ambient aerosol size distributions.

Interval Days	'Fine Aerosol'	'Typical Aerosol'	'Coarse Aerosol'
0	1	1	4
1	1	1	4
2	1	1	4
3	1	1	3
7	1	1	3
14	1	1	3
30	1	1	3
90	1	1	4

Fig 1. Experimental set-up for loading of VSCC with Arizona road dust

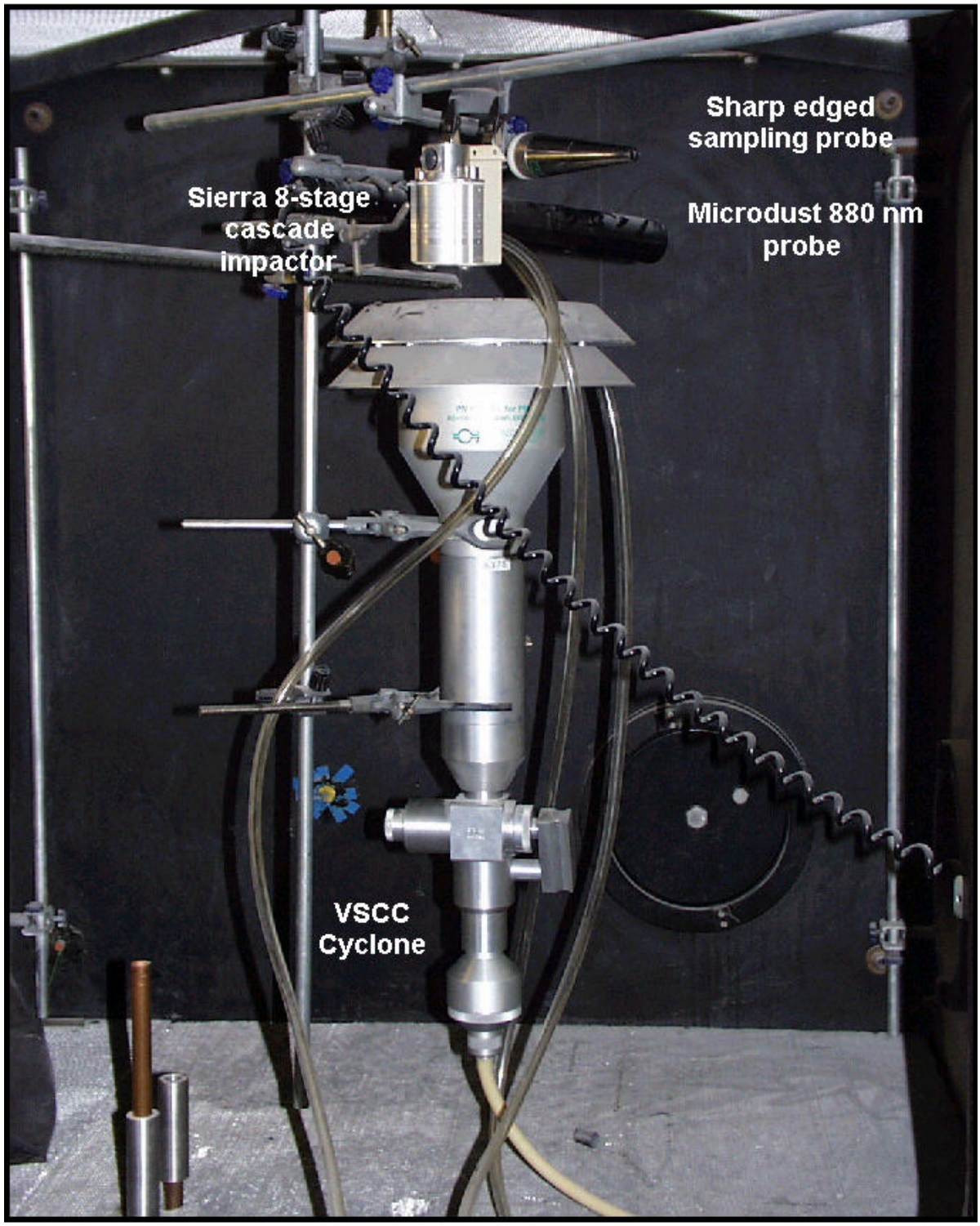


Fig 2. Loading of VSCC with Arizona road dust

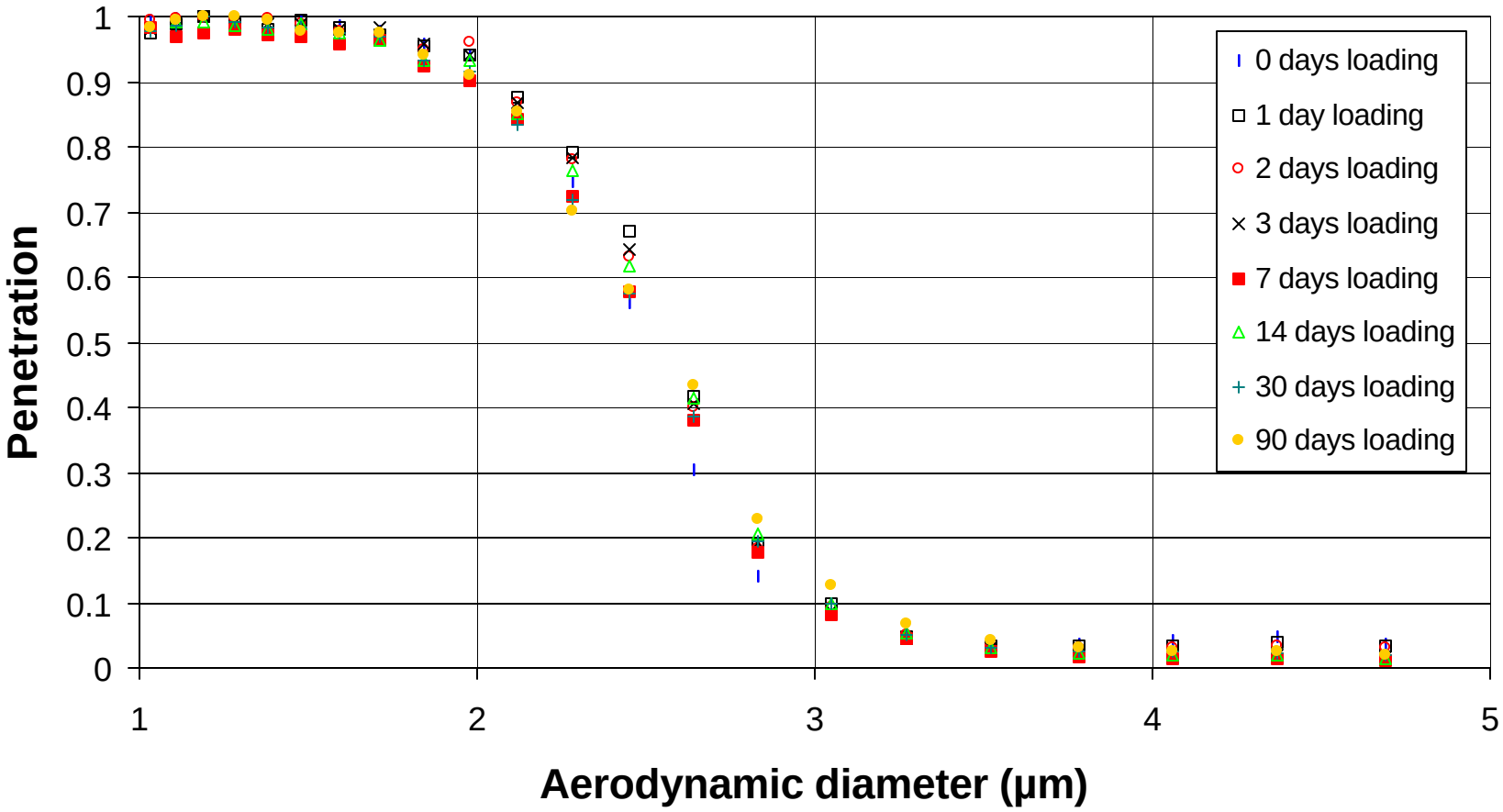
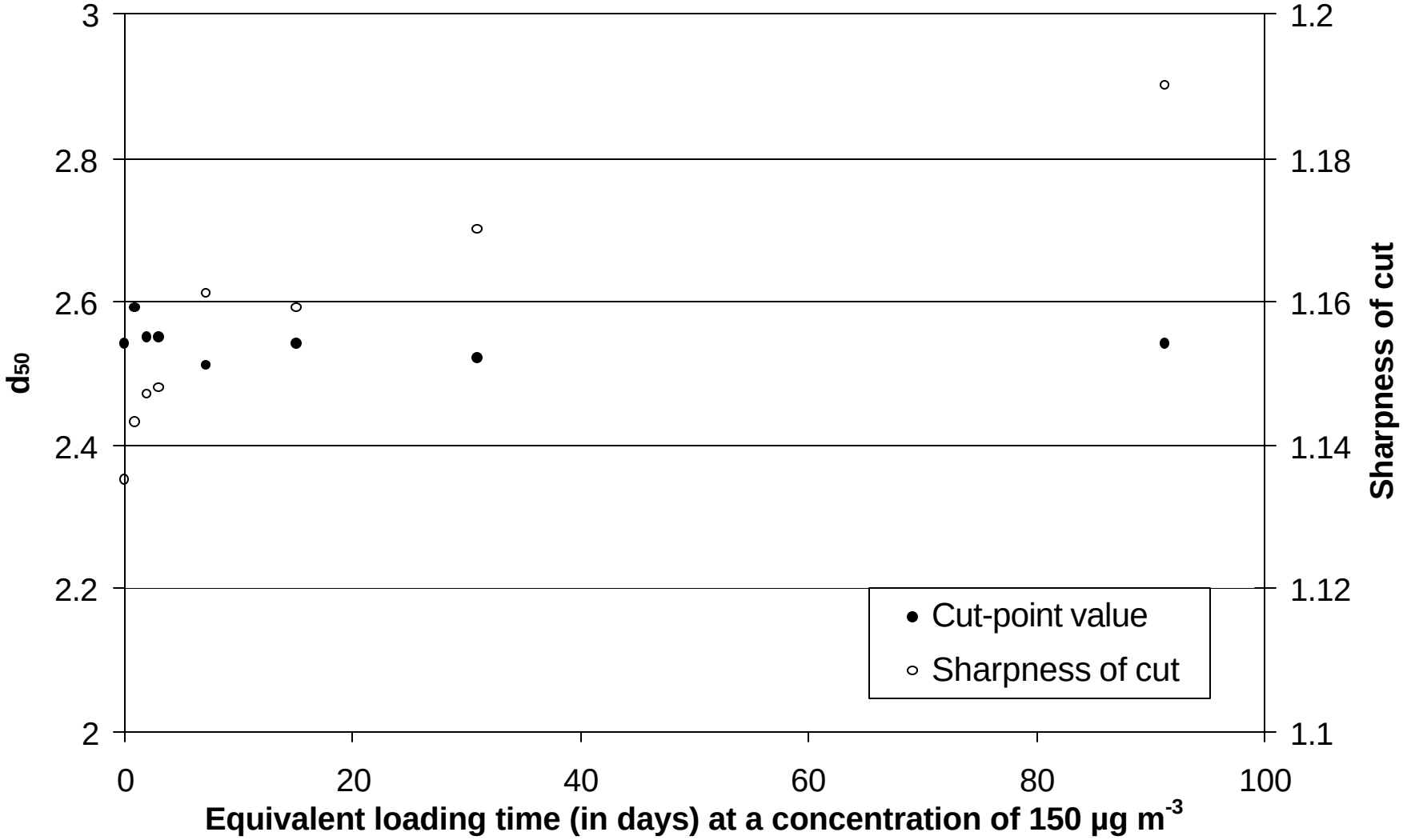


Fig 3. Effect of dust loading on VSCC d_{50} and sharpness of cut



Government of Alberta ■
Environment

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January, 6 2010

Shelly Pruden
Program Manager
Peace Air Shed Zone Association
P.O. Box 21135
Grande Prairie, Alberta T8V-6W7

Dear Ms. Pruden:

Subject: Peace Airshed Zone Association Ambient Air Monitoring Station(s) Audit File No 2009-292/314A

In regards to the letter dated December 10, 2009 to Al Clark regarding the response to items arising from the audits, the following are all noted and acceptable to Alberta Environment.

- The challenge of SO2 scrubbers on H2S/TRS analyzers more frequently than previous and documentation of these checks.
- The change in reporting of the data from wind speed and direction sensors at Evergreen Park and Valleyview to 10 meter height.
- The correction and resubmission of wind direction data from the Rover station.

Also, based on the findings submitted with the December 10 letter in reguards to particulate loading in sharp-cut cyclones, the data from the continuous particulate monitors with the heads noted as “excessively dirty” will not need to be treated or removed from the data base.

It is recommended that PASZA review with the contractor, the documented operating procedure of the particulate monitors with respect to frequency of the sampler head cleaning to ensure that frequency is adequate as per the manufacturer’s recommendations and the information in the research submitted.

Alberta Environment considers this audit closed.

Regards,

Harry Benders

Cc: Gary Sasseville: District Approvals Manager
Greg Smith: District Compliance Manager
Marilyn Albert: Industrial Monitoring Assessment Technologist
Janine Ross: Ambient Air Specialist
Jennifer Keturakis: Industrial Approvals Engineer
Gary Cross: Focus Corporation