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A Technical Overview on Beta-Attenuation Method for the Monitoring of Particulate Matter in Ambient Air

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ABSTRACT

Beta-attenuation technique is one of the widely used real-time technique for ambient particulate matter (PM) measurements since it allows continuous measurement while requiring minimal operator attention. Like any other technique, this method has several limitations that have been recorded in many studies. Beta-attenuation technique is dependent on the meteorological conditions as well as operational factors, which lead to over- or underestimation in the mass measurements in comparison to the reference method. However, the factors that affect its measurement and the variations in its performance under different conditions are not listed or reviewed in a comprehensive manner in a single document. Also, the systematic advancement of its development and implementation in ambient air measurements have not been documented in literature used by the air quality community. It is important for the user of this technique to have a detailed understanding of its principle and operation. Consequently, this article discusses the research, development, technology, and measurement of beta-attenuation method in depth. Although this review emphasizes primarily PM_{10} measurement results but some $PM_{2.5}$ studies are also included. Our review reveals that federal equivalent method (FEM) designated beta gauge monitors in various studies performed better (with slope < 1.5 and intercept < 2 $\mu g\ m^{-3}$) during high RH ambient conditions against reference or federal reference method (FRM). Studies related to PM_{10} showed that cut-off size, high mass loading and high ambient RH (> 80%) have impact on beta gauge measurements. Therefore, it is recommended to clean inlet once a week and use smart heater to control RH at or below 35%. $PM_{2.5}$ studies also confirm the effect of relative humidity on beta gauge measurements.

Keywords: Beta-attenuation technique, Gravimetric method, PM_{10}, $PM_{2.5}$, Relative humidity, Correction factor

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1 INTRODUCTION

There are several air quality standards (e.g., EN 12341:2014; U.S. EPA, 2017) for monitoring the air quality in different countries which include gaseous and particulate matter (PM) and associated pollutants. In the national ambient air quality standards specified by the U.S. EPA in the Code of Federal Regulations (CFR) in Title 40 Part 50, particulate matter is measured by either a federal reference method (FRM) or a federal equivalent method (FEM). Testing and performance criteria for designation of FRM and FEM sampler are specified in 40 CFR 53. The PM FRM is an integrated gravimetric filter-based sampling method for the measurement of PM (PM_{10}/$PM_{2.5}$) over a 24-hour sampling interval. The PM FEM includes real-time measuring systems based on beta-attenuation monitoring, tapered element oscillating microbalance, dichotomous air sampler and laser aerosol spectrometer. All FRM and FEM must be manufactured in an ISO 9001 accredited facility. In addition to meeting all FRM requirements, all FEMs must be tested and meet the

Table 1. U.S. EPA FEM designated devices for the measurement of PM using beta-attenuation.

Instrument	$PM_{10}/PM_{2.5}$	Temperature range (°C)	Flow rate (lpm)	Accuracy	Precision (µg m^{-3})	Beta ray source	Lower detection limit (µg m^{-3})
DKK-TOA models FPM-222/222C /223/223C	PM_{10}	0–40	16.7	± 10 µg m^{-3}	---	90 µCi, Promethium 147	---
Environment S.A. Model MP101M	$PM_{10}/PM_{2.5}$	10–40	16.7	± 5%	---	Carbon-14	0.5
Met One Instruments BAM-1020	$PM_{10}/PM_{2.5}$	0–50	16.7	---	---	Carbon-14	< 4.8(hourly) < 1 (24 hours)
Opsis Model SM200	$PM_{10}/PM_{2.5}$	5–35	8–25	---	---	Carbon-14	---
Teledyne Model 602	$PM_{10}/PM_{2.5}$	0–50	13.3–41.6	---	± 1	---	3 (hourly)
Thermo Scientific Model FH 62 C14/5014i	PM_{10}	–30–50	16.7	± 5%	± 2	Carbon-14	< 4 (hourly) < 1 (24 hours)

requirements for comparability to FRM, as described in 40 CFR 53 Appendix C (§53.30, 53.34 and 53.35). FEM designation is attained by the manufacturer for candidate sampler, where the process includes three FRM and three candidate samplers distributed at four sites each across the country and across seasons. The performance criteria for FEM approval must meet statistical metrics for multiplicative bias (slope) ranging between 0.9–1.1 and additive bias (intercept) between –2 to 2 µg m^{-3}, and correlation between FRM and FEM should be ≥ 0.95. Table 1 compiles the U.S. EPA FEM designated instruments based on beta attenuation monitoring and their specifications. There are also European standards maintained by European Committee of Standardization (CEN) for the determination of PM mass concentration by gravimetric method, i.e., EN 12341:2014 and technical specification CEN/TS 16450:2013 for automated measuring systems.

Beta gauge system working on attenuation of beta-rays is the most widely used real-time technique in ambient air quality monitoring stations worldwide. Several shortcomings have been reported in this technique leading to compromised data quality (Chang *et al.*, 2001; Salminen and Karlsson, 2003; Takahashi *et al.*, 2008; Shin *et al.*, 2011; Tsai *et al.*, 2006; Liu *et al.*, 2013; Le *et al.*, 2020b). Its performance is reported to be influenced by environmental factors such as ambient relative humidity, particle mass loading and composition of particulate matter (Chang *et al.*, 2001; Salminen and Karlsson, 2003; Tsai *et al.*, 2006). Therefore, this review aims to provide a clear description of principle, technology and application of beta-attenuation technique in ambient particulate matter measurement. In brief, our goals are three-fold: (i) to understand the basic technique, principle and components of beta gauge systems, (ii) to classify the developments taken place around the world in the modification and advancement of this technique for aerosol measurements, (iii) to identify the influential causal variables affecting the beta-attenuation technique when compared with reference method. Most of the review papers that we considered were limited mostly to the study of PM_{10} and a few $PM_{2.5}$ studies but they are not comprehensively discussed these three points. Therefore, the objective also includes to provide comprehensive understanding of application of beta-attenuation technique. In principal, this technique was used to develop a real-time automatic system by overcoming the drawbacks of manual sampling method. While it can provide peak event data with limited operator involvement, its operating principle is reported to be dependent on meteorological conditions which differ widely in many countries. Therefore, we provide a single document detailing the history of its development and implementation in ambient air measurements with studied factors influencing the measurement technique.

2 BACKGROUND OF BETA-ATTENUATION TECHNIQUE

For several years, beta gauges working on beta-ray attenuation principle have been used in applications requiring constant, nondestructive monitoring of thin films. A beta particle is a high-energy, high-speed electron or positron, which is emitted by the radioactive decay of an atomic nucleus during the process of beta decay. Beta rays can either be absorbed, reflected, or they can pass through a material. The amount of material present determines how much beta ray intensity is attenuated. This technique is often used in industries to determine the thickness or weight of different materials, including plastics, metals and paper since 1956. In order to assess the density of films used as cyclotron targets, Anders and Meinke (1956) devised a beta-ray gauge using a narrow pencil. This setup comprises of a Geiger-Müller detector and a microscope-style adjustable stage installed on the ^{147}Pm beta source (Fig. 1). It is sensitive for films (of density) up to 6 mg cm^{-2}. Kim *et al.* (2009) developed beta gauge device to measure the fabric density in real-time with high sensitivity. An ionization chamber was chosen as a beta radiation sensor and 3.7 GBq ^{85}Kr as a beta source. Arjhangmehr *et al.* (2014) used an industrial beta gauge to determine the thickness of a gold sheet coated on steel foundation. The system's radioisotopic generators in a fixed geometry have been tested individually as ^{3}H, ^{14}C, and ^{63}Ni pure beta emitters (Fig. 2).

A beta gauge system consists of two basic components—a radiation source and a detector, with the sample to be measured sandwiched between them. In addition, the information is processed from the detector and converted into a measurement result. When beta particles strike material, some of them pass through it, while a part gets absorbed. Increased thickness of material absorbs more beta particles. The material thickness is determined by the ratio between beta counts passing through the material and the counts without any material. In the pulp and paper industry, the sheet weight per unit area is an important feature which is measured by the encounter of beta particles with the sheet. ^{85}Kr (half-life of 10.76 years and maximum beta energy of 720 ke V), ^{147}Pm (half-life of 2.62 years and maximum beta energy of 225 ke V) and ^{14}C (half-life of 5730 years and maximum beta energy of 156 ke V) are the commonly used and commercially available beta particle sources (U.S. EPA, 2006).

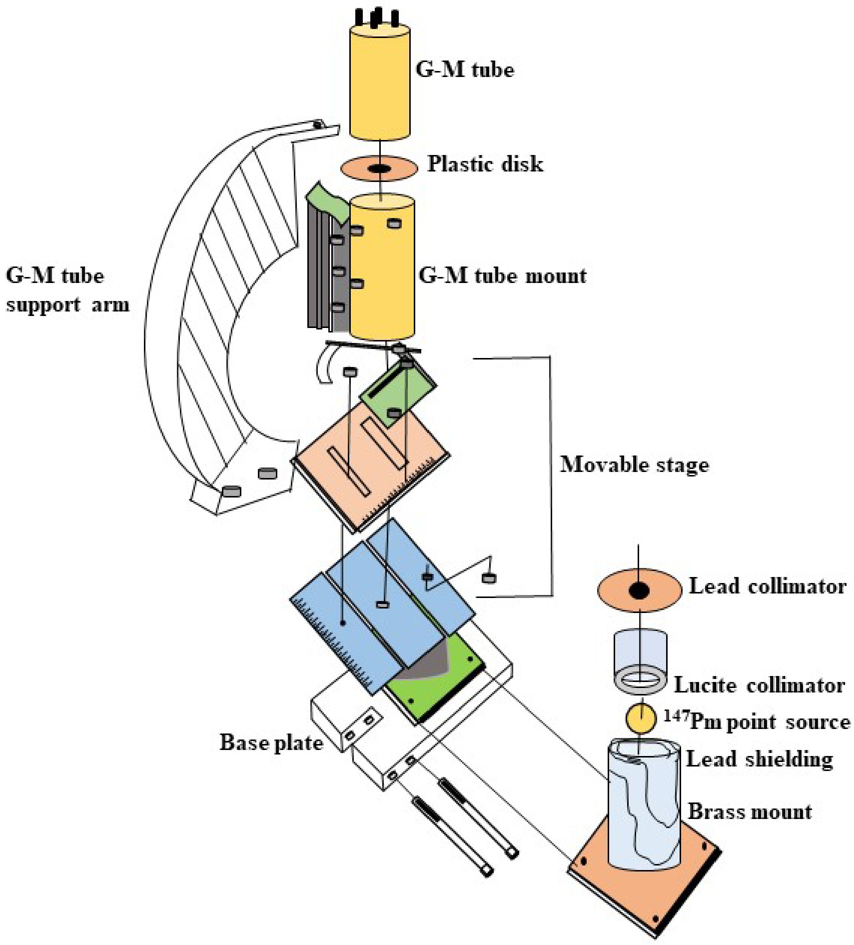

Fig. 1. Beta gauge setup devised in 1956.

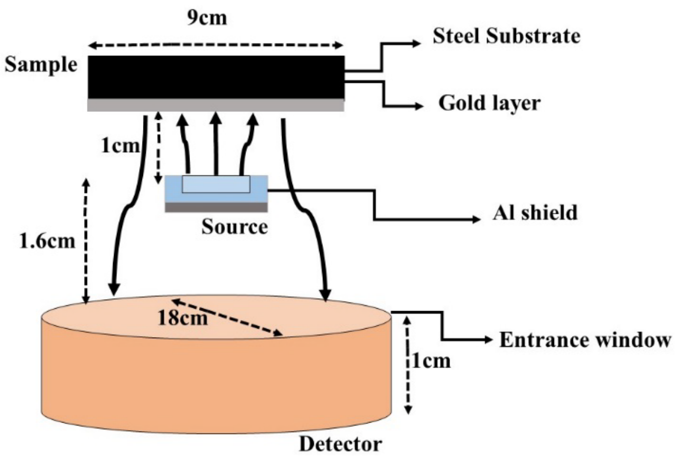

Fig. 2. Schematic of beta gauge system designed in 2014.

3 BETA-ATTENUATION METHOD APPLIED TO THE MEASUREMENT OF PARTICULATE MATTER

The gravimetric method is used as primary technique to estimate the concentration of particulate matter (PM) by measuring samples deposited on filters using high- or low-volume samplers over a 24-hour span (Aggarwal *et al.*, 2013). When employing the gravimetric method, a collection period of a few hours to 24 hours or even days is expected (U.S. EPA, 2016). As a result, the gravimetric approach is ineffective for monitoring peak concentration hours or observing short-term concentration changes. Furthermore, this technique necessitates weighing each filter separately prior to and after sampling, preventing sampling and measurement recording from being automated. Therefore, despite the availability of primary gravimetric method, there is still a need for a real-time automated technique that produce data which (i) directly correlate with mass; (ii) enable data from various cities and seasons to be combined for analysis; (iii) minimise handling of the fragile filter; (iv) allows short-term (1 to 8-hour intervals) ambient particulate concentration measurements in the same units ($\mu g\ m^{-3}$) like long-term (24-hour interval) samples. The short-term measurements should aid in assessing short events so that better policies can be formulated.

Many authors have used the beta-ray attenuation method to measure particulate matter obtained from the ambient sampling (Nader and Allen, 1960; Salkowski, 1964; Dresia and Spohr, 1971; Hussar, 1974). A schematic of the beta gauge monitor is shown in Fig. 3. It consists of a beta particle source, a detector, and filter holder for collecting sample deposits on filter tape (Chueinta and Hopke, 2001). The attenuated beta particles reach the detector after passing through the particulate deposited filter tape. The amount of radiation reaching the detector is decreased

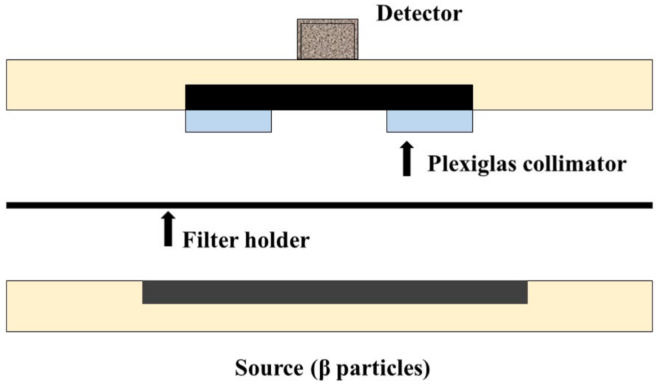

Fig. 3. Schematic of principle of beta gauge monitor.

as the mass of the particulate spot increases. This method has the advantages of non-destructive physical measurement and fast automated operation, both of which are desirable when dealing with large amounts of data requirement.

The beta gauge method is based on the attenuation of beta particles passing through a fine layer of particles. The relationship between the decrease in counts and particulate mass was computed initially in Jaklevic *et al.* (1981).

$$I = I_o e^{-\mu x} \tag{1}$$

where, I_o is the incident unattenuated beta counts, I is the attenuated beta counts through a substrate of mass density x (mg cm^{-2}) and μ is mass absorption or attenuation coefficient (cm^2 mg^{-1}). Measurement of I can be directly attributed to the mass of a sample deposit if μ and I_o are known. The values of μ and I_o are obtained by measuring I as a function of x for numerous known standards. Eq. (1) can be reorganised in the form of the mass density (x) of the substrate as:

$$x = \frac{1}{\mu}\ln\frac{I_o}{I} \tag{2}$$

The attenuation coefficient, μ is a constant specific to the absorbed material on filter tape. After knowing I and I_o, the mass density of the material can be determined. For a given time t, atmospheric air is sampled at a fixed flow rate Q and passed by a filter of surface area A. After determining x, the mass density of collected particles, the ambient concentration C (µg m^{-3}) of particulate matter can be calculated as:

$$C = \frac{A\ln\frac{I_o}{I}}{\mu Q t} \tag{3}$$

where A is in cm^2, μ is in cm^2 mg^{-1}, Q is in L min^{-1} and time in minutes.

3.1 Choice of Beta Source

The choice of a radioactive source for a specific application, depends on the beta particle spectrum of the source. Fig. 4 shows a beta-particle spectrum characterised by a continuous distribution of energy with a maximum energy E_{max} at end, which is specific to the isotope used. The shaded portion depicts the measured intensity I, while E_{disc} represents the discriminator level

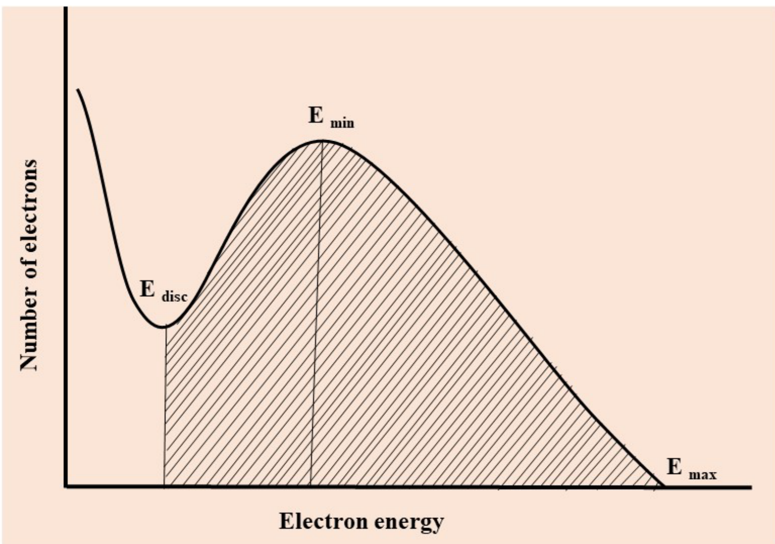

Fig. 4. Beta particle spectrum of a radioisotope source (reproduced from Jaklevic *et al.* (1981)).

below which the device is not responsive or capable enough to measure it precisely. The incident beta particles lose energy in a continuous manner as they travel through the solid sample between the source and the detector colliding with the particles in the sample. The energy spectrum in Fig. 4 does not attenuate evenly as when the material thickness increases, and it moves to lower energies, allowing the beta particles to stop completely. After passing the material thickness, the measurement counts the number of particles with energies greater than E_{disc} and E_{min} is the threshold limit below which attenuation cannot be used for the measurement of thickness precisely and accurately.

Matching the effective range (E_{min} to E_{max}) of the beta spectrum to the range of sample thickness to be assessed is important when choosing a radioactive beta-particle source. If the overall range of the particles energy in the distribution is less than the thickness to be determined, only a few electrons can reach the sample, and then Eq. (1) is no longer true. Likewise, if the particles are highly energetic in comparison to any reductions in a thin sample, there would be a little or no impact on the spectrum, making it impossible to make a sensitive mass measurement. As a result, the source is selected so that beta particle production is the most common mode of decay and the half-life is long enough to prevent replacement of source in a life of instrument. The beta particle sources which have been used in past include ^{63}Ni ($t_{1/2}$ = 85 y, E_{max} = 67 ke V), ^{14}C ($t_{1/2}$ = 5730 y, E_{max} = 156 ke V), ^{147}Pm ($t_{1/2}$ = 2.62 y, E_{max} = 225 ke V), and ^{85}Kr ($t_{1/2}$ = 10.76 y, E_{max} = 720 ke V) (Wedding and Weigand, 1993). Nickel is too soft to allow for any versatility in filter materials, while krypton is too energetic to achieve the desired resolution with attenuation process and has residual gamma emissions that complicate things further. Promethium has a short half-life that necessitates periodic re-standardization, while carbon, although somewhat less energetic, has a similar range and can be found in polymeric types. Hence, current beta gauge monitors are usually equipped with ^{14}C source (Jaklevic *et al.*, 1981).

3.2 Detector

To enable measurements with the required resolution, the detector must be receptive to beta particles (i.e., electrons) in the relevant energy range and able to count discrete events quickly. Since 1976, different types of detectors have been used in beta gauge systems. These detectors include- solid-state semiconductor, silicon surface barrier, ion-implanted silicon semiconductor, Geiger counter, and photomultiplier tube. The surface barrier detector is a p-n type silicon diode wafer made of n-type silicon on which one surface has been prepared by coating with a thin layer of gold (~40 µg cm^{-2}), and other surface coated with aluminium (~40 µg cm^{-2}) to provide electrical conductivity. It operates by doping thin silicon strips to create reverse biased diodes. Small ionisation currents are produced that can be detected and measured as charged particles pass through these strips. A Geiger-Müller tube with a sensing element that detects radiation and processing electronics constitutes a Geiger counter (Fig. 5). An inert gas, such as helium, neon, or argon, is injected into the Geiger-Müller tube at a low pressure while being exposed to a high voltage. When a particle or photon of incident radiation ionises the gas, the tube conducts electrical charge. Another type of detector which is widely used is photomultiplier tube with scintillation device. It has a sensitive photodetector (photomultiplier tube) that transforms light into an electrical signal after being exposed to radiation, electronics to process the signal, and a scintillator that produces photons in reaction to incident radiation. In 1982, Jaklevic *et al.* (1982) devised a precise beta gauge using a detector consisting of a plastic scintillator and a photomultiplier tube (Fig. 6). This detector shows enhanced counting rate capability allowing precision of ± 2 µg cm^{-2}. Current beta gauge monitors are usually equipped with photomultiplier tube with scintillation device.

4 BETA-ATTENUATION TECHNICAL DEVELOPMENT FOR PM MEASUREMENT

Beta gauge technique for particle measurement is used to calculate the mass accumulated on a filter by evaluating the relative shift in the intensity of the beta particle traveling through un-sampled (initial) and sampled (final) filter tape. Literature shows long time usage of beta gauges for mass determination. Initially, it was used mainly in the workplace to track aerosols around

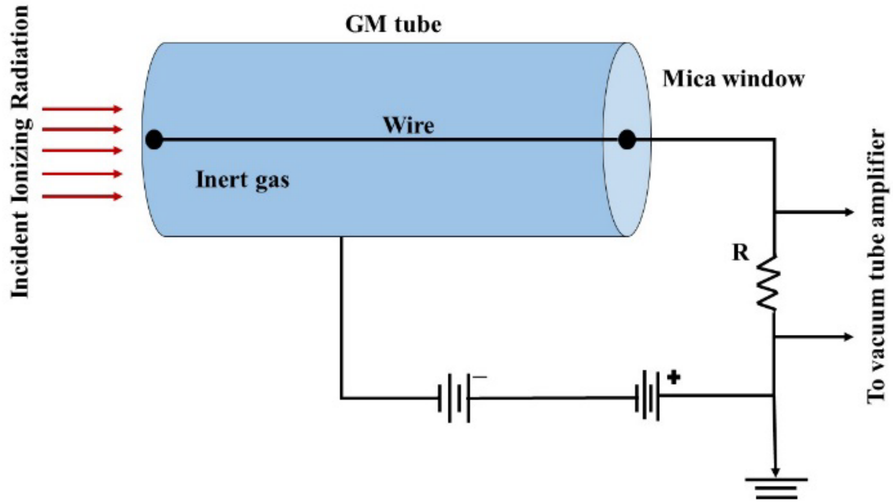

Fig. 5. Schematic of Gieger-Müller counter.

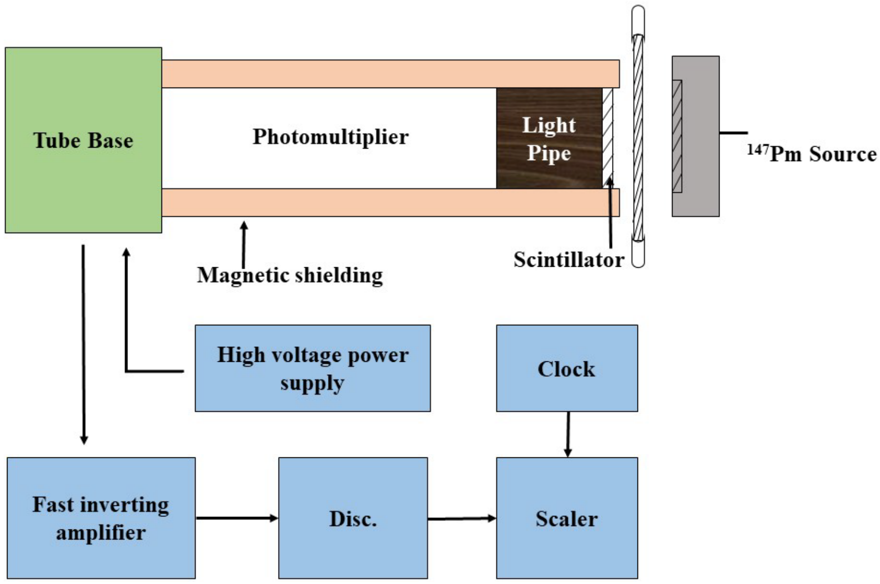

Fig. 6. Schematic diagram of scintillator with photomultiplier tube in beta gauge system.

smokestacks and in coal mines (Salkowski, 1964; Dresia and Spohr, 1971; Lilienfeld and Dulchinos, 1972). It was later used to monitor atmospheric aerosol concentrations with increased sensitivity (Husar, 1974; Stevens *et al*., 1980; Jaklevic *et al*., 1981, 1982; Courtney *et al*., 1982). As a consequence of this advancement, there are many industrial beta gauge instruments now accessible for persistent or semi-continuous particulate mass measurement. In this section, different types of developments made in the beta gauge system since 1976 are discussed, and summarised in Table 2.

Macias and Husar (1976) developed a two-stage on-line mass monitor with aerosol size separator (TWOMASS) based on beta attenuation technique which monitors atmospheric aerosol in 2 size ranges, i.e., coarse and fine particulate fraction. Initially coarse particles from the ambient air are separated by an impactor then remaining small particle fraction is accumulated on a high efficiency filter at a flow rate of 400 $cm^3\ s^{-1}$ (24 lpm) (Fig. 7). The impactor was created to be 50% efficient for particles that are 3.5 µm in diameter. Both the impactor and filtration section of TWOMASS monitor are equipped with independent source-detector systems. ^{14}C (3 mCi) was chosen as a beta source which is detected by a silicon surface barrier detector. Aerosols from a laboratory and the ambient were used to calibrate this instrument gravimetrically. For a 10 min collection interval, the precision and accuracy of the system was recorded as 4 µg m^{-3} and 11%, respectively.

Table 2. Beta gauge monitors developed over the years and their respective features.

Beta source	Detector	Flow (lpm)	Cutoff diameter (μm)	Accuracy (%)	Precision (μg m^{-3})	Reference
Carbon-14	Silicon surface barrier detector	24	3.5	11	4	Macias and Husar, 1976
Promethium-147	Silicon surface barrier detector	---	---	---	< ±5	Jaklevic *et al.*, 1981
Carbon-14	Geiger-Müller	16.2	15 ± 2	---	---	Spagnolo, 1989
Carbon-14	Solid-state semiconductor detector	18.9	10	---	---	Wedding and Weigand, 1993
Carbon-14	Ion-implanted silicon semiconductor (IISS)	25	10.4	---	2.3%	Park *et al.*, 2001
Carbon-14	Photomultiplier tube with scintillation device	16.7	0.15	---	---	Chakrabarti *et al.*, 2004
Carbon-14	Photomultiplier tube with scintillation device	16.7	2.5/10	< 10	< ±5	Met One BAM-1020
Carbon-14	Photomultiplier tube with scintillation device	16.7	2.5/10	< 10	< ±5	Met One E-BAM

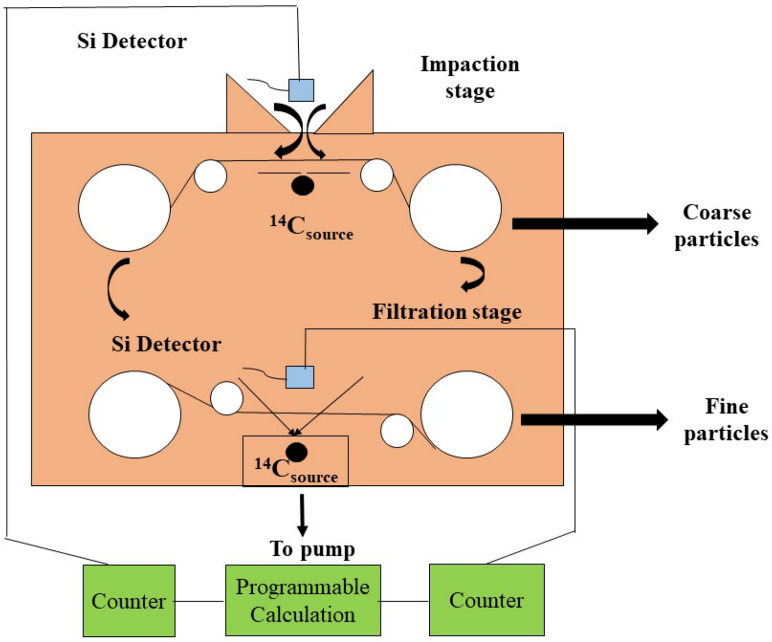

Fig. 7. Schematic of TWOMASS monitor.

Jaklevic *et al.* (1981) evaluated the regular estimation of aerosol mass using beta electrons attenuation method consisting of a beta radiation source, a detector and a sample. The source was ^{147}Pm with a silicon surface barrier detector. Fig. 8 schematically represents the related mechanical and electronic hardware. This design is ideal for the continuous measurement of mass deposit on Teflon filters used in advanced dichotomous samplers. The sample holder holds two regular trays, each with 36 samples, as well as five additional standards at the top and bottom. The coarse- and fine-particle fractions obtained from a manual dichotomous sampler are shown in the two trays. The thin film measurement constants are measured using the five standards at the top. The bottom standards are blank filters of the same kind as those used in the research, and they are used to double-check device stability and measurement efficiency. The instrument's precision was less than ± 5 μg cm^{-2} for a measuring interval of one minute per sample.

Spagnolo (1989) created a beta-particle attenuation instrument that could be used to measure the mass of particulates collected on membrane filters automatically. This instrument positioned the filters automatically into collecting and calculating holders and moving them back to the

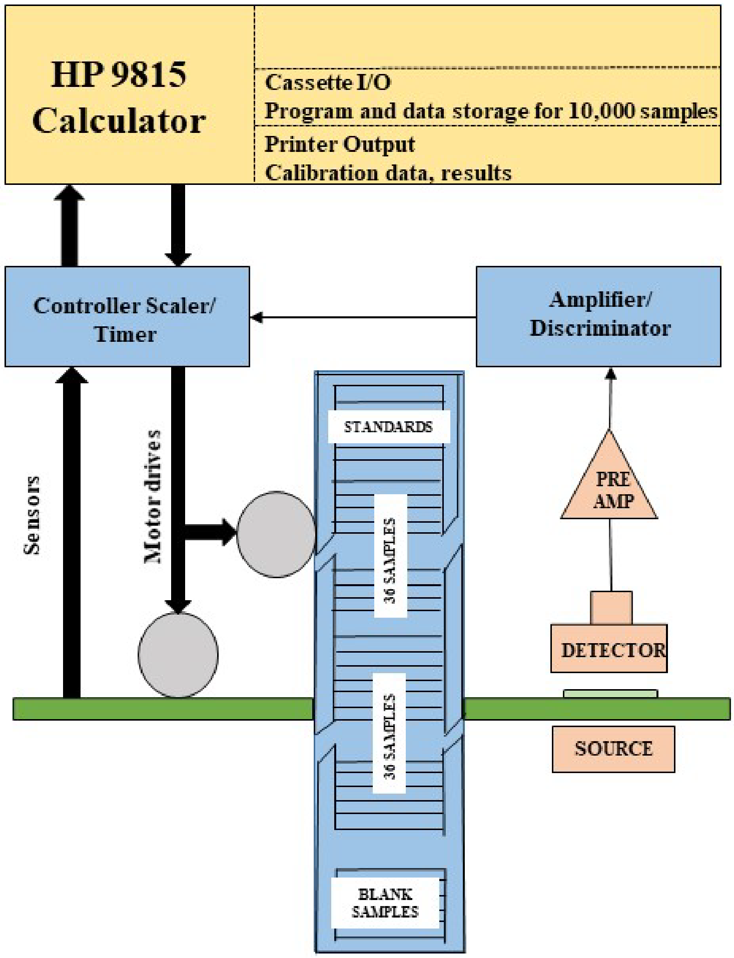

Fig. 8. Schematic of automatic sample handling and data acquisition system used with beta gauge instrument.

original location where they can be stored for the offline measuring purposes. It is designed to function with high sensitivity and low system "dead time". A source of ^{14}C, a Geiger-Müller tube, and a radiation shield are used to determine the beta value. The inlet probe has a 50% cutoff size of 15 ± 2 µm and is intended for a sampling flow rate of 2.7×10^{-4} m^3 s^{-1} (16.2 lpm).

Wedding and Weigand (1993) evaluated the performance of Wedding and associates PM_{10} beta gauge automated sampler, a U.S. EPA designated equivalent method (designation no. EQPM-0391-081). This sampler is equipped with Wedding PM_{10} inlet and Critical Flow Device (CFD). The beta particle source used was 100 µCi (3.7×10^6 Bq) ^{14}C with solid-state semiconductor detectors. The CFD regulates the sampling rate to 18.9 lpm ± 5% and has a 50% cutoff size of 10 µm. Instrument compared with 24-hour average samples obtained with Wedding reference method sampler, with the slope of 1.2 and intercept below 1.5 µg m^{-3} with R^2 of 0.99 or higher, and a resolution of less than 3 µg m^{-3} resolution. Wedding beta gauge sampler has been used in many studies and discussed in the later section (Tsai, 1995; Tsai and Cheng, 1996; Chang *et al.*, 2001; Tsai *et al.*, 2006).

Park *et al.* (2001) developed an automated beta gauge sampler with filter cassette mechanism for mass measurement of PM_{10}. This instrument's design includes continuous filter cassette mechanism, auto-calibration system, minimal sampling dead time, and high sensitivity. The three main components of this sampler are: (i) PM_{10} inlet system, (ii) filter movement set up, and (iii) data processing and control system. The atmospheric particulates are collected through PM_{10} inlet at steady volumetric flow rate of 25 lpm with cutoff diameter of 10.4 µm. ^{14}C was used as a beta source and fast response ion-implanted silicon semiconductor (IISS) as detector. Fig. 9 depicts the beta gauge particulate sampler with a defined mechanical system. The filter cassette holder can

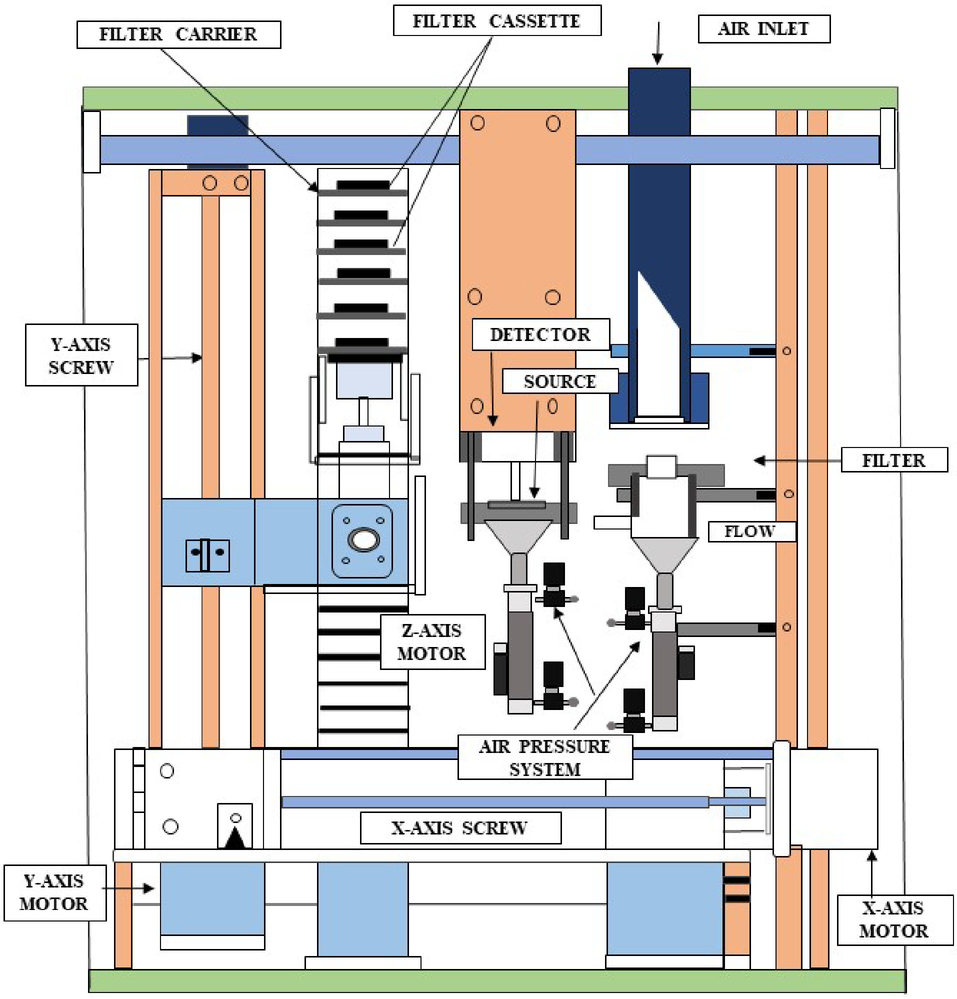

Fig. 9. Beta gauge sampler with defined mechanical system.

hold 15 filter cassette trays and two calibration trays. Since this instrument's mechanical system uses a single filter cassette rather than a roll-type filter tape, it eliminates sampling dead time and minimises the impact of long-term drift which occurs due to frequent calibration required when using roll-type filter tape. The field comparison confirms precision of the instrument to be within 2.3% satisfying U.S. EPA requirements. These beta gauge monitors developed over the years are currently not in use.

Chakrabarti *et al.* (2004) described the modification of Beta Attenuation Monitor (BAM, Model 1020, Met One instruments, Inc., OR, USA) for near continuous (~2 hour) measurement of submicron (i.e., < 0.15 µm or $PM_{0.15}$) particle concentration level in ambient air. This system consists of a standard BAM with 0.15 µm cutoff impactor that operates at 16.7 lpm with extremely low pressure drop. The authors confirmed sharp separation at cutoff 0.15 µm after laboratory evaluation of the impactor cutoff size. Collocated field study of modified BAM was conducted with scanning mobility particle sizer, aerodynamic particle sizer and a Micro-Orifice Uniform Deposit Impactor (MOUDI). The result of field study indicates excellent agreement between BAM and MOUDI with ($r^2 = 0.92$). BAM measurements of 0.15 µm PM mass concentration were more accurate and efficient compared to Scanning Mobility Particle Sizer (SMPS) due to high content of fractal-like particles during morning traffic peak, which tend to be defined in higher size ranges by SMPS, i.e., SMPS works on electrical mobility-based particle sizing followed by scattering based detection. Also, particle density is needed to be considered while calculating particle mass from its size (volume).

The Met One BAM-1020 particulate monitor is an U.S. EPA designated FEM for PM_{10}, $PM_{2.5}$ and $PM_{10-2.5}$. This instrument is currently used at most of the air quality monitoring stations worldwide. The BAM-1020 obtained designation as PM_{10} FEM in 1998 and $PM_{2.5}$ FEM in 2008. It was the first

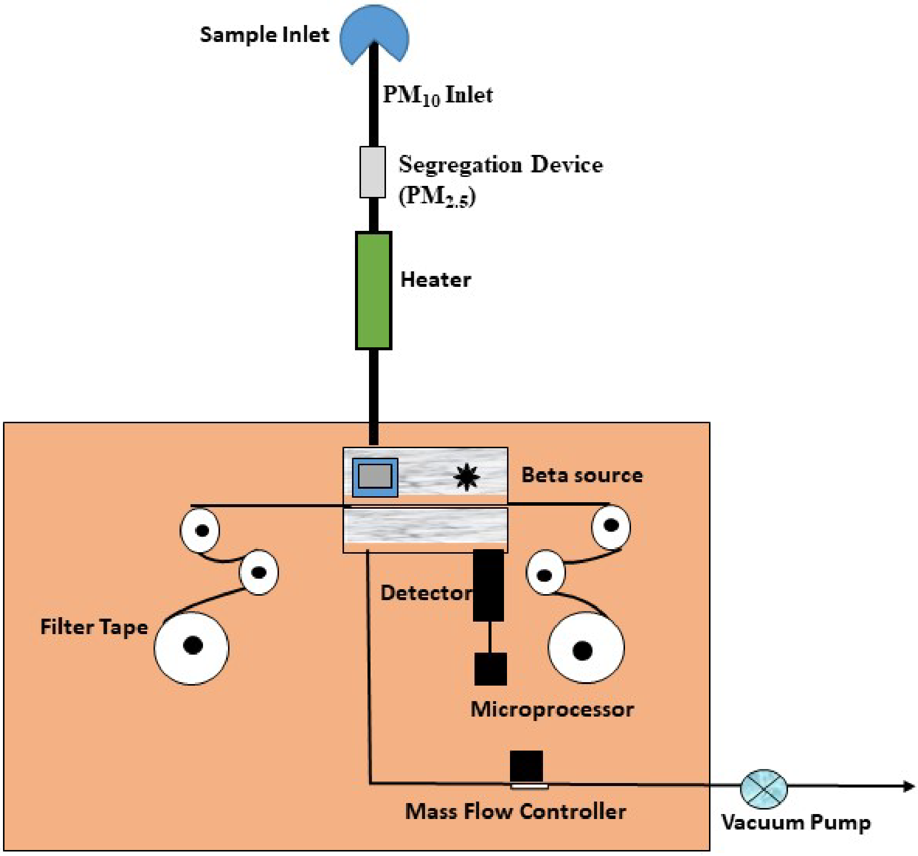

Fig. 10. Schematic of Met One BAM-1020.

instrument to obtain designation for $PM_{2.5}$ continuous particulate monitoring (EQPM-0308-170) after series of design improvement, as EPA criteria for $PM_{2.5}$ FEM designation testing are much more strenuous than the criteria for PM_{10} designation. New PM_{10} BAM-1020 includes all the latest hardware and calibration as in $PM_{2.5}$ FEM units except different firmware (only 4-minute beta counts allowed) and some extra accessories such as cyclone, zero filter and atmospheric temperature/barometric pressure sensor. Met One BAM-1020 consists of ^{14}C beta source (60 µCi) coupled to scintillation detector, FRM-type PM_{10} size selective inlet, followed by a $PM_{2.5}$ very sharp cut cyclone (VSCC) size fractionator and an integrated smart heater system to control the sample RH at or below 35% to be consistent with the FRM filter conditioning requirements and operate at 16.7 lpm (Fig. 10). When BAM-1020 compared to $PM_{2.5}$ FRM samplers for 24-hour average measurements, the slope ranged between 0.9–1.1 and intercept of about +2 to +3 µg m^{-3} (Met One, 2009).

Met One E-BAM (Environmental Beta Attenuation Mass Monitor) is a portable continuous real-time monitor used for $PM_{10}/PM_{2.5}$ measurement. It reports result in real time without human intervention, and because it can operate under ambient conditions it produces results comparable to reference method by sampling of semi-volatile compounds and nitrates without considerable losses thereby avoiding under measurement of particulates. It consists of ^{14}C beta source (60 µCi ± 15 µCi), photomultiplier tube with plastic scintillator as detector and operates at 16.7 lpm. Relative humidity is controlled by a smart heater (at or below 35%).

5 POTENTIAL BIASES OF BETA GAUGE TECHNIQUE

Gravimetric method (aerosol sampling on filter) is a direct method in the estimation of mass concentration and is considered as the primary method. It evaluates PM concentrations directly, ensuring that they are traceable to the International System of unit but it needs a collection period from a few hours to 24-hour or few days. Therefore, the gravimetric approach is not optimal for tracking high concentration events or detecting short-term concentration shifts. On the other hand, the beta gauge method can provide continuous particulate matter concentration in real-time. Due to their potential to deliver continuous measurements with little operator participation, this technique is one of the most widely used real-time systems for monitoring particulate matter. However, there are many reported errors associated with this technique since 1976. The initial publications were based on the development in instrumentation of this technique (Macias and Husar, 1976; Jaklevic *et al.*, 1981; Spagnolo, 1989; Park *et al.*, 2001; Chakrabarti *et al.*, 2004), after further evaluation, the effect of ambient conditions on beta gauge readings were also reported (Chang *et al.*, 2001; Salminen and Karlsson, 2003; Tsai *et al.*, 2006; Shin *et al.*, 2011). Many researchers have compared beta gauge method measurements of ambient PM with gravimetric reference method and reported the difference in the result of two methods (Tsai, 1995; Tsai and Cheng, 1996; Chang *et al.*, 2001; Salminen and Karlsson, 2003; Takahashi *et al.*, 2008; Shin *et al.*, 2011; Liu *et al.*, 2013; Le *et al.*, 2020b). Some reported factors which may cause variation between the measurement methods include particle size, filter inhomogeneity, different orientations of filter paper, effect of assembly geometry, soiling effect of the cyclonic inlet, variation in attenuation coefficient, variations of air density between source-detector gap due to fluctuations in ambient pressure and temperature, high relative humidity, water content of aerosols and secondary hygroscopic particles. Inappropriate performance of PM_{10}/$PM_{2.5}$ inlets used as size classifiers in beta gauge devices results in particle bounce or loading effect causing inaccurate measurements (Le and Tsai, 2017; Le *et al.*, 2019, 2020a). Also, there are reports of under-measurement of PM concentrations by gravimetric method due to evaporative losses of semi-volatile species, thereby affecting the performance of beta gauge instrument when gravimetric measurements are used for the comparison studies (Liu *et al.*, 2014, 2015; Barhate *et al.*, 2022). This section includes the review of the reported discrepancies associated with beta gauge technique to help in better understanding the field performance of beta gauge monitors. Number of field and laboratory studies have been conducted across many countries with different ambient conditions.

5.1 Factors Affecting Beta Gauge Measurements

For short- and long-term studies, Courtney *et al.* (1982) determined the reliability and validity of beta gauge measurements for aerosol mass. The beta gauge system used here was designed and fabricated by Lawrence Berkeley Laboratory as described in Jaklevic *et al.* (1981). The precision reported was 25 µg for short- and 27 µg for long-term experiment on Teflon filters for 6.5 cm^2 deposit. Ambient mass concentration measurements between beta gauge and gravimetric methods were in good agreement when sampled on the same Teflon filter and any biases found was less than 5%.

Tsai (1995) evaluated the performance of three ambient PM_{10} samplers (gravimetric-SA 1200, Wedding high-volume and beta gauge) at three monitoring stations in Taiwan. This study includes comparison of the daily measured PM_{10} concentration between the samplers along with the effect of loading on the measurements. The variation in measurements between two high-volume samplers- SA 1200 and Wedding high-volume sampler (flow rate 1130 lpm) was found to be less than 10% when the particle collection surface (impactor plate) was cleaned periodically reducing loading effect. Wedding beta gauge samplers running at flow rate 18.9 lpm measured regular PM_{10} concentrations within ± 10% of those of Wedding high-volume samplers. In both gravimetric and beta gauge samplers, loading effect was found, and to prevent it, it was recommended that the inlet be cleaned once a week in contaminated areas to keep the error to less than 10%.

Tsai and Cheng (1996) studied the effect of cutoff diameter on the efficiency of PM_{10} beta gauge sampler at three monitoring stations in Taiwan. For this, they compared the Wedding and Kimoto 180 beta gauge samplers, and SA (Sierra-Andersen) 1200 high-volume PM_{10} sampler was used as a reference to compare the measured daily 24-hour average of both beta gauge samplers to determine the accuracy of the measurements. The Wedding beta gauge sampler consists of 10 µm inlet, a ^{14}C source (100 µCi), a solid-state semiconductor detector and a CFD to control the volumetric flow rate (18.9 lpm). In a wind tunnel test, the D_{50} cutoff was determined to be 9.94, 9.96, and 9.51 µm for respective wind speeds of 2, 8, and 24 km h^{-1}. According to manufacturer's handbook, the Kimoto 180 consists of a cyclonic inlet of 6.5 µm, a ^{147}Pm source (less than 100 µCi), a scintillation detector and rotameter to regulate the flow at 18 lpm. The cutoff diameter of SA 1200 high-volume was reported as 9.5, 9.7 and 9.5 µm at wind speeds of 2, 8 and 24 km h^{-1}, respectively. The laboratory evaluation of Kimoto 180 indicates its D_{50} cutoff to be only 3.5 μm which is too small for it to be referred as PM_{10} sampler. Therefore, daily average PM_{10} concentrations measured by Kimoto 180 were much lower than the measurements of Wedding beta gauge and SA 1200 high-volume sampler because the cutoff size of its inlet was much smaller than 10 μm. The PM_{10} concentration measured by Wedding beta gauge sampler was identified to be more precise due to a cutoff size close to 10 μm. Within experimental errors, water vapour content has no effect on the Wedding beta gauge readings, but the fractional difference (difference between daily average PM_{10} concentrations from the Wedding or Kimoto 180 beta gauge and from the SA 1200 sampler, divided by the daily average PM_{10} concentrations from the SA 1200 sampler, versus water vapor content) of the Kimoto 180 tends to increase from –0.33 to –0.17 when water vapor content increase from 6 g m^{-3} to 21 g m^{-3}.

Chang *et al.* (2001) did 24-hour comparative study between PM_{10} concentrations determined by U.S. EPA designated FEM Wedding beta gauge monitor (designation no. EQPM-0391-081) and FRM, i.e., Anderson or Wedding high-volume sampler in Taiwan. They have reported equivalence in both the measurements only up to certain levels, i.e., below the deliquescence point of inorganic aerosols. However, as the deliquescence point was reached, the inorganic aerosols absorb more water leading to greater PM_{10} concentrations of the Wedding beta-gauge in comparison to reference high-volume samplers. The ratio of beta gauge PM_{10} to Anderson PM_{10} and Wedding PM_{10} changes from 1.08 ± 0.06 to 1.21 ± 0.22; 1.09 ± 0.12 to 1.27 ± 0.15, respectively with the increase in ambient RH. They also tried to develop a method for the estimation of amount of water in PM_{10} measured by beta gauge monitor by calculating theoretical water content of ambient aerosols by a gas/particle equilibrium model known as ISORROPIA (Nenes *et al.*, 1998). During high RH, they discovered that theoretical PM_{10} concentrations were far higher than real readings from the beta gauge monitor. This was due to unbound water evaporation from the aerosols accumulated on the beta gauge monitor's filter tape. In order to link theoretical hourly "wet" PM_{10} concentration with real measurements of beta gauge monitor, a correction factor was applied to compensate for the evaporative losses. These evaporative losses due to sudden pressure decline through the filter, dynamic variation of pollutant loading and environmental conditions were later on researched by this group and are reviewed in the following section.

Takahashi *et al.* (2008) examined 7 year-round discrepancies in suspended particulate matter (SPM) between beta attenuation method (BAM) and gravimetric method in Tokyo. They studied season-based trends showing BAM measurements to be higher than gravimetric methods in summer (30%) and gravimetric measurements higher in winter (20–30%). The authors clarified the difference by calculating the water content of the aerosols and discovered that in the summer, when humidity reaches the deliquescence point of ammonium sulphate, BAM measurements are higher. The effect of atmospheric aerosol water content on gravimetric SPM measurements causes gravimetric measurements to exceed BAM values in the winter because ambient absolute humidity during sampling is greater than the humidity of the weighing room.

Shin *et al.* (2011) analysed the measurement difference between beta ray absorption method (BAM) and manual gravimetric method (GMM) in South Korea. They estimated positive errors induced by moisture absorption on the filter in BAM using a gas/particle equilibrium model, SCAPE2. They report reduction in discrepancy between both methods from 69% to 25% after the consideration of water content in the measurements. Multiple regression analysis was also applied with meteorological factors (relative humidity, dust storm events, wind speed and direction, rain, temperature) as independent variables to identify other factors that might have affected the measurement difference.

Salminen and Karlsson (2003) evaluated the performance of beta gauge monitors at a low concentration site situated in Finland. The sampling was done during two seasons: autumn and early winter with 24-hour mean PM_{10} mass concentration recorded as 5.1 μg m^{-3} (1.5–18 μg m^{-3}). With a confidence interval of ± 1, this sampler was proven to be capable of recording trace levels as low as 2 μg m^{-3}. The comparison of beta gauge monitor with gravimetric reference sampler showed higher measurements by beta gauge monitor and mean ratio of monitor to reference sampler was 1.06 ± 0.12. High relative humidity (> 85%) caused by water absorption by the particles resulted in higher beta attenuation measurements. Ion chromatography analysis showed that 40% of the estimated PM_{10} mass concentration accounted for water soluble inorganic ions with sulfate having the largest relative proportion of the analyzed ions.

5.2 Effect of RH on Beta Gauge Measurements and Applied Correction Factors

The average temperature and relative humidity of the filter weighing room should be held between 20-23°C ± 2°C and 30-40% ± 5%, respectively, according to the U.S. EPA's standard operating procedure (2016). As a result of water absorption by inorganic aerosol particles collected on filters during beta gauge sampling, beta gauge measurements are predicted to be greater than gravimetric sampling at RH greater than deliquescence RH. From all the above reviewed papers it is clear that the data generated by beta attenuation technique cannot be considered equivalent under all ambient conditions to the reference gravimetric method because this technique is based on different principle which results variation in the data generated, especially under high RH condition.

The effects of relative humidity on beta attenuation technique used for atmospheric particulate monitoring have been discussed in many literatures. The reported effect is such that wet particles form when dry inorganic particles absorb water when relative humidity rises over a set point, and they continue to absorb as relative humidity increases leading to high concentration values. To resolve this problem, beta gauge monitors were upgraded with a heater system with a controller that heated the air stream to a predetermined relative humidity level. Since the RH of the beta gauge monitor was set below a particular point, the inlet heater was supposed to remove the hygroscopic and condensation effect of particles on the filter influencing the mass concentration readings. In some areas, the ambient RH is quite high, and at high ambient RH, the inlet heater's increased temperature could not be enough to lower the water content of particles in beta gauge. Therefore, it is critical to assess the beta gauge's performance in these circumstances using a range of RH set points. This section includes review of the studies conducted on RH effect on beta gauge measurements along with proposed correction factors.

5.2.1 Studies related to PM_{10} measurements

Chang and Tsai (2003) continued their investigation by developing a model to predict evaporative loss of water from particles accumulated on the filter of an U.S. EPA designated Wedding beta gauge PM_{10} monitor in both ambient and laboratory conditions. The evaporation of volatile particulate species including ammonium nitrate and ammonium chloride as a result of pressure drop through the filter has been studied extensively (Cheng and Tsai, 1997; Appel and Tokiwa, 1981; Zhang and McMurry, 1987, 1992). However, for the first time in this paper, evaporation of particle-bound water during the sampling process was addressed and measured, focusing on the fact that when RH is higher than deliquescence RH, water may be one of the most abundant species in particles, and particle-bound water can evaporate during sampling primarily due to pressure drop across the collection media. The simulated results of this study show that when the relative humidity in Taiwan is less than 85%, all of the absorbed water evaporates completely, but when the relative humidity is higher than this, complete evaporation is not possible, resulting in higher beta gauge monitor readings.

Tsai *et al.* (2006) explored the direct evidence of the effects of humidity on PM_{10} measurements on an hourly basis by beta gauge monitor in the field conditions along with the comparison of two theoretical models (ISORROPIA thermodynamic and water evaporation loss model) developed previously. This study was conducted on two collocated U.S. EPA designated Wedding beta-gauge monitors in Taiwan where inlet of monitor 1 was conditioned with water vapour so that it has higher RH than monitor 2. The results showed that PM_{10} concentration in both the monitors were nearly the same as long as RH remains below 80-85%. However, when RH surpasses this threshold, monitor 1's PM_{10} values are higher than monitor 2's, and this discrepancy grows as RH increases. Beta-gauge readings were simulated using the thermodynamic and evaporation model and the result shows that PM_{10} concentration readings simulated by water evaporation loss model are in good accordance with true readings in comparison to thermodynamic ISORROPIA model. The result indicates that the ISORROPIA model can predict water content of particles only when they are in air, whereas evaporation model gives better prediction of beta-gauge readings. This study can be helpful to the users of beta-gauge monitors to set RH levels for heater activation.

Jung *et al.* (2007, 2009) estimated BAM performance with an inlet heater at South Korea. Authors reported that PM_{10} concentration monitored by beta attenuation monitor equipped with inlet heater was comparable with gravimetric method showing percentage difference of 3–6%

and high correlation (r^2 = 0.98). However, an inconsistent result was observed by Kong *et al.* (2010) at South Korea, where BAM with inlet heater showed low correlation in summer with BAM reading higher than gravimetric at high RH (> 80%). This demonstrates that a heater might not be adequate to decrease the water in aerosols over 80% relative humidity.

Shin *et al.* (2012) estimated the optimum temperature for heated inlet air of beta attenuation monitor by comparing PM_{10} concentration measured at two coastal sites in Korea. Authors reported good degree of correlation between BAM and GMM at both the sites with BAM readings higher than GMM by 32% at site A and 5% at site B. Water content in aerosols was estimated by gas/equilibrium model SCAPE2 to determine the optimal temperature required to make BAM PM_{10} measurements comparable to GMM. This study suggested optimal heated inlet air temperature inside BAM should be 35–45°C to reduce evaporation of volatile aerosol components and to make BAM measurements equivalent to GMM.

Kiss *et al.* (2017) quantified the differences in hourly measurements of PM_{10} beta attenuation monitor by the interaction of water. This study was carried out in a temperature control observatory in Hungary with a U.S. EPA FEM designated Thermo Scientific FH62C14 continuous particulate monitor operating at a flow rate of 16.7 lpm with sample tube heater to prevent condensation of water vapor. The particles were extracted by replacing the PM_{10} inlet with a HEPA filter to research water absorption of filter material. When particle-free air is sampled, the mass concentration of PM varies on a daily basis, resulting in positive and negative errors. Study suggests heating of inlet at 40°C reduces artifact related to water adsorption and desorption but cannot completely eliminate it. As a result, 1-hour PM_{10} measurements must be used carefully, as water vapor adsorption on or desorption from the beta attenuation monitor's filter material may cause significant bias at low ambient concentrations.

5.2.2 Studies related to $PM_{2.5}$ measurements

Fine particles with diameter ≤ 2.5 µm ($PM_{2.5}$) contain microscopic solid or liquid droplets that cause major health issues because they can deeply enter into alveolar regions of the lung where gaseous exchange takes place. Therefore, it is important to monitor its concentration in ambient air which will help decision makers in establishing policies and generating health advisories. $PM_{2.5}$ is monitored regularly with a beta gauge monitor at many air quality monitoring networks around the world. But there are only few studies conducted on evaluating its performance in $PM_{2.5}$ concentration measurements which is further reviewed in this section.

Huang and Tai (2008) evaluated $PM_{2.5}$ concentration measured by collocated FEM designated portable E-BAM (Met One Instruments Inc.) and stationary BAM-1020 (Met One Instruments Inc.) with manual samplers at different relative humidity set points. Water vapor was used to condition the inlet of a portable beta attenuation monitor to compare the effect of relative humidity ranges with stationary beta attenuation monitor. The inlet heater's RH set point for stationary beta gauge was adjusted to 35% because deliquescence relative humidity of most particles was greater than 35%, and for portable beta gauge set points were 25%, 35%, 50% and 65%. The result showed that at RH set point of 35%, both the sampler readings were recorded very close to each other but when RH of portable sampler rose to 65%, the $PM_{2.5}$ reading of portable sampler exceeded the other whose set point was 35%. The impact of relative humidity on beta gauge measurements was confirmed in this study. Therefore, it is important to maintain the RH set point in an appropriate range for field monitoring of particulate matter.

Liu *et al.* (2013) performed comparative field study of $PM_{2.5}$ concentration estimated by beta attenuation monitor (non-FEM BAM-1020 without smart heater) and dichotomous sampler gravimetric sampler at three Taiwan air quality monitoring stations to quantify the difference and evaluate the factors influencing their measurement. Results show overestimation by beta attenuation monitor by 58.4 ± 37.4%, 29.8 ± 20.2%, 28.4 ± 19.0% for three stations. Different factors affecting the measurement discrepancies were investigated, including inorganic species volatilization, water content of aerosol and overestimation caused by acid gas adsorption by glass filter tapes. This study recommended that glass fiber filters be replaced with Teflon-coated glass fiber filters or some other acid gas adsorption-resistant material. Many studies related to the effect of RH on beta gauge performance were done in Taiwan, one of the possible reasons maybe it being a small island and having majorly humid conditions throughout the year.

Schweizer *et al.* (2016) compared widely used mobile particulate Environmental Beta Attenuation Monitor (non-FEM EBAM) for monitoring smoke in the western United States with the Beta Attenuation Monitor (FEM-BAM) permanently established in the field for $PM_{2.5}$ measurements. Both the BAM monitors were manufactured by Met One Instruments. Mobile monitors are useful to provide information during short duration events such as wildfires for public health decisions. Therefore, its field evaluation is important to accurately represent data for health advisories. The hourly (R^2 = 0.70) and daily means (R^2 = 0.90) of the instruments were found to be correlated with EBAM overestimating BAM by 24% (3 µg m^{-3}) during high ambient RH conditions. Hourly concentration fluctuations were reported more in EBAM and were not precise enough. As a result, when using EBAM, it was suggested to only use daily AQI estimates.

5.2.3 Correction applied to beta gauge measurements

Based on a limited number of gravimetric data, Gehrig *et al.* (2005) attempted to establish a method for linking PM_{10} concentrations from continuous beta-attenuation monitors to the reference method as per EN 12341 for obtaining reference equivalent data from automated monitors. This method was being developed as a tool for dealing with rapid meteorological changes and different aerosol compositions at different locations. Every fourth day, gravimetric data is collected for comparison. It entails calculating regular correction factors corresponding to the gravimetry/monitor ratio for days when gravimetric data were calculated, and days when gravimetric data were not available, as well as the mean of the gravimetry/monitor ratios of the two closest days. The study sites in Switzerland show good agreement between automatic beta attenuation monitors and the manual gravimetric method after applying correction factors to the generated data. The following process was used to rectify the monitor measurements:

- Case 1: Days *i* for which PM_{10} gravimetric value *gi* is collected

$$m_i\left(corrected\right)=m_i\frac{g_i}{m_i}=g_i \tag{4}$$

where, m_i is the uncorrected daily mean values of PM_{10}, g_i is the gravimetric PM_{10} value.

- Case 2: Days *i* for which no PM_{10} gravimetric value *gi* is measured

$$m_i\left(corrected\right)=m_i\cdot 0.5\cdot\left(\frac{g_p}{m_p}+\frac{g_f}{m_f}\right) \tag{5}$$

where, *p* is the nearest day preceding day *i* for which a PM_{10} gravimetric value is available. *f* is nearest day following day *i* for which a PM_{10} gravimetric value is available.

These correction procedures show good agreement at all the sites except at low particle pollution leading to greater uncertainty for single daily values.

Le *et al.* (2020b) conducted $PM_{2.5}$ comparisons between automatic Federal Equivalent Monitor (FEM BAM-1020 with smart heater) with manual Federal Reference Method (FRM) sampler in Taiwan. Results show good agreement of BAM with FRM with slope (1 ± 0.1), intercept (0 ± 2 µg m^{-3} and $R^2 > 0.93$) but it overestimates at temperature lower than 18°C, and either over or underestimate at temperature higher than 25°C due to acid gas adsorption and aerosol water content. To reduce the biases, authors derived empirical equations to convert automatic sampler data to manual data. Empirical equations were based on the relationship between $Diff_{B\text{-}FRM}$ (µg m^{-3}) and T (°C), RH (%), and $PM_{2.5,B}$ (µg m^{-3}):

$$PM'_{2.5,B} = PM_{2.5,B} - Diff_{fB\text{-}FRM} \tag{6}$$

where, $PM'_{2.5,B}$ is the converted $PM_{2.5}$ of the BAM to $PM_{2.5,FRM}$ with $Diff_{B\text{-}FRM}$ calculated as

$$Diff_{B\text{-}FRM}=\alpha\frac{PM_{2.5,B}\times\beta}{T\times RH\times 0.01}+\gamma \tag{7}$$

$$Diff_{B\text{-}FRM} = \alpha \times T + \gamma \quad (8)$$

$$Diff_{B\text{-}FRM} = \alpha \times \mathrm{T} \times RH \times 0.01 + \gamma \quad (9)$$

where, α, β and γ are empirical parameters at different ranges of *T*, *RH*, and $PM_{2.5,B}$. Correction results into decrease in mean normalized biased from +1.67 ± 12.43% to +0.63 ± 8.75% and $Diff_{B\text{-}FRM}$ from +0.66 ± 2.15 $\mu g\ m^{-3}$ to +0.01 ± 1.47 $\mu g\ m^{-3}$.

Shukla and Aggarwal (2021) investigated the beta gauge method's performance in an Indian urban city with high $PM_{2.5}$ mass loading and RH. It is the first study conducted so far in Indian conditions where humidity, temperature and particle mass loading vary greatly from location to location and season to season. A thorough understanding of the factors that affect the measurements of $PM_{2.5}$ concentrations by a beta gauge monitor in such extreme meteorological conditions is necessary to modify the instrument and to develop correction factors specific to geographical areas. The outcome demonstrates that RH has a significant role in how well the beta gauge method performs and data quality is better when particle mass loading is < 130 $\mu g\ m^{-3}$ and ambient RH is < 60%. When the relative humidity and $PM_{2.5}$ concentrations were known, correction factor techniques were used to adjust the disparity between the beta gauge measurements and gravimetric values.

- First approach includes development of constant correction factor known as constant proportion (CP) correction:

$$CP\ corrected\ \mathrm{PM}_{2.5_{BC}} = \frac{Original\ \mathrm{PM}_{2.5\_BC}}{\alpha} \quad (10)$$

where, α is the correction factor (i.e., the slope of regression) determined through the regression method comparing $PM_{2.5\_BG}$ against $PM_{2.5\_GM}$ measurements.

- Second approach include correction factor determined as a function of ambient RH and it is named as RH correction:

$$RH\ corrected\ \mathrm{PM}_{2.5_{BC}} = \frac{Original\ \mathrm{PM}_{2.5\_BC}}{\beta} \quad (11)$$

$$\beta = a + (b \times RH \times 0.01) \quad (12)$$

where, *a* and *b* are the intercept and slope parameters estimated through the regression method comparing ratio of beta gauge and gravimetric values against the measured ambient *RH* (expressed as a fraction of 100%).

- Both corrections are combined as total correction (TC):

$$TC\ \mathrm{PM}_{2.5,BG} = \frac{CP\ corrected\ \mathrm{PM}_{2.5_{BC}} + RH\ corrected\ \mathrm{PM}_{2.5_{BC}}}{2} \quad (13)$$

where, CP corrected $PM_{2.5\_BG}$ and RH corrected $PM_{2.5\_BG}$ are the result of constant proportion and RH corrections applied individually.

After correction, the mean normalized biases get reduce from 46.48 ± 26.78% (original $PM_{2.5\ \text{Beta gauge}}$) to 1.72 ± 18.60% (converted $PM'_{2.5\ \text{Beta gauge}}$) and 0.41 ± 6.11% (RH corrected $PM''_{2.5\ \text{Beta gauge}}$). These correction approaches for beta gauge measurements can be applied to other areas that have similar ambient conditions to these studies.

6 CALIBRATION ISSUE

The calibration of beta gauge monitor is performed by using a film of known mass density to determine beta-rays absorption efficiency but this attenuation coefficient is dependent on

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chemical composition of deposited particulate matter, also Jaklevic *et al.* (1981) used a set of established standards to estimate the mass absorption coefficient for beta radiation. For several substrates, the mass attenuation coefficient (μ) was calculated as a function of the atomic number to mass (Z/A). Results show that attenuation coefficient is not fixed, it depends on the composition of particulate matter present in ambient air. The chemical nature of the matter has been reported to have a distinct and continuous effect on the value of the mass absorption coefficient with considerable variation (Spagnolo, 1989). As a consequence of the reliance of mass absorption coefficient on atomic number, such measures must be taken when choosing a calibration standard. Inappropriate choice can affect the accuracy of measurement. This highlights the significance of maintaining a reliable beta gauge calibration configuration by incorporating complete correction for the sample composition. It is also important to maintain beta gauge in a stable identical configuration to avoid change in measurement conditions before and after exposure to beta rays (Gleason *et al.*, 1951).

Generally commercial beta gauge monitors include a calibration factor (multiplicative and additive bias) along with standard film of fixed mass density, which is generated during factory calibration in the controlled environment but the field ambient conditions are not similar to testing conditions. This brings focus on inclusion of onsite correction in the measurement to generate better quality data. Reviewed studies suggest RH to be the major factor affecting beta gauge measurement, including RH correction may reduce the biases in the data. RH depicts diurnal variations during day and night. Therefore, RH correction with higher time resolution should be applied to real-time beta gauge measurements. The correction factors developed by onsite calibration at a place may not be applied to other geographical areas due to variation in meteorological conditions and also cannot be applied to the same area during different season, therefore, it is important to develop site-specific correction factors for each individual unit of instrument.

7 CONCLUSION

Beta attenuation technique is used throughout the world in air quality monitoring stations for real time monitoring of particulate matter in air quality networks. However, dependency of its performance on the ambient conditions as well as several operational factors result in variation in measurements when compared with the reference method leading to inaccurate measurement of PM concentrations across the world. Thus, causing non-uniformity in air quality data. So, the objective of this review paper was to provide in-depth information on the application of beta attenuation technique and its associated errors identified and corrected by many researchers. Intriguingly, we attempted to review all the studies conducted starting from the method development, application in atmospheric measurements along with the limitation identified. Publications which have emerged over the past two decades in the field of PM monitoring using beta gauge technique, have been comprehensively reviewed. Based on our evaluation, calibration of this instrument is very vital and should be region specific. The instrument should be FEM designated with smart heater to reduce the discrepancy in the measurements when compared to FRM. Since the correlation established for a coal-burning city does not apply to a city with high dust concentration, each location with specific source, ambient condition and mass loadings of PM require its own calibration. Although it is possible to compare attenuated and un-attenuated beta-rays count but the stability associated with long-term calibration cannot be assured. As a result, each sequence of measurements should include specific calibration readings. To assess if any systematic calibration changes have occurred, standard samples should be measured repeatedly. Additionally, it's crucial to adjust the inlet heater system to the precise ambient RH ranges of the operational areas. As a result, for better and comparable air quality data generation, the beta gauge system's instrumentation must be modified along with the region-specific calibration method.

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