27 Ambient Air Sampling

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INTRODUCTION

Goals for ambient sampling for suspended particulate matter include (1) determining compliance with air quality standards; (2) evaluating the extent and causes of high mass concentrations, deposition, and visibility impairment; (3) enhancing understanding of the chemical and physical properties of atmospheric pollution; (4) apportioning the chemical constituents of suspended particulate matter to their emitting sources; and (5) evaluating adverse health effects. A sampling system that serves one objective does not necessarily meet the needs of other objectives. Most notably, filter samplers designed to determine compliance with mass-based air quality standards have limited applicability to sampling for chemical characterization, hourly and daily sequential sampling, quantification of volatile aerosols, and particle sizing.

Most of the world's data on suspended particle mass concentrations are obtained by drawing a measurable volume of air through a particle-efficient filter over a 24 h period. The filter is weighed in a temperature- and humidity-controlled laboratory before and after sampling to determine the particle deposit. The deposit weight is then divided by the sample volume to determine the particle mass concentration. The U.S. Environmental Protection Agency (EPA) has designated federal reference methods (FRMs) for total suspended particulate (TSP), PM-10, and PM-2.5 (mass of particles with aerodynamic diameters less than approximately 40 µm, <10 µm, and <2.5 µm, respectively), applying this method to determine compliance with national ambient air quality standards (NAAQS).

Current U.S. NAAQS (U.S. EPA, 1997a, 1998a) for particulate matter are (1) annual average PM-10 less than 50 $\mu g/m^3$, averaged over 3 years; (2) 99th percentile 24 h average PM-10 less than 150 $\mu g/m^3$, averaged over 3 years; (3) annual average PM-2.5 less than 15 $\mu g/m^3$, averaged over 3 years; and (4) 98th percentile 24 h average PM-2.5 less than 65 $\mu g/m^3$, averaged over 3 years. The use of percentiles is intended to provide a more stable measure of high concentrations than annual maxima that were the basis for prior NAAQS (U.S. EPA, 1987). Three year averaging was adopted to moderate the effects of uncommon emissions or meteorological events that might bias the indicator during a single year. FRMs have been optimized for accurate mass measurements over 24 hour periods with sixth-day, third-day, and everyday sampling frequencies.

Although these FRMs are necessary for the compliance monitoring objective, they are not sufficient for other research objectives. Many of the components developed for FRMs

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and other sampling systems can be used to assemble filter samplers tailored to a specific need, and the new NAAQS have stimulated substantial innovation in this area. This chapter specifies the generic requirements of ambient aerosol sampling systems, tabulates available components that can meet these requirements, and describes particle sampling systems that can be purchased or assembled to address noncompliance research objectives. Citations and references direct the reader to more detailed information on each of these topics.

SAMPLING SYSTEM COMPONENTS

Figure 27–1 illustrates the components of a generic particulate sampling system. Air enters the inlet where particles larger than the desired size are removed. The air stream containing the remaining particles passes through a transfer tube to a denuder that transmits more than 95% of the particles while removing gases that are particle precursors or are in equilibrium with particulate ammonium nitrate and organic compounds that have high vapor pressures. Denuder surfaces naturally retain these gases, or they are treated with gas-absorbing chemicals. Inlet and transfer tubes also remove gases to varying degrees, depending on the materials of which they are made and the gases of interest. The air stream is directed through a holder containing a collection filter that transmits the gases and retains more than 99% of the particles in an even deposit across its surface. Flat membrane or fibrous filters are selected to be compatible with the intended analysis methods. One or more backup filters that naturally absorb, or that are treated with absorbing chemicals that react with specific gases, are located behind the particle filter to capture gases in the air stream or those that volatilize from particles collected on the first filter. A flow measurement or control device behind the filter monitors the volume of air sampled, and a pump of sufficient capacity to obtain the desired flow rates draws air through the system.

Although Figure 27–1 is simple in concept, its practical implementation requires a careful integration of the components specific to the sampling objectives. Denuders and backup filters are commonly omitted owing to their high maintenance and cost, as is the case for FRMs. In many situations the omission of denuders and backup filters results in minimal bias to mass measurements, but there are other conditions under which deviations from actual ambient concentrations are large. The nature of the aerosol being sampled, environmental sampling conditions (e.g., temperature and relative humidity), and the types of chemical analyses applied to the filter deposit must be evaluated before the first sample is taken.

Size-Selective Inlets

Inertial classifiers (see Chapter 10) are used as size-selective inlets to remove particles exceeding a specified aerodynamic diameter. Inlets are characterized by sampling effectiveness curves, showing the fraction of particles that pass through as a function of aerodynamic diameter. Sampling effectiveness is summarized by a 50% cut point (d_{50}), the diameter at which half of the particles pass through the inlet, and a slope (or geometric standard deviation), which is the square root of the ratio of the diameter of particles with 84% removal (d_{84}) to the diameter with a 16% removal (d_{16}). A slope of 1 indicates a step function that is impossible to obtain in practice. Many inlets have slopes of up to 1.5; the lower the slope, the "sharper" the cut point.

Sampling efficiency quantifies the mass fraction of suspended particles passing through the inlet and depends on the particle size distribution as well as the inlet sampling effectiveness. Sampling efficiency is obtained by integrating the product of sampling effectiveness and aerosol mass–size distribution across all expected particle sizes (Watson et al., 1983; Wedding and Carney, 1983). Because many ambient mass–size distributions peak near 10 μm, but are

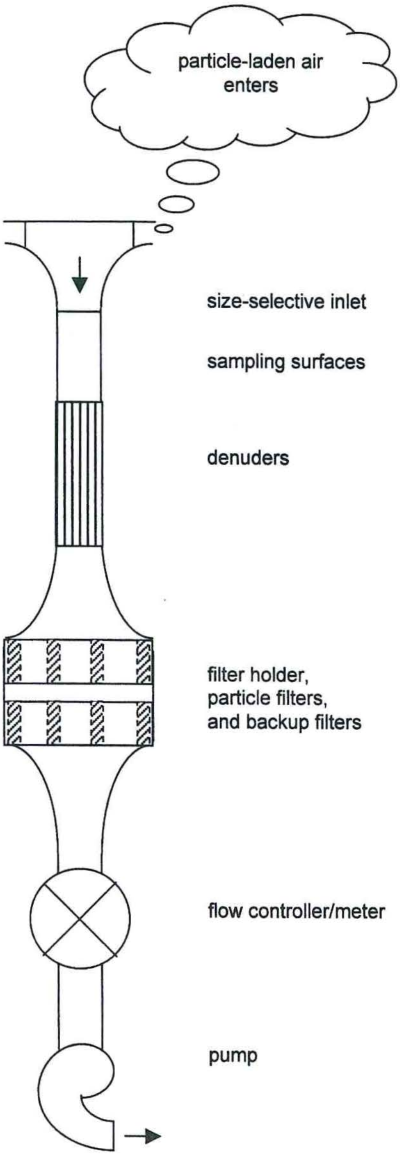

Fig. 27–1. Components of an aerosol sampling system.

at a minimum near 2.5 μm, changes in PM-10 inlet effectiveness curves have a larger effect on mass concentrations than do changes in PM-2.5 inlet effectiveness curves (Lundgren and Burton, 1995). PM-10 inlets with sharper cut points collect less mass than those with broader cut points. The dependence of mass on the sampling effectiveness slope is much smaller for PM-2.5 inlets.

Inlet transmission characteristics must be independent of wind speed and wind direction. The sampling efficiency of the rectangular peaked-roof inlet of the high-volume (hi-vol) sampler for TSP had a variable sampling effectiveness in response to wind direction and speed (Wedding et al., 1977; McFarland et al., 1980). PM-10 inlets have been symmetrically constructed to minimize these changes. Wind speeds and directions do not appreciably affect PM-2.5 cut points.

Chow (1995a), Hering (2001), and Chapter 10 describe a large number of size-selective inlets used for ambient, workplace, and personal exposure sampling. Table 27–1 identifies and describes several PM-10 and PM-2.5 inlets currently in use for ambient air sampling. Some of these are later models of those listed by Chow (1995a), although they are based on the same principles. Inlets of the same design are offered by different vendors under different names, and Table 27–1 attempts to classify these as a single design. Cut points and slopes of effectiveness curves are those given by the manufacturer, although different results are reported by independent tests from several of the citations. These differences result from a variety of test methods, the condition of the inlet at the time of the test, and experimental uncertainty. For PM-10 and larger size-cut inlets, large wind tunnels (McFarland et al., 1977; Wedding et al., 1977; Ranade et al., 1990) are used to examine changes over wind speeds of ~2 to 24 m/s.

Table 27–1 entries are grouped by the size separation principles (see Chapters 9 and 10) of direct impaction, impaction/elutriation, virtual impaction, cyclonic flow, and selective filtration. Direct impaction systems consist of one or more jets positioned above an impaction plate. The impactor dimensions are selected to allow particles with diameters exceeding the desired cut point to strike and adhere to the plate. Elutriator/impactors employ a vertical barrier before or after the impactor to further remove large particles by gravitational settling. When the particle settling velocity exceeds the upward air velocity, the particle is not transmitted through the inlet. The ***URG**** vertical elutriator precedes the impaction surface, while the other inlets in this category contain vertical transport pathways and sharp bends after the impaction surface. Virtual impactors replace the impaction surface with an opening that directs the larger particles elsewhere, sometimes to another filter; these impactors eliminate re-entrainment and separate PM-10 into PM-2.5 and coarse (PM-10 minus PM-2.5) fractions. Cyclones impart a circular motion to air entering the inlet with tangential vanes. This air enters a cylindrical or conical tube, and the centripetal force of the circular motion moves particles toward the walls of this tube and then to a collection hopper or "grit pot." Selective filtration uses filters or other porous materials that have consistent and measurable particle transmission properties. The Nuclepore etched polycarbonate filters (***CCO***) with 8 μm pores collect particles by interception and impaction in the vicinity of the pores to provide 50% cut points for particles between 2 and 3 μm at flow rates of ~$1.7 \times 10^{-4}\,m^3/s$ [10 L/min]. A ~0.4 μm pore size filter is place behind the 8 μm filter to collect the transmitted particles.

Mathai et al. (1990), in evaluating differences between several samplers used in western U.S. visibility studies, concluded that most differences between mass measurements from collocated sampling systems are caused by differences in inlet characteristics. These differences caused major controversies with respect to the development of PM-10 reference methods in the early 1980s (several of the citations in Table 27–1 address these controversies). Design theories for impactors (Marple and Willeke, 1976), virtual impactors (Loo and Cork, 1988; Sioutas and Koutrakis, 1998), and cyclones (Kenny and Gussman, 1997; Kenny et al., 2000) are in good agreement with empirical tests. However, as inlets become loaded with particles, their sampling effectiveness can change.

Impaction inlets require frequent cleaning and oiling or greasing to prevent impacted particles from disaggregating or becoming re-entrained in the air flow (e.g., John et al., 1991a,b). Even with the highly tactile surface used in the Well Impactor Ninety Six (WINS) PM-2.5 impactor/elutriator required in FRM samplers, Pitchford et al. (1997) observed a cone-like buildup that extended above the oil surface after 3 to 4 days of sampling. The tip of this could easily break off and become entrained in the air flow to the filter. Kenny et al. (2000) found that the WINS cut point shifted from 2.5 to 2.15 μm after its well was loaded with Aloxite

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* Appendix I for full maunfacturer addresses referenced to the italieiced three-letter codes.

TABLE 27–1. Size-Selective Inlets and Characteristics for Ambient Aerosol Sampling

Name, Manufacturer, References[a]	Inlet ID: d_{50} (μm), Slope[b], Flow (L/min)	Description and Comments
Impactors		
Airmetrics Minivol Impactor (***ARM***) (Turner, 1998; Wiener and Vanderpool, 1992)	MV10: ~10, NA, 5 MV2.5: ~2.5, NA, 5	Machined polymeric propylene plastic or machined aluminum. PM-10 and PM-2.5 inlets are used in series for PM-2.5 sampling. Apiezon vacuum grease dissolved in hexane is pipetted onto impaction surfaces before each sample to minimize re-entrainment
Harvard Sharp Cut Impactors (***ADE***) (Marple et al., 1987; Turner et al., 2000)	MST123: 1, 1.22, 23 MST24: 2.5, 1.02, 4 MST210: 2.5, 1.06, 10 MST220: 2.5, 1.25, 20 MST104: 10, 1.11, 4 MST1010: 10, 1.09, 10 MST1020: 10, 1.06, 20	Machined aluminum that can also be coated with FEP Teflon
Impactor/elutriators		
Andersen (***GRA***) hi-vol PM-10 (John and Wang, 1991; Kashdan et al., 1986; McFarland et al., 1984; Ranade et al., 1990; Wedding et al., 1985)	G1200: 9.7, 1.4, 1, 133	Anodized spun aluminum with a single stage of opposing jets. The body is hinged to facilitate cleaning and re-greasing of the removable impaction plate that is sprayed with an aerosol adhesive after cleaning. The G1200 was preceded by the SA-320 single-stage PM-15 inlet and the SA321A and SA321B dual stage and SA321C single stage PM-10 inlets that are no longer sold but may still be in use. It is not entirely clear which sampling effectiveness tests apply to each of these inlets
Andersen (***GRA***) med-vol PM-10 (Olin and Bohn 1983)	SA254I: 10, 1.6, 113	Spun aluminum with 10 impactor jets and a central elutriation tube. The inlet can be disassembled for cleaning. The SA254I was preceded by the SA254, or "Blue Head" owing to the color of its enamel coating, that was nearly impossible to disassemble for cleaning
Andersen (***BGI***, ***GRA***, ***R&P***, ***URG***) Flat Top PM-10 (McFarland et al., 1978; Van Osdell and Chen, 1990; Wedding et al., 1980; Lai and Chen, 2000)	246B Flat Top: 10.2, 1.41, 16.7	Machined aluminum with one impactor tube and three vertical elutriator tubes. Rain drops are blown into the inlet beneath the flat top and accumulate on the impaction surface. Water exits through a small drain attached to a bottle on the outside of the inlet. The top unscrews for cleaning the impactor surface
FRM (***BGI***, ***GRA***, ***R&P***, ***URG***) Louvered PM-10 (U.S. EPA, 1997a)	Louvered PM-10: 10, NA, 16.7	Same materials and design as the SA246B but with a top that curves over the inlet bug screen to minimize the entry of windblown raindrops. Also available with a PTFE Teflon® coating
URG, Inc. (***URG***) Elutriator Impactors	25A: 1–2.5 & 10, NA, 4 22D: 2.5, NA, 1–20 30KN: 2.5, NA, 1–20	FEP Teflon coated glass with an elutriator tube preceding the impactor. The impactor plate is after the jet at the top of the elutriator, facing the ground
EPA (***BGI***, ***GRA***, ***R&P***, ***URG***) Well Impactor Ninety Six (U.S. EPA, 1997a; Kenny et al., 2000)	WINS: 2.48, 1.18, 16.7	Machined aluminum well with a detachable impactor jet. The impaction surface consists of a 37 mm quartz fiber filter immersed in 1 mL of vacuum pump oil to minimize particle re-entrainment over multiple sampling days between cleaning

(continued)

TABLE 27–1. *Continued*

Name, Manufacturer, References[a]	Inlet ID: d_{50} (μm), Slope[b], Flow (L/min)	Description and Comments
Virtual Impactors		
Andersen (***GRA***) Dichotomous Virtual Impactor (McFarland et al., 1978)	SA241: 2.5, NA, 16.7	Anodized machined aluminum integrated into the dichotomous sampler body. $2.8 \times 10^{-5}\ \text{m}^3/\text{s}$ [1.7 L/min] goes through the virtual impactor to the coarse particle filter, with the remaining flow directed to the PM-2.5 filter. The unit can be disassembled for cleaning, but care must be taken to reassemble it such that the PM-10 inlet tube is over the virtual impaction tube rather than over the bypass zone to the PM-2.5 filter
VAPS (***URG***) Virtual Impactor	VAPSVI: 2.5, NA, 32	FEP Teflon coated aluminum. $3.3 \times 10^{-5}\ \text{m}^3/\text{s}$ [2 L/min] goes through the virtual impactor to the coarse particle filter with two streams of $2.5 \times 10^{-4}\ \text{m}^3/\text{s}$ [15 L/min] each directed to PM-2.5 denuders and filters
Harvard (***R&P***) Particle Concentrator (Sioutas et al., 1994a,b, 1997, 1998)	H1000: 2.5, NA, 1000	Particles are accelerated through a 0.32 × 280 mm rectangular nozzle and impact on an oil-soaked filter. Flow rates can be adjusted with different slit lengths. Particles less than 0.1 μm are diverted from the flow and not collected
Cyclones		
Wedding (***GRA***, ***TEI***) IP$_{10}$ (Wedding and Weigand, 1985)	IP10: 9.6, 1.37, 1133	RFPS-1087–062. Spun aluminum inlet cleaning port on top of inlet
Andersen (***GRA***)/California Air Industrial Hygiene Laboratory Cyclone (AIHL) (John and Reischl, 1980)	SA3.68: 2.7, 1.16, 24 SA3.68: 2.3, 1.18, 28	Machined aluminum used on Andersen RAAS and IMPROVE speciation samplers
Sharp Cut Cyclones (***BGI***, ***GRT***, ***R&P***) (Kenny et al., 2000)	BGI1.062: 1.0, 1.21, 3.5 BGI2.229: 1, 1.17, 16.7 BGISCCA: 2.5, 1.19, 16.7 GRT1.118: 2.5, NA, 2 GRT2.141: 2.5, 1.24, 6.8 R&P1.829: 2.5, 1.23, 5	Nickel-plated aluminum. The cyclone has a horizontal design, with the hopper at one end. Particles are collected over the lower surface of the vortex cone and in the grit pot. A cap at the end facilitates regular cleaning
Bendix/Sensidyne 240 Medium Volume Cyclone (Chan and Lippmann, 1977; Mueller et al., 1983)	B240: 2.5, 1.7, 113	Welded steel that can be coated with PFA Teflon. Operates in a vertical position with a hopper on the bottom
URG, Inc. (***URG***) Cyclones (Moore and McFarland, 1993; Kenny et al., 2000)	30EHB: 1, 1.34, 16.7 30EN: 2.5, 1.32, 10 30EH: 2.5, 1.35, 16.7 30ED: 2.5, NA, 3 30EC: 3.5, NA, 28 30ENB: 10, NA, 16.7 30EA: 10, NA, 28.3	FEP Teflon coated aluminum. Cyclones can be operated vertically and horizontally

TABLE 27–1. *Continued*

Name, Manufacturer, References[a]	Inlet ID: d_{50} (µm), Slope[b], Flow (L/min)	Description and Comments
Stacked Filters		
Nuclepore Filters (***CCO***) (Spurny et al., 1969; Cahill et al., 1977; Parker et al., 1977; John et al., 1983; Droppo et al., 1995)	N8: ~2, NA, 10	Large pore (8 µm) polycarbonate filters remove particles >2 to 3 µm by interception and impaction. Small particles pass through the pores to another filter. Extensively used in U.S. visibility networks during the 1970s and early 1980s
CIS Foam (***BGI***) (Vincent et al., 1993)	CIS10: 10, NA, 3.5 CIS4: 4, NA, 3.5 CIS25: 2.5, NA, 3.5	A polyurethane foam with different thickness transmits particles with varying degrees. Used for personal sampling

[a] Refer to Appendix I for manufacturer codes and information. References cited provide more complete descriptions of the inlet and tests of its collection and transmission properties. This is a relatively complete list of inlets that are commercially available for ambient air sampling and are currently in use. It complements, rather than replaces, lists published elsewhere.

[b] Inlet IDs have been assigned for this table to facilitate later reference. These are contractions of the manufacturer's part number, where possible. "d_{50}" is the aerodynamic diameter at which half of the particles pass through the inlet and the other half deposit in the inlet, as determined by presentation and detection of known particle sizes. Slope = $\sqrt{d_{84}/d_{16}}$, the square root of the particle diameter ratios for inlet penetration at 84% and 16%. Values given are those provided by the vendor for the specified flow rate, and these may differ from those reported in some of the citations owing to different test and inlet conditions. "NA" in the slope position indicates that this value was not available.

dust. The U.S. EPA (1998b) recommends cleaning the WINS after five 24 h samples. Kenny et al. (2000) determined that the Sharp-Cut Cyclone had a sampling effectiveness curve similar to that of the WINS with a much larger collection capacity; no shift in cut point was found with increased loadings.

Table 27–1 shows that different PM-10 and PM-2.5 inlets have different cut points. The U.S. EPA (1987) required a PM-10 cut point of 10 ± 0.5 µm for FRMs. The Wedding IP-10 inlet had a 9.6 µm cut point, while the original SA-321A inlet had a 10.2 µm cut point. This difference made the Wedding inlet more attractive to some users because sampling with a lower cut point decreased the PM-10 measured and lowered the probability of exceeding the NAAQS. The Andersen SA-321A (***AND***) was replaced by the SA-321B with a 9.7 µm cut point to meet this competition; new impactor jets were also provided for the SA-321A inlet. Although both of these were replaced with the G1200 inlet described in Table 27–1, many of the original inlets are still in use, and it is difficult to distinguish them from each other by their appearance.

Inlet flow rates fall into ranges appropriate for high-volume (~0.017 m^3/s [1000 L/min]), medium-volume (~0.0017 m^3/s [100 L/min]), low-volume (~1.7×10^{-4} to 3.3×10^{-4} m^3/s [10 to 20 L/min]), and mini-volume (<8.3×10^{-5} m^3/s [5 L/min]) sampling systems. A massive volume (>0.17 m^3/s [10,000 L/min]) inlet and sampler has also been developed (Fitz et al., 1983) to obtain several grams of suspended particles for health studies. The medium- and high-volume inlets are especially useful when samples are taken in parallel on several substrates because flow rates can be kept high enough to obtain an adequate deposit for analysis.

Sampling Surfaces

Anodized aluminum is the most commonly used material for inlets and transfer tubes. Copper, stainless steel, conducting plastic, and glass are also used as transfer tubes in some systems. Nonconducting plastic surfaces and glass can acquire an electrical charge that might attract suspended particles to them, though the dimensions of most ambient sampling systems are sufficiently large that this attraction is negligible (Rogers et al., 1989).

Certain materials absorb or react with gases and particles, thereby removing them from the air stream (John et al., 1986; Hering et al., 1988). This is especially the case for nitric acid vapor, which sticks to nearly everything. Removal of nitric acid in an inlet or sampling duct can change the gas–particle equilibrium of particulate ammonium nitrate, causing this substance to dissociate into ammonia and nitric acid gases (Stelson and Seinfeld, 1982). This is also true for some volatile organic species.

John et al. (1986) tested different materials with respect to their affinity for nitric acid and found that surfaces coated with perfluoro alkoxy (PFA) Teflon can pass nitric acid with 80% to 100% efficiency. These results were confirmed by Neuman et al. (1999), who found that aluminum, stainless steel, nylon, glass, fused silica, silane-coated glass, silica-coated steel, and stainless steel tubes removed more than 80% of nitric acid over a 0.3 m tube length. PFA Teflon surfaces should be washed with a dilute solution of nitric acid to season them before sampling. Several of the Table 27–1 inlets and their associated transfer tubes are available with a Teflon coating to minimize removal of reactive gases from the air stream.

Denuders

Denuders (Kitto and Colbeck, 1999) are placed in the air stream to remove more than 95% of selected gases while transmitting more than 95% of the particles (see Chapter 19). Molecules in the gas phase diffuse rapidly to the surfaces of the denuder, while particles having lower diffusion coefficients pass through the denuder to the filter. The denuder surface can be coated with chemicals that retain the gas molecules. When properly treated and handled, the denuders can be extracted in a solvent for laboratory analysis to determine average gas concentrations over the sampling period. The denuder difference method (Shaw et al., 1982) operates two samplers in parallel, one with and one without a denuder. Gases and particles are collected on filters that naturally adsorb or are impregnated with gas-absorbing chemicals and are subsequently analyzed for the desired chemical compounds; the gas concentration is the difference between the nondenuded and denuded concentrations.

Tubular, parallel plate, annular, honeycomb, and cloth denuders have been used, the ***URG*** glass and Teflon-coated annular denuders being the most common. A tubular denuder (Gormley and Kennedy, 1949) is a single tube or a bundle of tubes. A bundle of tubes >0.3 m long removes gases at typical flow rates; a single tube is only practical for low (less than approximately 8.3×10^{-5} [5 L/min]) flow rates, depending on the diffusion coefficient of the gases. A parallel plate denuder (Eatough et al., 1993) is formed from rectangular panels with a small gap between them. An annular denuder (Possanzini et al., 1983; Allegrini et al., 1987; Koutrakis et al., 1988) consists of a solid center inside a tube of slightly larger diameter. Particles pass through the annulus between the two surfaces while the gases diffuse to them. ***URG*** annular denuders create several annuli by positioning tubes of slightly larger diameters inside one another. The honeycomb denuder (Koutrakis et al., 1993; Sioutas et al., 1994c, 1996) is a thick piece of glass or aluminum through which many tiny holes have been drilled or etched. These denuders can be as short as a few centimeters, depending on flow rate, and can be treated as part of a filter stack. Fitz and Motallebi (2000) evaluated loosely woven rayon fabrics that can be soaked in different chemicals to remove gases. Their tests show that PM-2.5 is collected with >95% efficiency through the fabric while nitric acid is quantitatively recovered from extraction and analysis of the fabric. These fabric denuders can be handled as if they were another component of a filter pack.

Kitto and Colbeck (1999) describe many of the coatings applied to denuders to retain specific gases. Magnesium oxide, sodium fluoride, sodium chloride, and sodium carbonate have been used to retain nitric acid. Ammonia has been removed with oxalic acid, tungstic acid, phosphoric acid, phosphorous acid, and citric acid. Organic gases have been removed by quartz filter strips (Fitz, 1990), carbon-impregnated filters (Eatough et al., 1993), finely ground

XAD resin (Gundel et al., 1995), and potassium hydroxide (Lawrence and Koutrakis, 1994).

The most common use of denuders is to obtain an accurate measurement of particulate ammonium nitrate, which often volatilizes during sampling as temperatures exceed 288 to 293 K [15° to 20°C] (Hering and Cass, 1999; Stelson and Seinfeld, 1982; Watson et al., 1994). Accurate nitrate measurements are obtained by removing nitric acid from the sample stream, collecting nitrate particles on a filter, and recovering volatilized nitric acid on an absorbing backup filter. John et al. (1988), while examining methods to estimate nitric acid dry deposition, found that an anodized aluminum denuder had a large capacity for nitric acid removal and developed one for the dichotomous sampler. Fitz and Hering (1996) determined that an anodized aluminum annular denuder (Chow et al., 1993) became saturated after 3 years of monitoring at a photochemically active southern California location; re-anodizing the surfaces was sufficient to restore its capacity.

Filter Holders

A filter holder consists of a frame that seals the edges of the filter so that air is forced to pass through its porous center. A porous support grid downstream of the filter keeps it from being sucked through the holder by the pump vacuum. Lippmann (2001) and Chow (1995a) describe several different filter holders. Filter holders should mate to the sampler and to the flow system without leaks, be composed of inert materials that do not absorb reactive gases, create a uniform particle deposit on the filter surface, have a low pressure drop across the empty holder, accommodate the sizes of commonly available air sampling filters (e.g., 37 or 47 mm), and be durable and reasonably priced. They should also allow for filter transport to and from the field sampler without contamination, minimize adherence or damage to the filter, and minimize removal of the substances being measured.

Filter holders are configured as in line or open faced. In-line holders concentrate particles in the center of the substrate, and this biases the results when analyses are performed on portions of the filter (Chow et al., 1994; Chow, 1995b). Inhomogeneous support grids, or grids with a low porosity (<50%), may also result in nonuniform deposits. Filter holders should be open faced or preceded by a diffusion zone that disperses the particles before collection.

The PM-2.5 FRM (U.S. EPA, 1997a) specifies the dimensions and materials for 47 mm diameter filter holder rings made of Delrin plastic with a stainless steel grid into which 100 μm diameter holes are etched 100 μm apart. Nuclepore (***CCO***) polycarbonate plastic filter holders accommodate 25, 37, and 47 mm diameter filters and are adaptable to many sampling systems. Each one costs a few tens of dollars, making it possible to purchase many of them for laboratory loading and unloading. Nuclepore filter holders are modified by drilling out the outlet hole to reduce flow resistance. Multiple extender sections can be used to stack several filters in series without having them touch each other. The rubber O-ring in the Nuclepore holder has been found to raise the carbon blank levels on quartz fiber filters, an artifact that can be eliminated by replacing the rubber with a Viton O-ring (Tombach et al., 1987). Little information is available on the extent to which the filter holder material affects the quantification of reactive gases. Filter holders made of or coated with Teflon are used to minimize losses of nitric acid. Several stainless steel filter holders are available, many of them with in-line connectors. These are usually expensive and absorb volatilized nitrate (Neuman et al., 1999). The speciation samplers described below usually have specially constructed filter holders that are specific to those samplers.

Filters

Filter media are judged for specific applications based on their mechanical stability, chemical stability, particle or gas sampling efficiency, flow resistance, loading capacity, blank values, artifact formation, compatibility with analysis methods, cost, and availability. Chow (1995a), Lippmann (2001), and Chapter 9 describe various types of filters, while Chapter 11 shows how filter characteristics relate to desired chemical analyses. Some filters are also used for optical transmission or reflection to measure particle absorption (Horvath, 1997) or to distinguish organic from elemental carbon (Birch and Cary, 1996; Chow et al., 2001), filter color and internal scattering properties important for these purposes.

U.S. EPA (1987) filter specifications for PM-10 compliance sampling include 0.3 μm dioctyl phthalate (DOP) sampling efficiency in excess of 99.9%, weight losses or gains due to mechanical or chemical instability of less than a 5 μg/m^3 equivalent, and alkalinity of less than 25 μEq/g to minimize absorption of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). These are only the minimal requirements for samples that require chemical analyses. A sample from each batch (50 to 100 filters) must always be tested for contamination before sampling with that batch; high and variable blank levels typically invalidate subsequent quantification on particle deposits.

The most commonly used filter media for atmospheric particle and gas sampling are Teflon membrane, quartz fiber, nylon membrane, cellulose fiber, Teflon-coated glass fiber, etched polycarbonate membrane, and glass fiber. None of these materials is perfect for all purposes.

Ringed-Teflon membrane filters (***GEL***, ***WHA***) consist of a thin, porous polytetrafluoroethylene (PTFE) Teflon sheet stretched across a polymethylpentane ring; the thin membrane collapses without the ring, and the filter cannot be accurately sectioned into smaller pieces. The white membrane is nearly transparent and has been used to estimate light absorption (Campbell et al., 1995). PTFE Teflon is very stable, absorbing negligible water or gases. It has inherently low contamination levels, but chemicals have been found in some batches by acceptance testing. This filter is commonly used for mass and elemental analyses. The thin membrane is especially appropriate for X-ray and proton-induced fluorescence (XRF and PIXE) analyses that obtain elemental concentrations while leaving the filter intact. Teflon is hydrophobic, and emulsifiers (such as ethanol) need to be added for water-extraction methods for ion analysis. Carbon cannot be measured on Teflon membranes because of its high carbon content, although aerosol carbon has been inferred from hydrogen measurements (Kusko et al., 1989). Because of their high flow resistance and need for a ring support, high-volume flow rates are not attainable, though it is possible to obtain flow rates required for low-volume and medium-volume inlets. A variation on this filter consists of a PTFE Teflon membrane mounted on a woven PTFE mat instead of a support ring. This filter has a higher density, but it can be obtained in larger sizes for higher volume samples. The membrane and the mat sides are similar in appearance, and care must be taken to prevent mounting it upside down, particles being drawn through the mat rather than onto the surface of the membrane in this case.

Quartz fiber filters (***PAL***, ***WHA***) consist of a tightly woven mat of quartz filaments. These filters meet requirements in most categories. Quartz fiber filters adsorb hydrocarbon gases during sampling (McDow and Huntzicker, 1990), as determined by placing a clean quartz filter behind a Teflon filter (Turpin et al., 1994). The extent to which this is a positive bias due to gas adsorption or a negative bias due to the collection of volatilized particles is uncertain (Cui et al., 1997, 1998). Quartz filters are baked at ~117 °K before sampling to remove adsorbed organic vapors. Blank levels are high and variable for several elements (especially aluminum and silicon), though newer formulations are cleaner than earlier formulations. These filters are widely used for ion and carbon analyses. The greatest drawback of quartz fiber filters is their fragility; they require extremely careful handling for accurate mass measurements. The Whatman QM/A quartz fiber filter contains a 5% borosilicate glass binder that minimizes its friability. This filter is often used in high-volume PM-10 samplers for mass measurements. The Pallflex 2500 QAT-UP filter is pure quartz and undergoes a distilled water washing (thus the "UP," or "ultrapure," designation).

Nylon membrane filters consist of thin sheets of porous nylon and are used almost exclusively for the collection of nitric acid. Nylon filters have high flow resistance that increases with filter loading. These filters passively absorb nitric acid, depending on how long they have been exposed to an acid-rich environment, and they should be washed in a sodium bicarbonate solution followed by distilled water before use in the field. They also absorb small amounts of ammonia (Masia et al., 1994) and sulfur dioxide (Sickles and Hodson, 1999), thereby limiting their use in front of filters intended to collect these gases. Gelman Nylasorb (***GEL***) is most commonly used for ambient air sampling.

Cellulose fiber filters (***WHA***) consist of a tightly woven paper mat. These filters meet requirements in most categories with the exception of sampling efficiency and water vapor artifacts. Particle penetration for submicrometer particles have been observed, but these are highly dependent on the filter weave (Biles and Ellison, 1975). Cellulose fiber is hygroscopic and requires precise relative humidity control in the filter processing environment to obtain accurate mass measurements (Demuynck, 1975). These filters have low chemical blanks except for carbon, and they can be used for elemental and ionic analyses of the deposit. Cellulose fiber filters can be impregnated with gas-absorbing compounds, similar to those described above for denuders, and located behind more efficient particle-collecting filters. Nitric acid, ammonia, sulfur dioxide, and nitrogen dioxide gases are determined by this means. The most commonly used cellulose fiber filter is Whatman 41.

Teflon-coated glass fiber filters (***PAL***) imbed a Teflon slurry onto a loosely woven glass fiber mat. These filters meet requirements in all categories except blank element and carbon levels. Though a small amount of nitric acid absorption has been observed (Mueller et al., 1983), it is tolerable in most situations. These filters are used for ion analyses and for specific organic compounds, but not total carbon analyses owing to their Teflon coating. The most commonly used Teflon-coated glass fiber filters are Pallflex TX40HI20 and T60A20 (***PAL***).

Etched polycarbonate membrane filters (***CCO***) are constructed from a thin polycarbonate sheet through which pores of uniform diameter have been produced by radioactive particle penetration and chemical etching. Depending on pore size, these filters have variable particle collection properties, as noted in Table 27–1, that are used for size-specific measurements. These filters are nearly transparent and have been used to estimate light absorption (Horvath, 1993). Polycarbonate membrane filters have low elemental blank levels and are appropriate for elemental and ion analysis. They are the best filter media for single-particle analysis by electron microscopy because particles are easily distinguished from the flat filter surface. These filters are not used for thermal evolution carbon analysis owing to their carbon composition. The filters hold an electrostatic charge that influences mass measurements unless substantial effort is invested in discharging them with a small radioactive source (Engelbrecht et al., 1980). Electrostatic discharging is good practice for all filter media, even though others do not retain as much charge as the polycarbonate membranes. The Nuclepore 8.0 and 0.4 μm filters are most commonly used in ambient aerosol sampling. While the 0.2 μm pore size filter provides a higher sampling effectiveness, its higher flow resistance requires a large pressure drop across the filter for $>1.7 \times 10^{-4}\,m^3/s$ [10 L/min] flow rates.

Glass fiber filters (***WHA***) are obsolete and should not be considered for use in particle sampling. These filters consist of a mat of borosilicate glass filaments. The high alkalinity of these substrates causes sulfur dioxide, nitrogen oxides, and gaseous nitric acid to be adsorbed (Coutant, 1977; Spicer and Schumacher, 1979), thereby biasing mass and chemical measurements. Blank levels for most elements of interest are extremely high and variable (Witz et al., 1983). As with quartz filters, glass fiber filters adsorb organic carbon vapors that are measured as particulate carbon during analysis. Unlike quartz filters, the sodium in glass fiber filters catalyzes the combustion of elemental carbon at lower temperatures, causing biases in the quantification of the light-absorbing carbon fraction (Lin and Friedlander, 1988). Although their cost per filter is lower than that of the other filters, the savings are not worth the expense of compromised data.

Flow Measurement and Control

The quantity of air per unit time must be precisely measured and controlled to determine particle concentrations and to maintain the size-selective properties of the inlet. Manual volumetric, automatic mass, differential pressure volumetric, pump speed volumetric, and critical orifice volumetric flow control principles have been applied to aerosol samplers.

Manual control is accomplished when the operator initializes a setting, such as a valve adjustment, and then relies on the known and constant functioning of sampler components, such as pumps and tubing, to maintain flows within specifications. Flow rates that are set manually change as the collection substrate loads up and presents a higher flow resistance. For most concentrations ($<200\,\mu g/m^3$), the flow will not change by more than 10% during sampling, and the average of flow rates taken before and after sampling provides an accurate estimate of the actual flow.

Mass flow controllers use temperature sensors that measure the heat transfer between two points in the gas stream. To a first approximation, the heat transfer is proportional to the number of gas molecules passing between the two points, and hence the mass flow controller is able to sense the mass flux. An electronic feedback loop compensates for temperature and pressure variations of the gas and the sensing probe. Wedding (1985) estimated potential differences in excess of 10% between mass and volumetric measurements of the same flow rates, depending on temperature and pressure variations.

Differential pressure volumetric flow control maintains constant pressure across an orifice (usually a valve that can be adjusted for a specified flow rate) by a control valve located between the filter and the orifice. When the pressure between the filter and the valve increases, as it does when filters load up, the valve control opens to allow more air to pass.

The pump volumetric method changes the dc current to a variable speed pump in response to a flow sensor at the pump inlet or exhaust. As the flow rate decreases with filter loading, more current is supplied to the pump, thereby increasing its speed and throughput.

A critical orifice consists of a small circular opening between the filter and the pump. When the downstream pressure at the minimum flow area downstream of the orifice is less than 53% of the upstream pressure, the air velocity attains the speed of sound and it will remain constant, regardless of increased flow resistance. Critical orifices provide stable flow rates, but they require large pumps and low flow rates (typically less than $3.3 \times 10^{-4}\,m^3/s$ [20 L/min] with commonly available pumps) to maintain the high pressure difference. Wedding et al. (1987) developed a "critical throat" that uses a diffuser arrangement to recover much of the energy expended in back pressure behind a critical orifice. This design allows higher flow rates to be obtained with a given pump.

Flow Movers

Air is passed through the sampling substrates by means of a vacuum created by a pump. Monteith and Rubow (2001) and Chow (1995a) describe commercially available air pumps and their capacities and operating principles. High-volume samplers typically use a radial flow fan that rotates curved blades at a high velocity to move substantial quantities of air. The original fans for the TSP hi-vol were manufactured for household vacuum cleaners and do not tolerate large pressure drops caused by complex inlets, tightly woven filters, and stacks of filters and denuders. Hinds (1999) shows that a 20 kPa [15 cm Hg] resistance across the hi-vol fan reduces the flow to zero. Diaphragm and piston pumps convert the rotary motion of a driveshaft into the movement of a flexible membrane or piston that draws air through an opening on the backside of the filter and pushes it out through another opening at the pump exit. Hinds (1999) shows diaphragm pumps capable of 80 kPa [60 cm Hg] vacuum when flow is reduced to zero. The rotary pump turns carbon vanes within a circular chamber with an offset driveshaft. The centripetal force of the vanes seals their ends against the chamber surface. Air enters when the volume between vanes is large and exits when the volume decreases where the driveshaft is closest to the chamber walls. These pumps can create a vacuum of up to 93 kPa [70 cm Hg] (Hinds, 1999) and can pull more than 0.0017 m^3/s [100 L/min] through a stack of filters with high flow resistance. Carbon vane pumps are noisy, and their exhaust must be filtered as the carbon vanes are continually abrading into small particles.

SAMPLING SYSTEMS

Monteith and Rubow (2001), Hering (2001), and Chow (1995a) describe a large number of systems for ambient aerosol sampling. Chow (1995a) cites many researchers who have assembled different components (Fig. 27–1) to achieve research objectives beyond those of compliance monitoring. Typical research needs are

- Simultaneous sampling on multiple filters for different analyses: Parallel samples on Teflon membrane and quartz fiber filters are needed for simultaneous mass, elemental, ionic, and carbon analyses.
- Higher sample volumes for shorter sampling intervals: Samples of 3 to 6 h duration are needed to evaluate the diurnal evolution of chemical components, and higher flow rates are often needed to obtain enough sample for laboratory quantification.
- Gas and particle phase measurements of volatile species: Accurate measurements of ammonium nitrate and some volatile organic compounds require denuders and backup filters. Gas phase precursors collected by denuders are also needed when equilibrium models are used to determine which precursors limit particle formation.
- Multiple sequential samples without operator intervention: It is not practical or cost-effective for an operator to change samples every few hours for diurnal sampling or at midnight for everyday sampling, thereby requiring an automated sampler changer.
- Several particle size fractions: Multiple inlets, in series or in parallel, are needed to separate particles into different size fractions, with PM-10, PM-2.5, and coarse (PM-10 – PM-2.5) being the most widely used fractions.

Many of these systems are based on FRMs developed for PM-10 or PM-2.5 compliance monitoring. Table 27–2 specifies sampling systems that have attained FRM or federal equivalent method (FEM) status with their EPA designation numbers and *Federal Register* announcements.

High-volume samplers designated for PM-10 compliance monitoring are being replaced by low-volume samplers that are similar for PM-10 or PM-2.5; the PM-2.5 include a WINS inlet behind the PM-10 inlet. Most of the newer units control the volume throughout sampling by measuring the mass flow and then adjusting this for ambient temperature and pressure conditions. These units are controlled by a microprocessor that also logs flow rate, temperature, and pressure over periods as short as 1 min throughout the sampling period.

Chow et al. (1996) outline various strategies for applying FRMs to chemical speciation, including duplicate samplers with different filter media, collocated high volume and dichotomous samplers with quartz and Teflon filters, and supplementing a permanent FRM sampler with temporary "mini-vol" samplers using complementary filter packs and size-selective inlets.

The Oregon Department of Environmental Quality PM-10 Sequential Filter Sampler (SFS) has proved itself very adaptable for a variety of purposes. The transfer tube has been filled with aluminum denuder tubes, and quartz filters have been backed with sodium chloride or nylon filters to measure nitrate accurately. Two filter packs can be sampled in parallel with Teflon membrane and quartz fiber filters for different analyses. Flow rates from

TABLE 27–2. PM-10 and PM-2.5 Federal Reference Methods and Federal Equivalent Methods[a]

Sampler, EPA FRM Designation, Federal Register Notice	Description
Federal Reference Methods	
Andersen (***GRA***) RAAS10-100 PM-10 Single Channel PM-10 Sampler, RFPS-0699-13064, FR 33481, 06/23/99 RAAS2.5-100 PM-2.5 Sampler, RFPS-0598-119, 63 FR 31991, 06/11/98 RAAS10-200 PM-10 Audit Sampler, RFPS-0699-131, 64 FR 33481, 06/23/99 RAAS2.5-200 PM-2.5 Audit Sampler, RFPS-0299-128, 64 FR 12167, 03/11/99	Louvered PM-10 $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] inlet with anodized aluminum sampling surfaces. FRM Delrin 47 mm ringed filter holder. Variable speed diaphragm pump. Volumetric flow measured by dry test meter at pump outlet that modulates pump speed. PM-2.5 samplers include a WINS impactor in the sample line after the PM-10 inlet. Audit samplers are of similar design but more compactly packaged for periodic collocated sampling with a permanent unit
Andersen (***GRA***) RAAS10-300 PM-10 Sequential Sampler, RFPS-0699-132, 64 FR 33481, 06/23/99 RAAS2.5-300 PM-2.5 Sequential Sampler, RFPS-0598-120, 63 FR 31991, 06/11/98	Similar to RAAS10-100 and RAAS2.5-300, but with a circular tray into which six 47 mm ringed filter holders can be located. A timer rotates the tray at preset intervals, and a plunger compresses the holder into the sample flow stream
BGI, Inc. (***BGI***) PQ100 FRM PM-10 Sampler, RFPS-1298-124, 63 FR 69625, 12/17/98 PQ200 or PA200A PM-10 FRM Sampler, RFPS-1298-125, 63 FR 69625, 12/17/98 PQ200 or PQ200A PM-2.5 FRM Sampler, RFPS-0498-116, 63 FR 18911, 04/16/98	Louvered PM-10 $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] inlet with anodized aluminum sampling surfaces. FRM Delrin 47 mm ringed filter holder. Variable-speed double diaphragm pump controlled by mass flowmeter adjusted every minute to ambient temperature and pressure for volumetric equivalent. The PM-2.5 unit is identical to the PM-10 sampler with addition of a WINS impactor after the PM-10 inlet. The audit sampler (PQ200A) is of similar design but more compactly packaged for periodic collocated sampling with a permanent unit. These units can operate for 24 h on a battery
Rupprecht & Patashnick (***R&P***) Partisol FRM 2000 PM-10 Sampler, RFPS-1298-126, 63 FR 69625, 12/17/98 Partisol FRM 2000 PM-2.5 Sampler, RFPS-0498-117, 63 FR 18911, 04/16/98 Partisol 2000 Audit Sampler, RFPS-0499-129, 64 FR 19153, 04/19/99	Louvered PM-10 $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] inlet with anodized aluminum sampling surfaces. Delrin 47 mm ringed filter holder with a tapered edge for sequential version. Differential pressure flow control using a servo-controlled valve controlled by a mass flowmeter adjusted every minute to ambient temperature and pressure for volumetric equivalent. WINS inlet added for the PM-2.5 model. An optional insulating jacket is available for cold weather. The audit sampler is packaged for portability
Rupprecht & Patashnick (***R&P***) Partisol Plus 2025 PM-10 Sequential Sampler, RFPS-1298-127, 63 FR 69625, 12/17/98 Partisol-Plus 2025 Sequential Sampler, RFPS-0498-118, 63 FR 18911, 04/16/98	Same as R&P Partisol FRM 2000 samplers but with a pneumatically controlled sampler insertion mechanism. Up to 18 47-mm filter holders can be stacked in a tube and inserted into the sample stream at preset intervals
Rupprecht & Patashnick (***R&P***) Partisol 2000 PM-10 Sampler, RFPS-0694-098, 59 FR 35338, 7/1/94	Similar to *R&P* Partisol FRM 2000 samplers, but not meeting all PM-2.5 FRM specifications. The sampler consists of a hub unit with up to three satellite units for sequential sampling

TABLE 27-2. *Continued*

Sampler, EPA FRM Designation, Federal Register Notice	Description
Thermo Environmental Instruments, Inc. (***TEI***) 605 "CAPS" PM-2.5 Sampler, RFPS-1098-123, 63, FR 58036, 10/29/98	Similar to the above FRM PM-2.5 samplers, but never made commercially available. Included here for completeness
URG Corp. (***URG***) URG-MASS100 Single PM-2.5 Sampler, RFPS-0400-135, 65 FR 26603, 5/8/2000 URG-MASS300 Sequential PM-2.5 Sampler, RFPF-0400-136, 65 FR 26603, 5/8/2000	Louvred PM-10 $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] inlet with anodized aluminum sampling surfaces followed by WINS impactor with FRM Delrin 47 mm filter holders. Variable-speed diaphragm pump with volumetric flow measured by a dry test meter at the pump outlet that modulates pump speed. The sequential system contains a circular tray holding six filters. Filters are rotated into the sampling section at preset intervals and compressed into the flow stream with a mechanical plunger
Andersen/GMW (***GRA***) 1200 High-Volume PM-10 Sampler, RFPS-1287-063, 52, FR 45684, 12/01/87, 53 FR 1062, 01/15/88 321-B High-Volume PM-10 Sampler, RFPS-1287-064, 52 FR 45684, 12/01/87, 53 FR 1062, 01/15/88 321-C High-Volume PM-10 Sampler, RFPS-1287-065, 52 FR 45684, 12/01/87, 53 FR 1062, 01/15/88	Andersen G1200 $1.9 \times 10^{-2}\,m^3/s$ [1130 L/min] single-stage greased PM-10 inlet and 8 × 10 inch framed filter holder with steel screen support. Spun and sheet aluminum surfaces. Flow controlled by mass flowmeter that varies the speed of a blower motor. Also available with a critical throat, thus two designation numbers. The 321B and 321C were identical, but equipped with earlier versions of the G1200 that did not open for cleaning. These are no longer sold, but many are still in service. When the inlet is replaced with a peaked roof, this sampler is identical to the hi-vol TSP sampler that is widely used throughout the world
Andersen/GMW ***(GRA)*** SA241 and SA241M Dichotomous PM-10/PM-2.5 Sampler, RFPS-0789-073, 54 FR 31247, 07/27/89	Flat top SA246B PM-10 inlet and dichotomous virtual impactor for $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] flow rates. Made from machined aluminum. Flow rates are controlled by a differential pressure regulator and a single-speed diaphragm pump. Ten percent of the fine particles are sampled on the coarse particle filters, and corrections must be made to the coarse particle measurements to compensate
Oregon DEQ PM-10 Sequential Filter Sampler, RFPS-0389-071, 54 FR 12273, 03/24/89	SA245I PM-10 inlet at $1.9 \times 10^{-3}\,m^3/s$ [113 L/min] on top of a ~0.4 m aluminum transfer tube that leads to a large removable plenum. 47 mm Nuclepore polycarbonate filter holders are located in quick disconnect fittings under the plenum. Solenoid valves beneath the plenum are switched by a timer for up to 12 sequential samples without operator intervention. Flow rates are controlled by a differential pressure regulator and a GAST 1022 or 1023 carbon vane vacuum pump with filtered exhaust
Wedding 600 ***(TEI)*** High-Volume PM-10 Sampler RFPS-1087-062, 52 FR 37366, 10/06/88	Wedding IP-10 cyclonic flow inlet followed by an 8 × 10 inch filter frame with flow controlled by a critical throat before the blower fan. Larger capacity blowers are used owing to the larger pressure drop across the throat

(continued)

TABLE 27–2. *Continued*

Sampler, EPA FRM Designation, Federal Register Notice	Description
Federal Equivalent Methods (FEM)	
Met One ***(PAC)*** BAM 1020, GBAM 1020, BAM 1020-1, and GBAM 1020-1 PM-10 Beta Attenuation Monitors, EQPM-0798-122, 63 FR 41253, 08/03/98	Flat-top 246B style $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] PM-10 inlet, aluminum transfer tubes. Particles are collected on a quartz fiber filter tape each hour. The attenuation of electrons from a radioactive source is related to mass loading by calibration to athin metal sheet. Hourly PM-10 measurements are possible
Andersen ***(GRA)*** FH621-N PM-10 Beta Attenuation Monitor, EQPM-0990-076, 55 FR 38387, 09/18/90	Similar in principle to Met One BAM, but with different radioactive electron source, tape advance unit, and data-processing system
Wedding ***(TEI)*** 650 PM-10 Beta Attenuation Monitor, EQPM-0391-081, 56 FR 9216, 03/05/91	Similar in principle to the Met One unit, but using a Teflon membrane tape. No longer available but included for completeness
Rupprecht & Patashnick ***(R&P)*** TEOM Series 1400/1400a PM-10 Monitors, EQPM-1090-079, 55 FR 43406, 10/29/90	Flat-top $2.78 \times 10^{-4}\,m^3/s$ [16.7 L/min] PM-10 inlet. Aluminum inlet, copper transfer tube, and a heater (323 K [50°C]) for PM-10 equivalence, but adjustable to other temperatures. $5 \times 10^{-5}\,m^3/s$ [3 L/min] of air is drawn through a 12.7 mm diameter quartz filter on a hollow glass tube that vibrates. The vibration frequency changes as the filter mass increases with aerosol deposit, and this is related to mass concentration. Five minute averages are attainable in ambient air. A bypass is available to collect the remaining $2.28 \times 10^{-4}\,m^3/s$ [13.7 L/min] of makeup air on a filter for other analyses

[a] Reference and equivalent method requirements are specified in 40 CFR Part 50 and by the U.S. EPA (1987, 1997b). FEMs are designated after collocated sampling with FRMs in several different environments.

3.3×10^{-4} to $1.9 \times 10^{-3}\,m^3/s$ [20 to 113 L/min] have been drawn through the filter packs, with a makeup flow supplying the difference to retain the inlet cut point. A Bendix 240 PM-2.5 replaces the SA254I inlet for PM-2.5 particle measurements. Chow et al. (1993) demonstrated how a variation of this sampler could be coated with PFA Teflon for sampling of reactive species.

The *I*nteragency *M*onitoring of *Pro*tected *V*isual *E*nvironments (IMPROVE) network has operated at U.S. National Parks and Monuments since 1987 to provide a long-term database of chemical concentrations in support of regional visibility assessment. The IMPROVE sampler (Eldred et al., 1988) consists of different modules controlled by a common sample switching system. Each module can be tailored to a specific type of measurement. The standard configuration acquires one PM-10 sample for gravimetric and proton-induced X-ray emission (PIXE) elemental analyses and three PM-2.5 samples, one on a Teflon membrane for gravimetric and PIXE analyses, one on a nylon membrane for ion analysis, and one on a quartz fiber filter for carbon analysis. Up to four sequential samples can be taken without operator intervention by using a timer to switch solenoid valves. Flow rates are controlled by critical orifices.

The initiation of a PM-2.5 speciation monitoring network by the U.S. EPA has resulted in several commercially available monitoring systems. Figure 27–2 shows a typical configuration

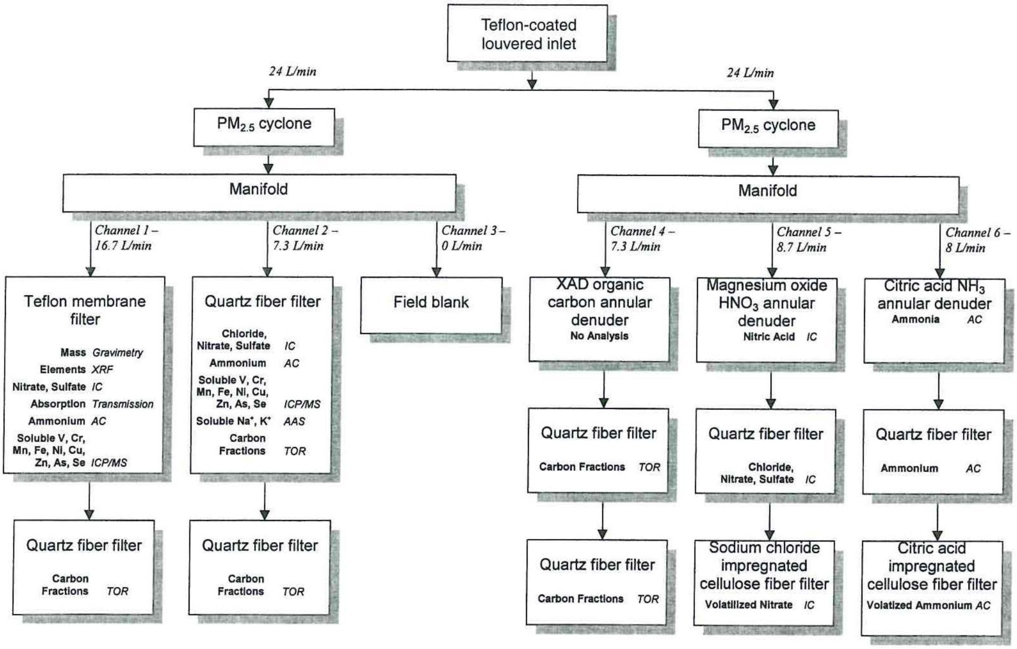

Fig. 27–2. Example sample configuration and analyses for the ***AND*** PM-2.5 RAAS. AAS, atomic absorption spectrometry; AC, automated colorimetry; IC, ion chromatography; ICP/MS, inductively coupled plasma/mass spectrometry; TOR, thermal/optical reflectance; Transmission, light transmission; and XRF, X-ray fluorescence.

based on the Reference Ambient Air Sampler (RAAS) speciation monitor (***GRA***). The sampler pulls $8 \times 10^{-4}\,m^3/s$ [48 L/min] through a louvered PM-10 inlet without impaction jets that removes very coarse particles to minimize maintenance of the PM-2.5 inlets. The flow is split and directed through two AIHL cyclone inlets into manifolds to which custom filter holders are attached. The filter holders are configured to contain up to three filters in series. Flow is controlled by critical orifices behind each filter with a vacuum created by a large rotary vane pump. The six available channels can be configured in different ways with flow rates varied by changing the orifices. All of the aluminum and stainless steel parts are coated with PTFE Teflon. Similar speciation monitors include the MASS and VAPS units from URG, Inc. (***URG***), the SASS from MetOne (***PAC***) and the Partisol 2300 and 2025 from Rupprecht & Patashnick, Inc. (***R&P***).

Good examples of aerosol samplers assembled from existing parts for specific purposes are represented by the "BOSS" (Brigham Young University Organic Sampling System) series of samplers (Eatough et al., 1993, 1995, 1996; Tang et al., 1994; Cui et al., 1997, 1998). These samplers allow filters to be located before and after denuders to evaluate the difference between artifact vapor adsorption and adsorption of volatilized particles. The PC-BOSS (Cui et al., 1998; Pang et al., 1998) uses the Harvard virtual impactor to concentrate particles for organic compound speciation. Annular denuders are used for inorganic species, while parallel plate denuders lined with carbon-impregnated filters are used for organic measurements.

Several cascade impactors have been developed to partition PM-10 into smaller size ranges on substrates suitable for chemical analysis. Each of these impaction methods uses low pressure stages to attain the lower particle cut points. The Low Pressure Impactor (LPI) (Hering et al., 1979a,b), the Davis Rotating-drum Unit for Monitoring (DRUM) (Raabe et al., 1988), the Berner impactor (Berner et al., 1979), and the Micro Orifice Uniform Deposit Impactor (MOUDI) (Marple et al., 1981) have been applied in ambient aerosol chemistry and visibility studies.

The low flow rate ($1.7 \times 10^{-5}\,m^3/s$ [1 L/min]) and nonuniform deposits, as well as substantial handling of the substrates, make the LPI impractical for many studies, though it was a precursor to the later impactors and provided valuable information for its time. The DRUM is a cascade impactor sampling at $5 \times 10^{-4}\,m^3/s$ [30 L/min] with low-pressure stages that acquires particle deposits in nine size ranges from 0.07 to 8.5 μm. Mylar impaction substrates are mounted on cylinders that rotate below the impaction jet so that particle deposits can be monitored as a function of time and analyzed by PIXE. The MOUDI and Berner cascade impactors are different in design but similar in function. These impactors operate at $5 \times 10^{-4}\,m^3/s$ [30 L/min] and have been used to acquire carbon and ion deposits on substrates that are amenable to chemical analysis by thermal evolution carbon analysis on aluminum foils and sulfate and nitrate analyses on Teflon substrates in at least eight size ranges from 0.03 to 15 μm.

SELECTING A SAMPLING SYSTEM

This chapter is not intended to identify every existing or every conceivable ambient aerosol sampling system. It concentrated on sampler components and sampler configurations in common use for which a body of knowledge and confidence have been established. Nevertheless, the practitioner is presented with many choices when confronted with the challenge of designing, installing, operating, and using the data from a sampling network to accomplish a specific purpose. The following steps can be used to select and implement a particle sampling system.

The first step is to clearly define monitoring objectives (see Chapter 7). Five types of monitoring goals were given as examples in the first part of this chapter. The specific objectives should be as comprehensive as possible. For example, networks of PM-10 and PM-2.5 FRMs have been established for the immediate objective of determining compliance with NAAQS. If one or more of these samples exceeds a standard, then the objectives broaden to include source apportionment. Sampling that meets the first objective is typically inadequate for the source apportionment objective that requires a speciation monitor and chemical analysis.

The second step is to determine the particle size fractions, chemical analyses, sampling frequencies, and sample durations needed to address the objectives. More frequent samples, or samples taken at remote locations, may require a sequential sampling feature. Shorter sample durations may require a larger flow rate to obtain an adequate sample deposit for analysis.

The third step is to calculate the expected amount of deposit on the filter for each chemical species and compare it with typical detection limits for the analyses being considered. The types of analyses and size fractions desired affect the number of sampling ports and different filter media needed. Chow (1995a) specifies lower quantifiable limits for many analysis methods that can be translated into the needed aerosol deposit. Urban samples acquire adequate deposits for analysis with flow rates as low as $\sim 3.3 \times 10^{-4}\,m^3/s$ [20 L/min] for as low as 4 h durations, while samples at nonurban sites may require larger flows and sample durations to obtain an adequate deposit. The analytical laboratory should be involved at the sampler design stage to ensure compatibility between sampling methods, analysis methods, filter media, and detection levels for the analytical methods.

The fourth step is to create, adapt, or purchase a sampling system that provides the most cost-effective and reliable means of meeting the monitoring needs. It is also worthwhile to contact the authors of cited references for the noncommercial sampling systems because these investigators may be in a position to loan, rent, sell, or build one of these units to meet a special need. If no existing unit can fulfill all of the requirements, then it will be necessary to assemble different sampling components into a new configuration that will meet those needs.

The final step is to create or adapt an operating procedure that specifies methods and schedules for inlet cleaning, filter transport and handling, calibration and performance tests, and record keeping. Sampling systems described here have such written procedures that can serve as guides for specific procedures.

CONCLUSIONS

Ambient aerosol sampling systems have evolved in order to meet different monitoring needs. Sampler inlets, monitoring surfaces, denuders, filter media, filter holders, flow monitors, flow movers, and operating procedures have been developed and tested. These components have been integrated into various sampler configurations for application in dozens of studies. Using these components and the lessons learned from previous studies, it is possible to develop sampling systems customized to meet specific objectives without extensive original development and testing.

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