Met One Instruments BAM-1020 Beta Attenuation Mass Monitor US-EPA $PM_{2.5}$ Federal Equivalent Method Field Test Results

Paper # 2008-A-485-AWMA

David Gobeli, Ph.D., Herbert Schloesser, Ph.D. and Thomas Pottberg

Met One Instruments Incorporated, 1600 Washington Blvd., Grants Pass OR, USA 97526, dgobeli@metone.com, hschloesser@metone.com, tpottberg@metone.com

ABSTRACT

Recently enacted regulations by the US-EPA provide a clear approach for manufacturers of continuous particulate monitors to obtain designation as $PM_{2.5}$ Federal Equivalent Methods (FEM). FEM designation regulations require demonstration of substantial correlation with minimal additive and multiplicative bias between Candidate Method Monitors, such as the Met One Instruments BAM-1020, and $PM_{2.5}$ Federal Reference Method (FRM) Samplers in five testing campaigns across four geographically diverse sites in winter and in summer.

For the winter test campaigns Met One Instruments deployed triplicate BAM-1020 $PM_{2.5}$ monitors at sites in Bakersfield California, Logan Utah and Allen Park Michigan. For the summer test campaigns Met One Instruments deployed triplicate BAM-1020 monitors at sites in Bakersfield California and New Haven CT. Triplicate $PM_{2.5}$ FRM samplers were also deployed at each of these test sites. All test sites were pre-approved by the US-EPA as they provide normal, diverse and challenging ambient conditions likely to be encountered in continuous $PM_{2.5}$ monitoring. Conditions encountered at these test sites included widely varying $PM_{2.5}$ concentrations between 0 and ~100 $\mu g/m^3$, widely varying ambient temperatures between -25 °C and +30 °C, and nitrates and other semi-volatile component levels known to exceed 30 percent of measured concentration levels. Comparison tests between the triplicate BAM-1020 Candidate FEM monitors and the triplicate FRM samplers at the winter sites were completed in March, 2007 and at the summer sites in August 2007. Application for designation was submitted to the US-EPA in September 2007.

The BAM-1020 beta attenuation mass monitor became the first ever designated Class III $PM_{2.5}$ Federal Equivalent Method with the announcement being published in the US Federal Register on March 12, 2008. The designation number is EQPM-0308-170.

INTRODUCTION

The United States Environmental Protection Agency (US-EPA) recently amended regulations for the monitoring of Criteria Pollutants, which includes PM_{10} and $PM_{2.5}$ (US Federal Register). Of particular interest are new regulations concerning the monitoring of particulate matter and new clear and concise test procedures that would allow the manufacturers of continuous $PM_{2.5}$ monitors to apply for and receive Federal Equivalent Method (FEM) designation. Instruments with such designation could be used instead of Federal Reference Method samplers for $PM_{2.5}$ for enforcement and compliance purposes.

Because no $PM_{2.5}$ FEM monitors existed for many years after $PM_{2.5}$ regulations were introduced in 1997, those involved with regulatory compliance for particulate matter had to rely, in large part, on manual $PM_{2.5}$ Federal Reference Method (FRM) samplers. FRM samplers cannot provide real time or near real time $PM_{2.5}$ data. In addition, $PM_{2.5}$ FRM samplers require far more human intervention than a $PM_{2.5}$ FEM monitor would. Handling, storing, weighing, conditioning and transporting of filters presents significant cost, quality and logistical challenges for those entities involved in the design, funding and quality control of $PM_{2.5}$ monitoring programs. As US-EPA regulations are often the basis for regulations outside of the United States, the development of a $PM_{2.5}$ monitor capable of obtaining FEM designation is likely to generate global interest.

Beta attenuation is one of several methods used to continuously monitor particulate matter. The method was first developed more than 60 years ago as a process control instrument in the manufacturing of paper. Approximately 40 years ago it was adapted for use in ambient particulate monitoring (Williams). Indeed, several beta attenuation mass monitors have received designation from the US-EPA as Equivalent Methods for PM_{10}.

Beta attenuation monitors have participated in several government-sanctioned studies in which their performance had been benchmarked against FRM and FEM reference standards (Cowan), (Dutcher). These studies have allowed unbiased comparison of beta attenuation monitors, in particular the Met One Instruments BAM-1020, against other beta attenuation monitors as well as monitors employing different principles of operation. These studies reveal that beta attenuation mass monitoring techniques compare favorably to other techniques terms of accuracy, which is defined as relative deviation from a reference standard, such as the $PM_{2.5}$ FRM.

To the best of our knowledge, no data published in any recent high-profile field study indicate that any currently used method for the continuous monitoring of $PM_{2.5}$ would be capable of meeting the new performance standards for $PM_{2.5}$ FEM designation. Indeed, results of these studies (Dutcher, Cowen) show that commonly used automatic, continuous $PM_{2.5}$ monitors have quite strong seasonal and geographic variations in their calibration. In other words, it would be necessary to calibrate the output of these monitors against the $PM_{2.5}$ FRM on a site-by-site and season-by-season basis.

The Met One Instruments BAM-1020 was physically and operationally modified. The new method, which is now a designated Equivalent Method for $PM_{2.5}$ (EQPM-0308-170), has demonstrated geographic and seasonal insensitivity to comparison with the $PM_{2.5}$ FRM without adding layers of complexity. At the same time, the method has demonstrated adequate sensitivity to meet all US-EPA precision requirements for $PM_{2.5}$ FEM designation.

TECHNICAL APPROACH

Principle of Operation

The principle of operation of beta attenuation mass monitors has been discussed in detail elsewhere. (Gleason), (Williams), (Macias), (Lilienfeld). This section will present a brief overview of the theory of operation of beta attenuation monitors and how it relates to ambient aerosol monitoring of fine particulates.

When the high-energy electrons emanating from the radioactive decay of ^{14}C (carbon-14) interact with nearby matter, they lose their energy and, in some cases, are absorbed by the matter. These high-energy electrons emitted through radioactive decay are known as beta rays and the process is known as beta ray attenuation. When matter is placed between the radioactive ^{14}C source and a device designed to detect beta rays, the beta rays are attenuated. This results in a reduction in the number of beta particles detected. The magnitude of the reduction in detected beta particles is a function of the mass of the absorbing matter between the ^{14}C beta source and the detector, which for the BAM-1020 is a photomultiplier tube with a scintillation device.

For the Met One Instruments BAM-1020, glass filter tape passes through the gap between the ^{14}C source and the detector. At the start of every measurement cycle, the flux of beta rays is measured across clean filter tape, resulting in the measurement of I_0. After the measurement of I_0, the filter tape is advanced and ambient air is sampled thereby impregnating the tape with $PM_{2.5}$. After the sampling is complete, the tape retracts and the beta ray flux through the particulate-impregnated tape is measured.

The beta ray flux reaching the detector depends on the particulate mass deposited onto the filter tape. The beta ray flux reaching the detector decreases nearly exponentially with the mass through which it must pass. To a very good approximation, Equation 1 shows this relationship.

$$I = I_0 e^{-\mu x}$$

Equation 1

In Equation 1, I is the measured beta ray intensity (counts per unit time), of the attenuated beta ray (dust laden filter tape), I_0 is the measured beta ray intensity of the non-attenuated beta ray (clean filter tape), μ is the absorption cross section of the material absorbing the beta rays (m^2/kg), and x is the mass density of the absorbing matter (kg/m^2).

Equation 1 may be rearranged to solve for x, the mass density of the absorbing matter. This is shown in Equation 2.

$$x = \frac{1}{\mu} \ln\left[\frac{\mathrm{I}_0}{\mathrm{I}}\right]$$

Equation 2

The absorption cross section, μ, is a physical constant of the material through which the beta rays are passing. Once I, and I_0 are measured, the mass density may be determined.

In practice, ambient air is sampled at a constant flow rate (Q) for a specified time t. This sampled air is passed through a filter of surface area A. Once x, the mass density of collected particles, has been determined, it is possible to calculate the ambient concentration of particulate matter (in kg/m^3) with Equation 3.

$$\mathrm{c}\left(\frac{kg}{\mathrm{m}^3}\right) = \frac{\mathrm{A}(\mathrm{m}^2)}{\mathrm{Q}\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)\mathrm{t(s)}}\, x\left(\frac{kg}{m^2}\right)$$

Equation 3

In Equation 3, c is the ambient particulate concentration (kg/m^3), A is the cross sectional area of the tape spot over which dust is being deposited (m^2), Q is the rate at which ambient air is being sampled (m^3/s), and t is the sampling time (s). Combining these equations yields the final expression for the ambient particulate concentration in terms of measured quantities. This is shown in Equation 4. The constant "D" has been introduced to simplify the expression. It represents the sampling time, flow rate, sampled area and a factor of 10^9, which allows the final answer to be expressed in the traditional $\mu g/m^3$.

$$c\left(\frac{\mu g}{m^3}\right) = \frac{D}{\mu}\ln\left(\frac{I_0}{I}\right)$$

Equation 4

The key to the success of the beta attenuation monitor is in part due to the fact that μ, the absorption cross section, varies little among commonly sampled particulate matter such as C, Fe_2O_3, NH_4NO_3 $NH_4(SO_4)_2$, or SiO_2 (Williams). This permits the device to be calibrated during the manufacturing process and permits the user to accurately measure $PM_{2.5}$ concentrations without having to know in advance the chemical composition of the aerosols being sampled.

Practical Considerations for Beta Attenuation Mass Monitors

Sampling under conditions of high relative humidity tends to cause beta attenuation monitors to produce measurements that are often 20-50% higher than results obtained from collocated FRM samplers. This bias is caused by accumulation of moisture onto the particulate matter trapped on the filter tape, which is subsequently measured as mass. Met One has addressed this issue through the introduction of a "Smart Heater" system in which the relative humidity of the sampled air is controlled by warming the sampled air. When the moisture content of the air exceeds a user-selected value, typically 35% or 45%, the sampled air is warmed until the reduced to below the specified limit. Met One Instruments ran its designation testing with the BAM-1020 set to maintain the relative humidity at the measurement point to 35% or below.

Another important consideration in the manufacture of a beta monitor has to do with the selection of the beta source. Commercially available particulate monitors using the beta attenuation method typically employ ^{14}C, ^{85}Kr or ^{147}Pr. The half-life of ^{14}C is 5,730 years, whereas the half-lives of ^{85}Kr and ^{147}Pr are 10.8 years and 5.5 years respectively. The beta output of a monitor employing a ^{14}C source will remain stable over the useable life of the monitor. Monitors employing ^{85}Kr or ^{147}Pr sources will experience substantial decays in beta output over several years because of the relatively short half-lives of these isotopes. This will in turn necessitate the replacement of the source (and require recalibration of the equipment) several times over the useable life of the equipment.

A single roll of filter tape will predictably last for two months in the BAM-1020. In other methods using different principles of operation, filter replacement must occur when loading reaches a certain level. It is not possible to predict in advance when such filter loading will occur as it is related to the levels of particulate matter in the air, which often are quite variable. Data may be lost as a result of this issue, whereas with the BAM-1020 filter tape replacement will always occur at two months.

TEST PROCEDURE

Siting

The test procedure requires that a total of five test campaigns be successfully executed in order for the candidate method monitor, in this case the BAM-1020, to earn designation as a $PM_{2.5}$ FEM.

Winter test sites are required to be located in California, in a cold-weather Rocky Mountain state, and in a cold weather Midwest state. Met One Instruments selected test sites at Bakersfield California, Logan Utah and Allen Park Michigan because these sites comply with the site requirements and because of generally high, historic $PM_{2.5}$ concentrations (US Federal Register). Additional site requirements are found in the regulations. All sites were pre-approved by the US-EPA. The Bakersfield and Allen Park sites are in use by the California Air Resources Board "CARB" and the Michigan State Department of Environmental Protection. The Logan site was at a local government authority and in close proximity to monitoring sites maintained and operated by the State of Utah. The summer test sites were in Bakersfield CA, which is operated by CARB and in New Haven CT, which is operated by the Connecticut DEP.

FRM Samplers

At each of the four test sites Met One Instruments deployed triplicate BGI PQ-200 $PM_{2.5}$ FRM samplers equipped with "Very Sharp Cut Cyclone" $PM_{2.5}$ inlets. Each of the three samplers at each of the four test sites was set up and calibrated according to the instruction manual. Samplers were sited such that their inlets were between 1 and 1.5 meters apart, in accordance with the regulation. All FRM samplers were deployed on the roofs of the shelters holding the BAM-1020 candidate monitors. It should be mentioned that the regulations do not permit the use of sequential (multiple event) FRM samplers for this test.

Candidate Monitors

At each of the three test sites Met One Instruments deployed triplicate BAM-1020 beta attenuation mass monitors. The BAM-1020s were installed in temperature-controlled shelters and set up in accordance with the procedures set forth in the operating manual. Inlet tubes extended through the roofs of the shelters to permit sampling at the same elevation as the FRM samplers. Shelter temperatures were maintained at approximately 20°C for the duration of the test campaign.
All BAM-1020 units were equipped with "Smart Heaters". These devices monitor external relative humidity and warm the sampled air if relative humidity rises above a user selected value. For these tests, the "Smart Heater" was set to control the relative humidity to no higher than 35%. The BAM-1020 monitors were configured for 42 minutes of sampling time per hour.

Data Collection

FRM samplers and the BAM-1020 monitors were run daily. Start times varied from site to site. Twenty-three valid hourly BAM averages were used to generate each daily average. FRM samplers were run for 23 hours to permit filter replacement and servicing on a daily basis. Occasionally, days were missed due to power, site, or instrument issues. For the most part however, data collection was uninterrupted.

Data Validation

FRM data was validated in accordance with the procedures set forth in the operational manual, weighing laboratory, and US-EPA quality assurance documents. Daily data sets consisted of 2 or 3 valid FRM results and 2 or 3 valid BAM daily averages.

TEST RESULTS

A minimum of 23 valid, daily data sets were required for each test campaign. Met One Instruments collected substantially more than 23 valid data sets at each of the winter test sites. To be considered valid data, FRM daily means of the triplicate samplers must have exceeded 3 $\mu g/m^3$. In addition, FRM results must pass an outlier test. No such outlier test was allowed for the BAM-1020 results however. BAM data was qualified by verifying that no alarms indicating instrument malfunction occurred during the measurement event.

Linear regressions were performed on each completed data set. The results of the linear regressions are shown in Table 1.

Table 1: Linear Regression Results

Site	n	m	b	r^2
Bakersfield CA	50	0.9620	-.0761	0.9916
Logan UT	42	0.9598	-.8627	0.9801
Allen Park MI	30	0.9404	-.9552	0.9943
New Haven CT	29	1.020	0.585	0.9977

In Table 1, n is the number of valid data sets collected at the test site, m is the slope of a linear regression of FRM v. BAM, b is the y-intercept in $\mu g/m^3$ and r^2 is the correlation coefficient. Figures 1 through 4 show the regression plots of BAM v. FRM at each of the four test sites. Data plotted represents the mean of triplicate BAM-1020 monitors and the mean of the triplicate FRMS for each valid day.

DISCUSSION

The BAM-1020 meets the US-EPA comparability criteria by a comfortable margin at each of the four test sites. US-EPA requirements for precision were also met at each of the test sites, but will not be presented here. Examination of the results summarized in Table 1 and in Figure 1 through Figure 4 indicates minimal multiplicative or additive biases at any of the test sites

Figure 1: Allen Park Michigan Winter Campaign Regression

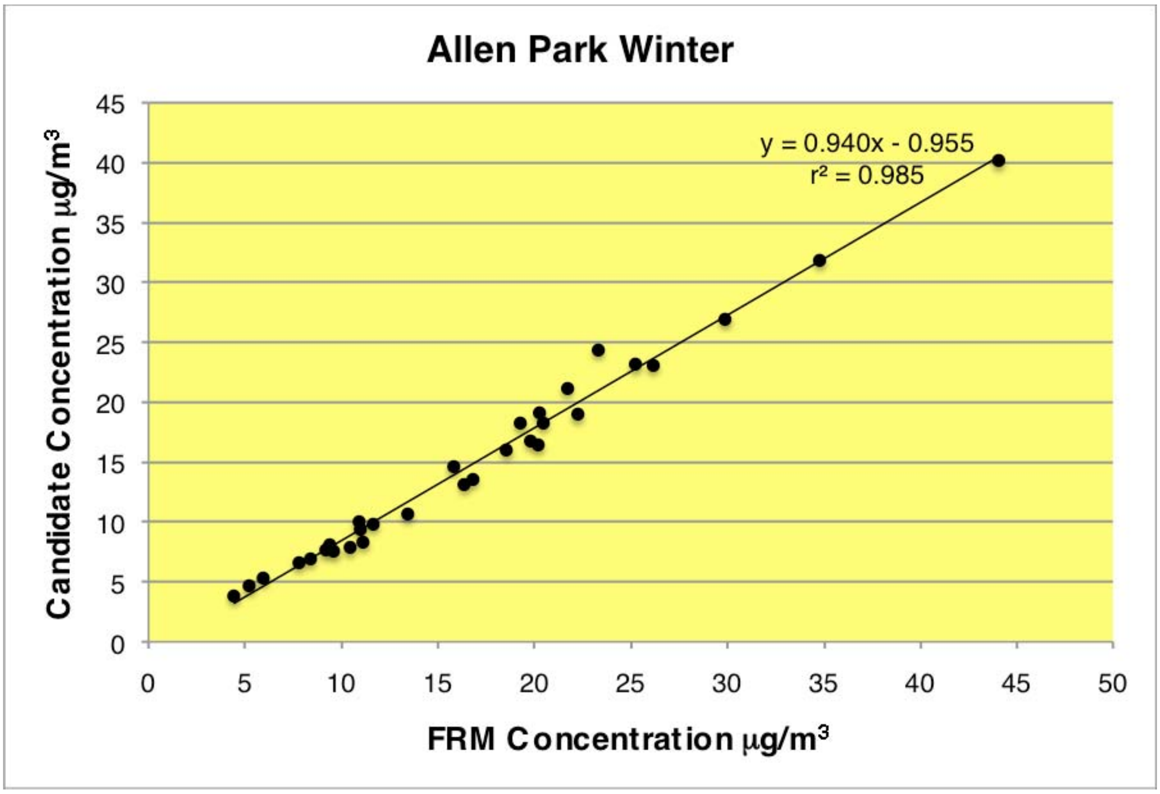


Figure 2: Logan Utah Winter Campaign Regression

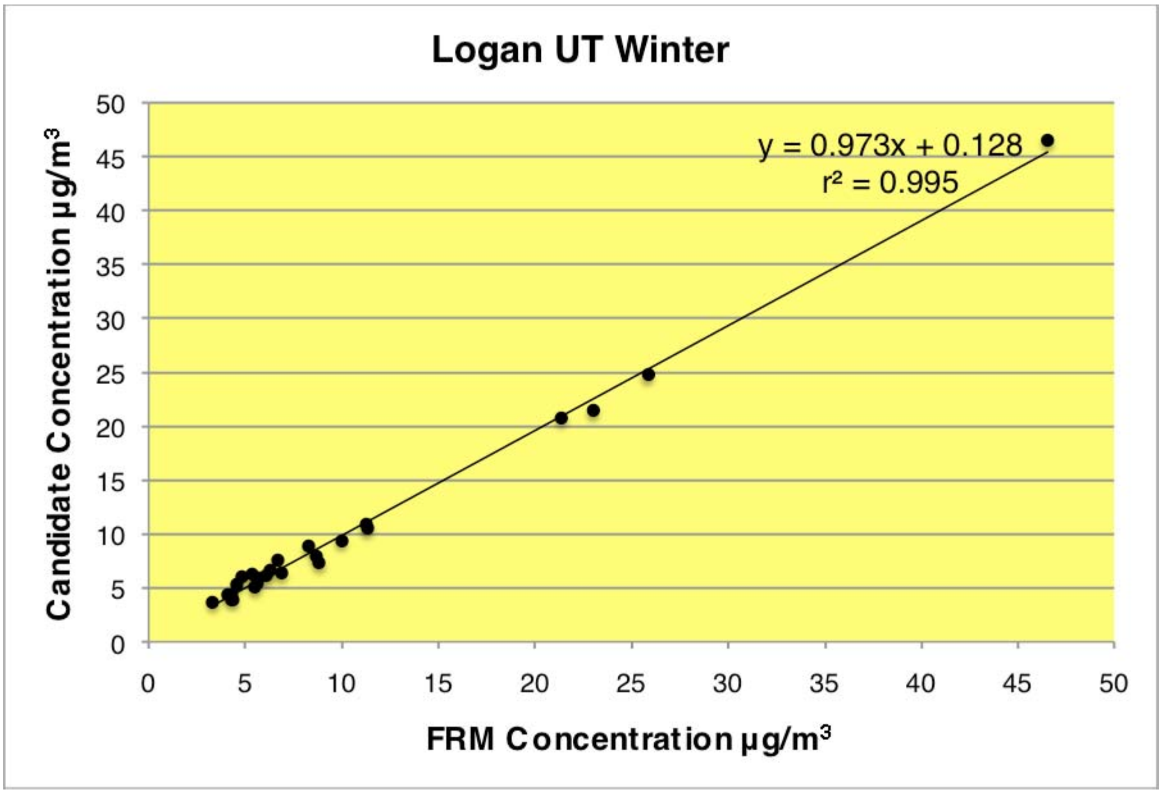


Figure 3: Bakersfield California Winter and Summer Campaign Regression

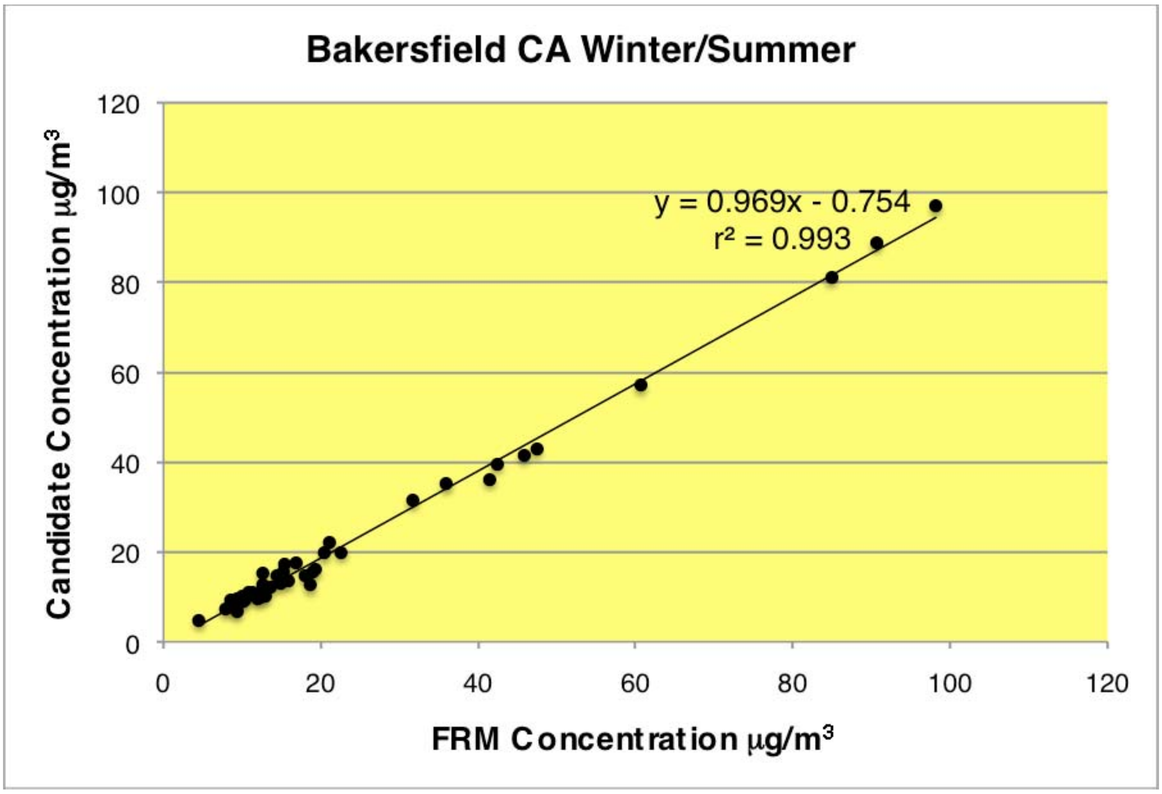
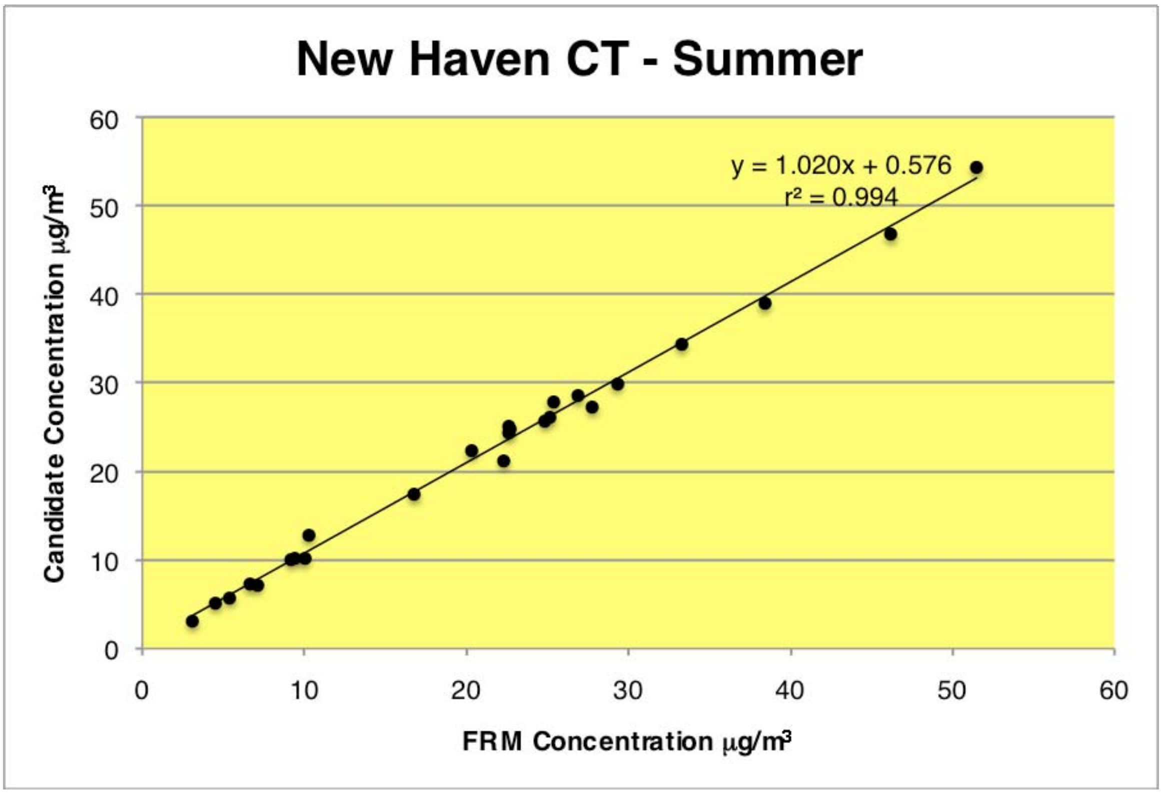


Figure 4: New Haven CT Summer Campaign Regression



The linear regressions, as shown in Figures 1-4, reveal minimal multiplicative or additive bias and clear compliance with the new designation regulations. Additional data from Phoenix AZ, Rubidoux CA and Dearborn MI, which is being used to support $PM_{10-2.5}$ designation for paired BAM-1020 monitors, is consistent with the results from each of these five test campaigns: minimal multiplicative or additive bias and no indication of seasonal or geographic impact on the calibration of the equipment. This data will be reported in the future. We feel confident, as a result, that the BAM-1020, when operated as an FEM $PM_{2.5}$ Method as set forth in the operational manual, should have minimal seasonal or geographic influence.

Earlier versions of the BAM-1020 often showed a moderate (10-15%) positive multiplicative bias as well as a moderate (1-2 $\mu g/m^3$) additive bias. Although this level of performance compares favorably to commonly used continuous monitors for $PM_{2.5}$, especially when data correction to the $PM_{2.5}$ FEM is not permitted, it was inadequate to meet the new standards. We have attributed these biases to the previous factory calibration procedure, heterogeneous equilibria issues at the measurement point involving moisture as well as instrument artifacts. These have been mostly eliminated with the new method, which employs a new, improved factory calibration procedure, physical improvements, software changes and firmware changes.

Relevant specifications for the new method are given in Table 2.

Table 2: Partial BAM-1020 Specifications

PARAMETER	SPECIFICATION
Measurement Principle:	Particulate Concentration by Beta Attenuation
US-EPA Existing Designations:	PM_{10}: EPA EQPM-0798-122 $PM_{2.5}$: Class III EPA EQPM-0308-170 $PM_{10-2.5}$: Paired units: Candidate Method (3/08)
Standard Range:	0 - 1000 mg/m^3 (0 – 1.000 mg/m^3)
Lower Detection Limit (2σ) (1 hour):	< 4.8 $\mu g/m^3$ from 0.000 mg to 0.100 mg/m^3 < 4 $\mu g/m^3$ from 0.000 mg to 0.100 mg/m^3 (typical)
Lower Detection Limit (2σ): (24 hours)	< 1 $\mu g/m^3$
Resolution:	± 0.1 $\mu g/m^3$
Measurement Cycle Time:	1 hour
Accuracy:	Exceeds US-EPA Class III $PM_{2.5}$ FEM standards for additive and multiplicative bias

Referring to Table 2 it should be mentioned that σ, the instrument noise, is determined through by the relative standard deviation of a sample of at least 72 one-hour averages of zero-air under controlled conditions. Instrument accuracy, which may be defined as either the absolute or the relative difference between the measured concentration and the actual concentration, is best specified by comparison to a standard. This is because defining the actual concentration depends upon which method is used. For the purposes of the specifications used in Table 2, the method is a single-event $PM_{2.5}$ FRM equipped with a very sharp cut cyclonic separator. We also cite adherence to the EPA $PM_{2.5}$ Class III performance requirements as they take into consideration both relative and absolute accuracy.

The US-EPA Method Designation wording is shown in Figure 5.

Figure 5: BAM-1020 $PM_{2.5}$ FEM US-EPA Designation

Met One BAM-1020 Monitor - $PM_{2.5}$ FEM Configuration ***Automated Equivalent Method:*** **EQPM-0308-170**

"Met One Instruments, Inc. BAM-1020 Beta Attenuation Mass Monitor - $PM_{2.5}$ FEM Configuration, configured with a $PM_{2.5}$ particle size separator," operated for 24 hour average measurements with firmware revision 3.2.4 or later, with or without an inlet tube extension (BX-823), with or without external enclosures BX-902 or BX-903, in accordance with the BAM 1020 Particulate Monitor operation manual, revision F or later, and equipped with BX-596 ambient temperature and barometric pressure combination sensor, internal BX-961 automatic flow controller operated in Actual (volumetric) flow control mode, the standard BX-802 EPA PM_{10} inlet head and a $PM_{2.5}$ very sharp cut cyclone (BX-808), BX-827 (110V) or BX-830 (230V) Smart Inlet Heater, with the heater RH set to 35% and the temperature control set to "off", the 8470-1 revision D or later tape control transport assembly with close geometry beta source configuration, used with standard glass fiber filter tape, COUNT TIME parameter set for 8 minutes, the SAMPLE TIME parameter set for 42 minutes, BX-302 zero filter calibration kit required.

CONCLUSION

Met One Instruments' Model BAM-1020 beta attenuation mass monitor is the first automated, continuous method to earn Class III Federal Equivalency (EQPM-0308-170).

ACKNOWLEDGEMENTS

Met One would like to acknowledge the California Air Resources Board, in particular Mr. Phil Powers, Ms. Debra Henson, Mr. Ken Stroud and Mr. Mac McDougall for their assistance. Met One would like to acknowledge Professor Randy Martin of Utah State University, and Mr. Neal Olson of the Utah Department of Environmental Protection for their assistance. Met One would like to acknowledge the assistance of Mr. Craig Fitzner and the Michigan Department of Environmental Protection. Met One would like to acknowledge the assistance of Dr. Pete Babich, Mr. Paul Norton and the Connecticut Department of Environmental Protection. Met One would like to thank Mr. George Allen of NESCAUM for his invaluable feedback over the years. Finally, Met One would like to acknowledge the contribution of Mr. Erik Zamurs of Akrulogic in Toronto Canada for his assistance in executing the program.

REFERENCES

Cowan, K., Kelly, T., Coutant, B., and Riggs, K. (2001) 'Met One Instruments BAM 1020 Particle Monitor', Environmental Technology Verification Report, Battelle, Columbus OH 43201.

Dutcher, D., Chung, A., Kleeman, M., Miller, A., Perry, K., Cahill, T. (1999). 'Instrument Intercomparison Study Bakersfield, CA 1998-1999' California Air Resources Board, Research Division, Sacramento California USA Report Number 97-536.

Gleason, G. I., Taylor, J. D., and Tabern, P. L. (1951) 'Absolute beta counting at defined geometries'. Nucleonics 8:12.

Lilienfeld, P. 1975. Design and operation of dust measuring instrumentation based on the beta-radiation method. Staub-Reinhalt Luft 35:458.

Macias, E. S., and Husar, R. B. 1970. 'High resolution online aerosol mass measurement by the beta attenuation technique. In Proc. 2nd Internat. Conf. on Nucl. Methods in Environ. Research, ed. Vogt, J. R. and Meyer, W. pp 413 CONF-740701.

Williams, K., Fairchild, C., Jaklevic, J. Dynamic Mass Measurement Techniques., In Aerosol Measruement. Principles, Techniques and Applications (Willeke, K., Baron, P., editors). Van Nostrand Reinhold, New York 1993 pp. 296-312.

United States Federal Register v. 71, no. 200, p. 61236-61328 October 17, 2006.

Keywords: $PM_{2.5}$ Federal Equivalent Method, beta attenuation monitor