



Chapter 7

SAMPLING FOR THORACIC AEROSOL

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7.1 GENERAL REQUIREMENTS — THE IDEAL SAMPLER

There are two possible approaches to sampling for thoracic particulate matter (TPM). The simplest is to use a sampler whose collection efficiency as a function of particle aerodynamic diameter (d_{ae}) satisfies the acceptance criteria. Such a TPM sampler consists of an inlet, a size-fractionating stage, which is sometimes integral with the inlet, and a particle collector, which is usually a filter. The U.S. Environmental Protection Agency (EPA) has defined the PM₁₀ sampling convention to have a 50% cut point at $d_{ae} = 10 \mu\text{m}$. The slope of the PM₁₀ curve is similar to, though differs slightly from, the TPM curve (see Figure 7.1) (John, 1993). The most significant difference is at the large particle ends of the curves. The bias of the PM₁₀ convention relative to the thoracic convention is calculated and presented in Figure 7.2 for a range of lognormal particle size distributions. This figure shows that although the difference is small over a wide range of conditions, it can become significant if the particle size distribution being sampled is rich in coarse particles. It should be noted, however, that some PM₁₀ samplers have an efficiency curve with a large-particle tail approximating that of the thoracic curve (see Figure 7.1).

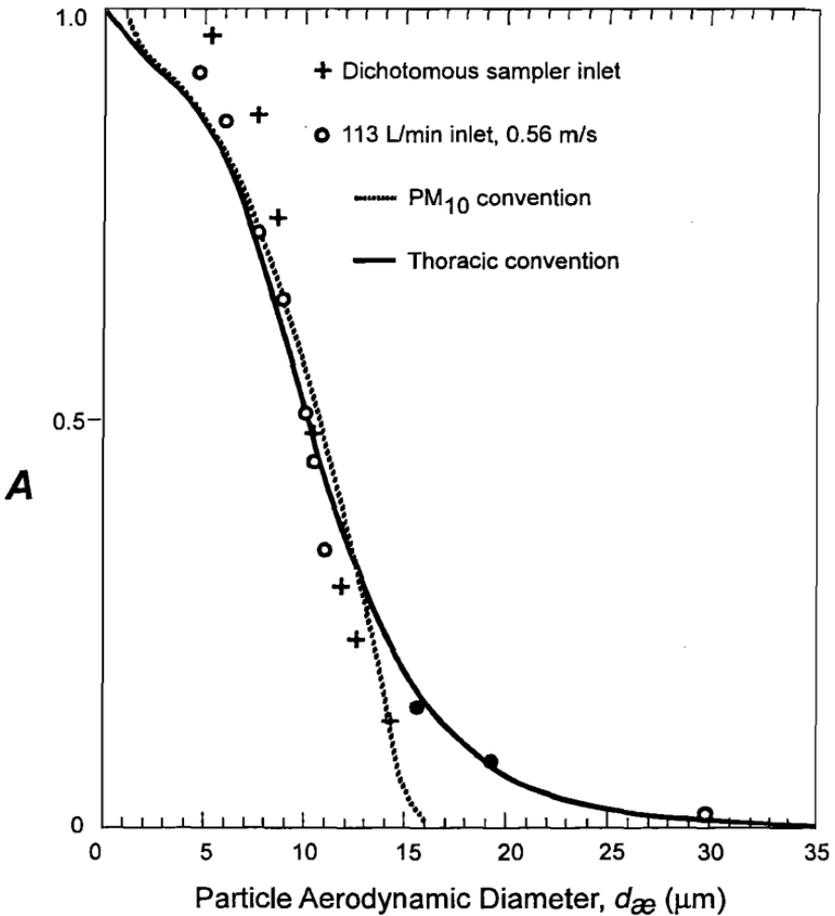


FIGURE 7.1. Thoracic and PM₁₀ sampling criteria with data for two PM₁₀ samplers — the dichotomous sampler (Wedding, 1982) and the 113 L/min sampler (Wedding, *et al.* 1983)

An alternative approach is to determine the aerodynamic particle size distribution; for example, by sampling with a cascade impactor. The thoracic mass fraction is then calculated from the data and the TPM criteria. This approach provides more detailed information, but it has disadvantages including a large increase in the number of samples to be analyzed, the complexity of the required calculations, and the limited collection capacity of cascade impactors.

The measurement of TPM can be carried out both for personal exposure and for environmental monitoring. For personal monitoring, the inlet of the sampler should comply with the requirements for an inhalable inlet with a pre-classifier selecting the TPM.

The sampling of particles having $d_{ae} = 10 \mu\text{m}$ and somewhat larger

for environmental monitoring requires an inlet designed to be independent of wind direction and windspeed (Wedding *et al.*, 1977 and 1980; Liu and Pui, 1981; Wedding, 1982; Tufto and Willeke, 1982). Indoor windspeeds are of the order of 0.1–1 m/s, while mine and outdoor environments have higher windspeeds (Berry and Froude, 1989). The EPA (1987) requires PM₁₀ (particulate matter, 10- μ m cut point) samplers for ambient air to be tested at 2, 8 and 24 km/hr (0.56 to 6.67 m/s). Testing of a thoracic sampler should include placing it on a mannequin and ascertaining the susceptibility of its inlet to wind direction and velocity biases. The sampling efficiency is measured at several wind velocities between stagnant air and 4 m/s and averaged over 360°. Future standards may select specific wind velocities and orientations for the test protocol. Little such testing for thoracic samplers has so far been carried out.

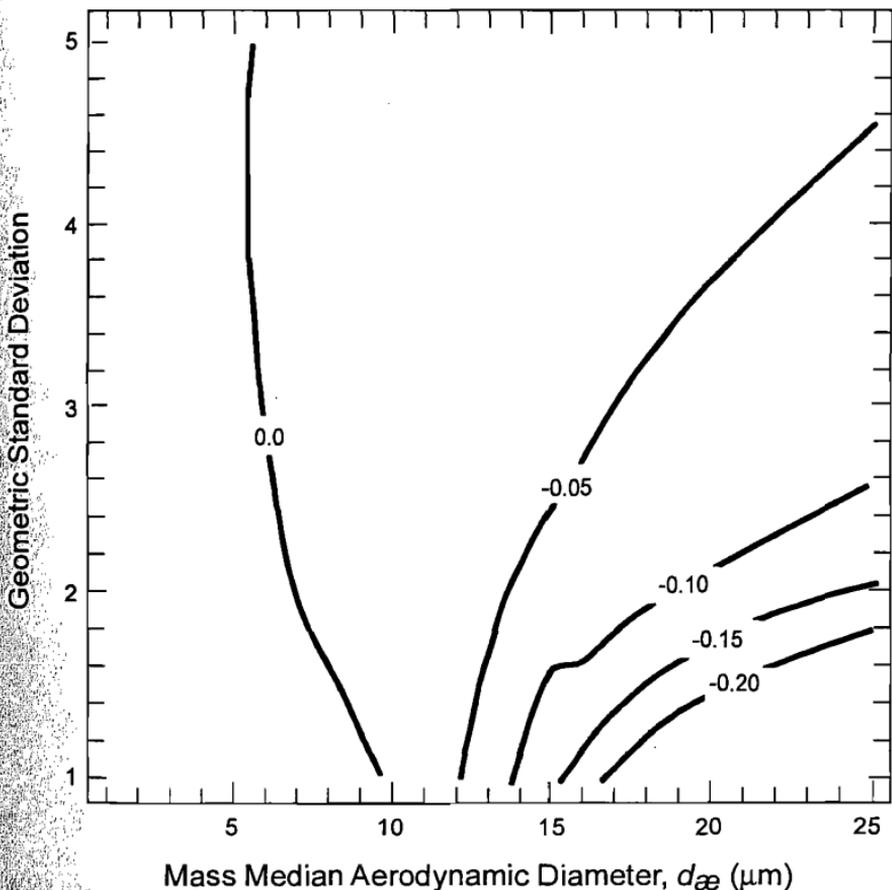


FIGURE 7.2. A bias map of PM₁₀ sampling convention relative to the thoracic convention. The contours represent lines of constant bias, ranging from 0.0 to 0.2.

TABLE 7.1. Principal types of filter media for sampling

Type	Notable Characteristics
Cellulose fiber	Initial efficiency low, increasing rapidly with loading, hygroscopic, low ash, high purity
Glass fiber	Low pressure drop, produces sulfate and nitrate artifacts, tolerates high temperatures, high loading capacity
Quartz fiber	Brittle, low artifact formation
Plastic fiber	Lower pressure drop than membranes, poor mechanical strength
Membrane	Available in cellulose nitrate, cellulose triacetate, polyvinyl chloride, Nylon, polypropylene, polyimide, polysulfone, Teflon and silver. High filtration efficiency, particles retained near surface, useful for microscopy, X-ray fluorescence analysis, clog easily
PVC membrane	Low hygroscopicity
Teflon membrane	Low mechanical strength, high purity, low artifact formation
Silver membrane	Useful for X-ray diffraction analysis, organic analysis
Nucleopore	Unique straight-through pores allow penetration of particles smaller than pores, solid particles can bounce and penetrate. Polycarbonate material is strong, non-hygroscopic, high purity. Useful for microscopy, X-ray fluorescence

Note: For more information on filter media, see Lippmann (1995).

The TPM criterion requires aerodynamic separation or sizing of the particles. In practice this is frequently accomplished by inertial impaction, which implies the need for precautionary measures against excessive penetration due to particle bounce and reentrainment (Rao and Whitby, 1977; Wesolowski *et al.*, 1977). Also, deagglomeration can lead to excessive penetration (John *et al.*, 1991).

The choice of filter media for particle collection depends on the physical and chemical properties of the particles to be sampled, the sampler, and the analysis to be performed. Important filter characteristics (see Table 7.1) are the collection efficiency (John and Reischl, 1978; Lippmann, 1995), the pressure drop, mechanical strength, hygroscopicity, chemical purity and possible artifact production (gas-to particle conversion). The filter holder must seal securely against air leakage around the filter or to the outside. The sampler should have a flow controller to stabilize the flowrate as the pressure drop increases with filter loading or the environmental temperature changes.

The current state of knowledge of fluid and aerosol mechanics permits the basic design of TPM samplers from first principles. However, some important details involve empiricism. So the performance

of the prototype sampler must be verified in the laboratory. Inlet testing involves the use of aerosol generators in wind tunnels. Subsequently, the samplers are tested in the field to investigate real-world problems. Obviously, samplers vary in the degree to which they approach ideal performance. So the user must choose a sampler with acceptable performance which also satisfies the particular requirements of the application.

7.2 THORACIC SAMPLING DEVICES

The selection of a TPM sampler is made, first, by considering whether personal or environmental sampling is required and, second, by the flowrate. The first commercial TPM personal sampler was the so-called "personal environmental monitor" (or PEM) (Marple, 1989; Buckley *et al.*, 1991) which was aimed at personal exposure based on the PM₁₀ environmental standard. Additional personal samplers have only recently been developed subsequent to the adoption of the sampling conventions. Although there has therefore been relatively little evaluation of these devices, it is an area of active research. Because of the limited availability of TPM samplers, the discussion here and Table 7.2 include samplers that vary in the degree with which they satisfy the TPM criteria. It also includes samplers which at present exist only as prototypes and so are not yet commercially available. The user must make an informed choice of sampler depending on the application and actual availability.

Environmental TPM samplers can be classified into low volume ($Q < 20$ L/min), medium volume (20 L/min $< Q < 150$ L/min) and high volume ($Q > 150$ L/min) samplers (see Table 7.2). Samplers are currently available in each of these ranges in part as a result of the sampler development program of the EPA in support of its particulate standard for ambient air (EPA, 1987; John, 1993).

Several personal samplers were designed for the collection of the thoracic particulate mass fraction. A personal environmental monitor developed by Marple has a single, sharp impactor cut at $d_{ae} = 10$ μm (Marple, 1989; Buckley *et al.*, 1991). The PEM (see Figure 7.3) collects particles larger than 10 μm on an oiled substrate, and the thoracic fraction is collected on a downstream filter. The CIP10 sampler used in France was modified to include the measurement of thoracic as well as respirable dust (Fabries *et al.*, 1989). This sampler uses the inertia of air within a rotating head to draw air through porous foam that collects the thoracic fraction. Thus, the air moving device is integral to the particle size-selector of the CIP10 sampler. Particles smaller

TABLE 7.2. Thoracic particulate fraction samplers

Flowrate	Sampler
A. Personal	
1.6 L/min (not verified)	Kenny-Gussman (Kenny and Gussmann, 1997)
2 L/min	PEM (Marple, 1989)
2 L/min	Vincent foam sampler (Vincent <i>et al.</i> , 1993)
5.2 L/min	CIP 10 (Fabries <i>et al.</i> , 1987)
2 L/min	Cascade impactors (Gibson <i>et al.</i> , 1987; Rubow <i>et al.</i> , 1987; Hering, 1995)
B. Low	
6 L/min	NBS portable ambient aerosol sampler (Bright and Fletcher, 1983) IOM thoracic sampler (Vincent <i>et al.</i> , 1993)
7.4 L/min	Vertical elutriator (Görner <i>et al.</i> , 1994)
16.7 L/min	Dichotomous sampler (Loo <i>et al.</i> , 1976) Dzubay <i>et al.</i> , 1977; Loo <i>et al.</i> , 1979)
16.7 L/min	Monocut (John <i>et al.</i> , 1983)
< 20 L/min	Cascade impactors (Hering, 1995)
C. Medium	
113 L/min	Wedding 4 CFM ambient aerosol sampler (Wedding <i>et al.</i> , 1983)
113 L/min	McFarland (McFarland and Ortiz, 1982)
20–150 L/min	Cascade impactors (Hering, 1995)
D. High	
1133 L/min	Size-selective inlet for Hi-Vol (McFarland <i>et al.</i> , 1984; Wedding and Weigand, 1985)
> 150 L/min	Cascade impactors (Hering, 1995)

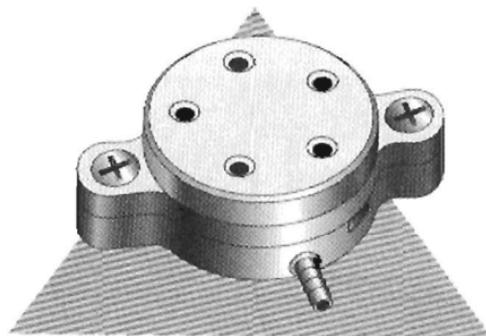


FIGURE 7.3. Personal environmental monitor (PEM) sampler from SKC Inc.

than about $d_{ae} = 1 \mu\text{m}$ are not collected by the foam in the CIP10, resulting in a negative bias for aerosols containing fume-sized particles. Vincent and co-workers developed a combined inhalable/thoracic/respirable sampler using the inlet of the IOM sampler and separating the fractions using sections of porous plastic foam (Vincent *et al.*, 1993). The respirable dust is collected on a filter, while the larger fractions are measured by analyzing the dust collected on the foam sections. For the latter, it should be noted that each foam material being considered for use should be tested for moisture absorption prior to its use in this application. Kenny and Gussman (1997) developed a cyclone (see Figure 7.4) that collects the thoracic fraction at about 1.6 L/min or the respirable fraction at 4.2 L/min. The initial study estimated the flowrate to achieve the TPM curve by use of a model. Further experimentation is needed to obtain an accurate measurement of the optimal flowrate for TPM measurement. However, the performance curve for this cyclone appears to have a slope that matches the thoracic curve more accurately than most other cyclones, and Kenny and Gussman give an empirical equation for selecting cyclone dimensions for operating at other flowrates (for the same particle size fraction). Except for the IOM sampler, none of the personal thoracic samplers have been tested in wind tunnels to measure inlet efficiency at moderate to high windspeeds.

Person-wearable cascade impactors have been developed which can be used to sample the thoracic fraction. Ramachandran and Vincent (1997) discuss data inversion techniques for retrieving the inhalable, thoracic and respirable fractions from the raw data obtained using such instruments. The Andersen 290 sampler (Graseby-Andersen, Smyrna, GA), also known as the "Marple" (named after its originator) can be used with up to eight stages having cut points from $d_{ae} = 0.5$ to $20 \mu\text{m}$ (Marple and McCormack, 1983). The impaction stages each have six radial slots that are staggered relative to subsequent stages. This allows a jet plate to be the collection substrate for the previous stage. Two of the stages have cuts at $d_{ae} = 9.8$ and $3.5 \mu\text{m}$ respectively, allowing nearly direct measurement of the thoracic and respirable fractions. The overall design is compact and light and has been used extensively for measuring particle size distributions in the workplace. A similar device, the *personal inhalable dust spectrometer* (PIDS) (SKC Inc., Eighty-Four, PA), was developed in the UK for making personal exposure size distribution measurements (Gibson *et al.*, 1987). This device has so far been used to estimate inhalable, thoracic and respirable dust fractions in coal mines (Mark *et al.*, 1988), the primary lead production industry (Spear *et al.*, 1998), and elsewhere.



FIGURE 7.4. GK2.69 cyclone from BGI Inc. This device is designed to sample TPM at 1.6 L/min and RPM at 4.2 L/min.

A person-wearable cascade virtual impactor, called the "RespiCon," has been introduced (TSI Inc., St. Paul, MN) that collects IPM, TPM, and RPM simultaneously (see Figure 7.5). At present, however, no independent evaluations of this device have been published.

In the low volume category, the cotton dust vertical elutriator operating at 7.4 L/min was originally designed to have a 50% cut point at $d_{ae} = 15 \mu\text{m}$ based on vertical flow in the body of the sampler. But due to jet formation at the inlet and internal turbulence, it has been found by separate researchers to have an actual measured 50% cut point at $d_{ae} = 12 \mu\text{m}$ (Claassen, 1981) and $10.7 \mu\text{m}$ (Fabries *et al.*,

1989). This particular sampler has been used for over twenty years to estimate the exposures of cotton dust workers at risk from byssinosis.

Also in the low volume category, the dichotomous sampler (Loo *et al.*, 1979) is a virtual impactor having a flowrate of 16.7 L/min. The thoracic particulate mass fraction is selectively passed through the inlet; the virtual impaction stage further fractionates the aerosol into coarse and fine fractions with a cut point at $d_{ae} = 2.5 \mu\text{m}$.

A small portable sampler, operating at 6 L/min, has been developed by Bright and Fletcher (1983). The thoracic cut is provided by the inlet, which contains a single stage impactor with an oil-soaked porous plate to suppress particle bounce. A second particle size cut is made at $d_{ae} = 3 \mu\text{m}$ by a Nuclepore filter (the sampler could be operated without it). The collection efficiency of the sampler's inlet, determined in a wind tunnel, is more sensitive to windspeed than the other samplers described above, but the performance may be adequate for relatively calm air or air which is slowly moving relative to the worker.

For thoracic aerosol mass sampling alone, the virtual impaction stage of the dichotomous sampler is unnecessary. The fractionating inlet can be coupled directly to a filter to form a sampler that has been called the "Monocut." Such a sampler using the earlier dichotomous sampler inlet with a $d_{ae} = 15 \mu\text{m}$ cut point performed well (John *et al.*,



FIGURE 7.5. The "RespiCon" sampler for IPM, TPM and RPM from TSI, Inc., St. Paul.

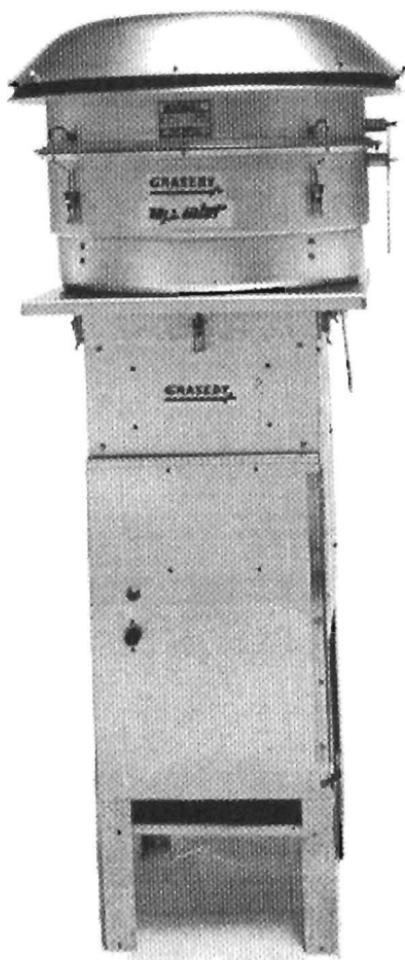


FIGURE 7.6. The high-volume PM_{10} sampler from Graseby-Andersen.

1983). The newer $10\text{-}\mu\text{m}$ cut point inlets should work equally well, affording an alternative to the dichotomous sampler.

Medium-volume samplers have been developed by McFarland and Ortiz (1982) and by Wedding *et al.* (1983). McFarland and Ortiz employed a sampler geometry that fractionates particles by a combination of impaction and sedimentation. The tortuous air path also suppresses particle bounce. A high volume sampler based on a similar geometry, called the "size-selective inlet" (SSI), converts a standard "hi-vol" sampler into a thoracic sampler (McFarland, *et al.*, 1979) (see Figure 7.6). The SSI can be used only with glass fiber or quartz filters.



FIGURE 7.7. The Wedding high-volume PM_{10} sampler.

The Andersen "Dichot" inlet (Liu and Pui, 1981; Shaw *et al.*, 1983) is based on the design of McFarland *et al.* (1978). Independence of wind direction is assured by cylindrical symmetry about the vertical axis. Wind tunnel tests verified that the dependence of the sampling efficiency of this device on wind direction was within the EPA-prescribed tolerances (EPA, 1987). Another inlet, developed by Wedding *et al.* (1982) (see Figure 7.7), is cylindrically symmetric about the vertical axis but employs a cyclonic action produced by turning vanes

to achieve the thoracic fractionation. This inlet has also undergone wind tunnel testing with satisfactory results. A PM₁₀ sampler using a dichotomous inlet with the capability of sequential sampling onto multiple filters is also commercially available. So too are real-time PM₁₀ samplers using dichotomous inlets. One version, the "tapered element oscillating microbalance" (or "TEOM"), uses an inertial mass sensor (Patashnick and Rupprecht, 1991), another uses a beta gauge (Williams *et al.*, 1993).

In Figure 7.1, the measured sampling efficiencies of two of the samplers discussed above are compared to the TPM sampling criterion. For these, oleic acid particles were generated in wind tunnels operated at a windspeed of 0.56 m/s. The data points are seen to lie within the accepted range. These particular samplers were chosen for illustrative purposes only. A later chapter discusses the question of how to determine whether a sampler meets the performance criteria for TPM.

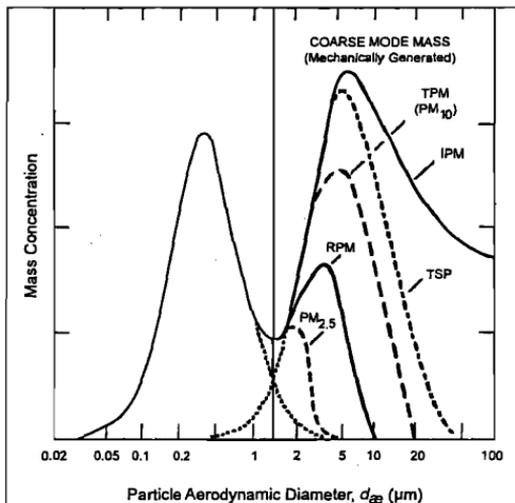
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PARTICLE SIZE-SELECTIVE SAMPLING OF PARTICULATE AIR CONTAMINANTS



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