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Title:

Performance Evaluation of LANL Environmental Radiological Air Monitoring Inlets At High Wind Velocities Associated with Resuspension

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Los Alamos
NATIONAL LABORATORY

I. Introduction

Environmental air monitoring for radioactive particles is a vital component of radiation workers protection during certain contaminated site remediation activities, and in similar circumstances such as may occur in nuclear accident response in the environment. Air monitoring is also an indispensable component of site perimeter monitoring for demonstrating compliance with the Clean Air Act regulations, and related concerns for spread on contamination by wind of federal facilities sites such as LANL.

Assessment of health risks associated with airborne aerosols implies that measurements be made defining the aerosol characteristics, concentrations and exposures that contribute to, or simply correlate with, adverse health effects. The application of sampling and analytical systems for aerosols must recognize that particles exist modally as size distributions generated by distinctively different source categories and having distinctly different chemistries. Two important reasons for making size-specific aerosol measurements are (a) to relate the in-situ aerosol size characteristics to the potential lung deposition sites, and thus toxicity, and (b) separation of the size distribution modes to identify sources, transformation processes or aerosol chemistry.

Environmental air monitors contain some combination of a sampling inlet through which an aerosol sample must be drawn, and an aerosol particle-collecting device inside of the monitor (e.g., air filter). The sampling inlet design, which may vary considerably depending on the air monitor application, determines the aerosol sampling efficiency. The inlet effectiveness (sampling efficiency) of a sampler, E_s, is defined as the ratio of the aerosol concentration for given particle size determined by sampling with the inlet under defined test condition, C_s, to the aerosol concentration determined with an isokinetic probe sampling the same test aerosol conditions (assumed to be the true aerosol concentration), C_0 (McFarland and Ortiz, 1982):

$$E_s = \frac{C_s}{C_0}, \tag{1}$$

For example, the PM$_{10}$ (particles with an aerodynamic diameter less than or equal to a nominal 10 micrometers) air quality standard for particulate matter is defined by the U.S. EPA (EPA 1999a) as 50 micrograms per cubic meter (µg m^{-3}) annual arithmetic mean concentration, and 150 µg m^{-3} 24-hour average concentration measured in the ambient air. Only inlets fulfilling the performance parameters of PM$_{10}$ samplers prescribed in EPA (1999b) in terms of their sampling efficiency can be used for measurements to demonstrate compliance with the standard. One such performance parameter is the particle size transmission characteristic (i.e., sampler effectiveness) of the sampler inlet for particles in the PM$_{10}$ size range. Of particular importance is the particle size at which the sampler effectiveness is 50% (i.e., the DP$_{50}$ particle size cutpoint). Another variable of sampler inlet performance is its collection efficiency as a function of wind speed. Wind speed can greatly influence collection of larger size particles, and deposition losses on inlet surfaces. For example, collection efficiency for the Andersen 321A PM$_{10}$ inlet is shown in Figure 1 based on data by McFarland *et al.* (1984).

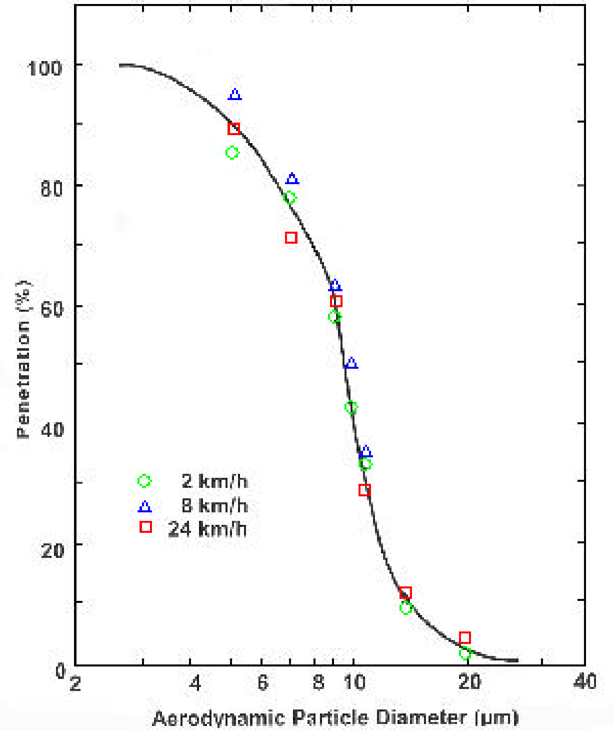

Figure 1. Collection performance (%penetration) versus aerodynamic diameter illustrating the influence of wind speed for the Andersen 321A PM$_{10}$ inlet (adapted from McFarland et al. 1984).

In light of the dependency of inlet performance on particle size and wind speed, the sampling inlet is a critical element in every aerosol measuring system. Inlets must be designed with care, and their performance characteristics under ambient conditions understood. An ideal inlet should be designed such that all particles of interest (including toxic components that might be present), enter and arrive at the collecting zone, while excluding precipitation (rain and snow), insects, plant matter, and other debris (Liu and Pui, 1981). And most importantly, the desired performance characteristics (DP$_{50}$ cut point, internal losses, etc.) of the inlet should be unaffected by wind speed up to the design limit. Unfortunately, there can be a conflict between the need to protect sampler components from rain and debris, and the need to obtain a representative sample of the aerosol of interest under environmental wind conditions. This can lead to design compromises that balance component protection against sampling performance. Examples of inlet designs found in ambient air monitoring instruments include the simple weatherproof louvered housing design used in typical hi-vol monitoring stations such as the AIRNET stations operated on and off-site at LANL, a modified flat plate University of Minnesota Inhalable Particulate Matter (UM IPM) air sampling inlet design used with and without such protective housings for resuspension studies by ESH-4, and the more elaborate size-selective inlet design developed for the LANL/Canberra alpha Environmental Continuous Air Monitor (alpha-ECAM) to be deployed by the Accident Response Group (ARG). For a given inlet design, inlet efficiency E_s will be a function of particle size, wind speed, and sampling flow rate, and sometimes the orientation of the inlet with respect to the wind direction. High efficiency is easily achieved for particles having a small aerodynamic diameter (AD<2.5 µm). For larger particles and high wind speeds, good inlet efficiency can only be obtained by careful design (Liu and Pui, 1981).

The matter of what constitutes acceptable performance depends on the goals of the air monitoring application. The alpha-ECAM for ARG applications, for example, is designed to provide worker respiratory protection information on resuspended Pu contaminated soil particles during recovery operations. Thus its inlet is designed to have good performance for inhalable particles (AD∗15 µm) under a wide range of wind speeds. For resuspension monitors, the aim is to measure environmental levels of airborne radionuclides associated with wind-blown soil particles. These data can be used not only for detecting elevated air concentrations, but also to identify and control sources of migrating contaminants such as contaminated soil at the waste disposal sites. In the case of contaminant migration, particulate radioactivity that can be transported by wind is typically associated with soil particles having aerodynamic diameters (AD) ranging from sub-micron size up to 15 µm or 30 µm. Since particulate resuspension is a threshold phenomenon, not arising until wind speeds of 5–10 m s^{-1} have been achieved, the assessment of environmental inlet efficiency should be carried out under wind speed conditions in the range 5-15 m s^{-1} so that the combination of particle size and inlet velocity conditions can be evaluated. Generating such test conditions is particularly challenging and not easily done in small wind tunnels. That may be why data on inlet efficiency of these types of environmental monitoring inlets at high wind speed is practically non-existent. The requirements for aerosol inlets performance evaluation, and basic factors that should be considered for such tests were analyzed by Mark *et al.* (1992). Their recommendation combined with the EPA procedures (EPA 1999b) were the basis for the test program of the commonly used inlets in the LANL under ambient air conditions. It was determined that a high-velocity, large cross-section aerosol wind tunnel was needed to meet the objectives of the test program.

II. Inlets' tested in the study

1. Open-face-inverted Inlet

Open-face-inverted inlets for atmospheric sampling consist of a simple filter holder operating face down, as shown in Fig. 2. These two particular filter holders (HI-Q model RVPH-102 or RVPH-25)[1], are for filters of 102-mm and 47-mm diameter, respectively. Both open-face inlets are operated at a flow rate of 113 L min^{-1}. Inverted inlets have been previously tested by the Southern Research Institute (SRI) (Bird *et al.*, 1973). Their DP$_{50}$ efficiencies were found to be 39%, 30% and 20% for 5 μm AD particles at wind speeds of 2.6, 12.8 and 18.9 m s^{-1}, respectively. For 12-μm AD particles the DP$_{50}$ efficiencies were 35%, 12%, and 35% at the same wind speeds. In this project the inverted inlets were used to established baseline performance in field test with uncharacterized ambient aerosols.

Figure 2. 102-mm and 47-mm filter holders as inverted open-face atmospheric aerosol samplers.

2. University of Minnesota (UM) IPM Inlet

To correct the deficiency of open-face inverted inlets in terms of their aspiration efficiency, Liu and Pui (1981) proposed a new, modified inlet capable of better performance under high wind conditions. This new Inhalable Particulate Matter (IPM) inlet has a flange (2.4-cm wide) surrounding the filter holder, and circular top to keep out rain and snow. This inlet was evaluated in a wind tunnel at various wind speeds up to 2.5 m s^{-1}. The aspiration efficiency of the inlet for 8.5- and 11-μm AD particles was about 100±10%. However, it was less (about 80%) for 13.4 μm AD particles at higher wind speed.

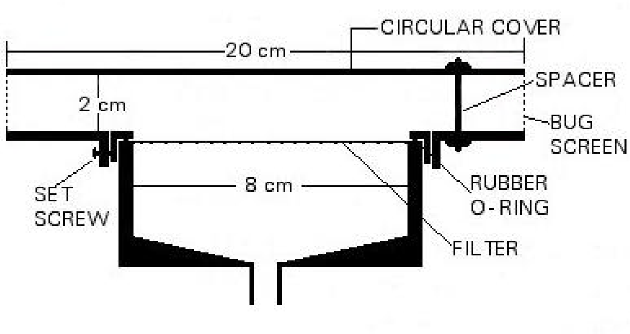

Figure 3. Schematic diagram of the LANL/CSU inlet based on design by Liu and Pui (1981)

The modified UM IPM filter was reproduced for the LANL/Colorado State University (CSU) collaborative project on airborne transport of contaminated soils via resuspension. The LANL/CSU inlet diagram and physical realization are presented in Figs. 3 and 4. The inlet uses a commercial 102-mm diameter filter holder (Hi-Q Model RVPH-102) with custom-made parallel plate flanges. The inlet slot is protected with a coarse metal anti-bug screen. The typical airflow rate use for this inlet is 113 L min^{-1}.

Figure 4. LANL/CSU inlet based on design by Lui and Pui (1981).

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[1] HI-Q Environmental Products Company, 7386 Trade St, San Diego, CA 92121

3. AIRNET Air Sampling Station

Figure 5. AIRNET Station

For compliance purposes the LANL Air Quality Group (ESH-17) operates network of more than 50 environmental air stations (called AIRNET) to sample radionuclides in ambient air. A typical station is shown in Fig. 5 with its housing open for sample changeout. Each sampler is equipped with a pump and sample collectors located inside a 122-cm high x 61-cm deep x 76-cm wide (48"x 24"x30") weather housing with dual louvered openings on all four sides of the enclosure[2]. A polypropylene filter mounted in a filter holder is used to collect a particulate matter sample (for gross alpha/beta counting, gamma spectroscopy and radiochemical determinations). A silica gel cartridge in parallel with the filter is used to collect a water vapor sample for tritium determination. The oil-less pump generates a sample flow rate of about 113 L min^{-1} through the filter and 0.2 L min^{-1} through the cartridge inside the housing, which therefore is the inlet of this sampler (Fig 6). Instrumentation within the housing records the total time the pump ran during the sample period and the flow in the particle and the tritium sampling trains. With the recent heightened interest in the health effects of beryllium, some AIRNET filter samples are being analyzed for this contaminant as well as radioactivity.

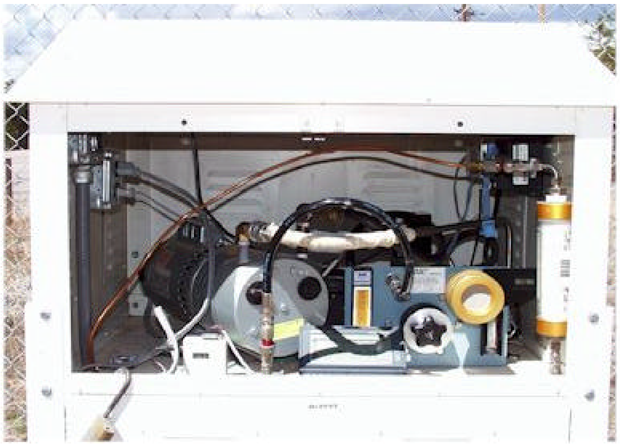

Figure 6. Interior of AIRNET station (visible filter holder, tritium cartridge and pump)

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[2] SAIC RADeCO Model 210B; SAIC, Safety and Security Instruments 16701 West Bernardo Drive, San Diego, CA 92127

4. PM$_{10}$ Graseby-Andersen Inlet

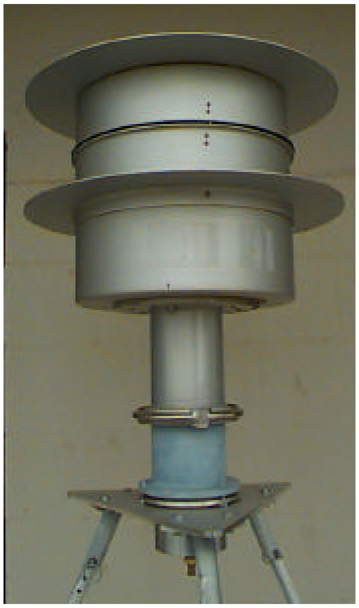

Figure 7. G-A PM10 inlet

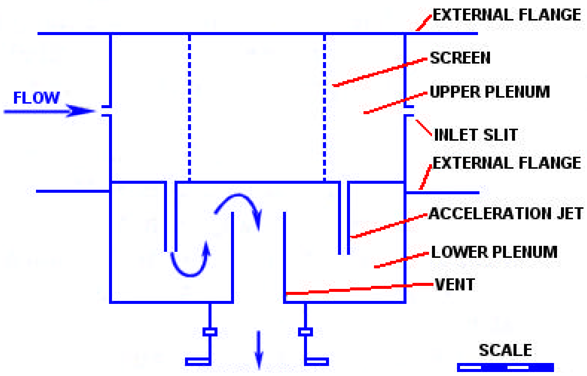

Figure 8. Schematic diagram of the G-A PM10 inlet

The PM$_{10}$ Graseby-Andersen (G-A) inlet (Figs. 7 and 8) is part of the Graseby PM$_{10}$ Medium Flow Air Sampler[3]. The sampler is designed and optimized to collect representative samples of particulates for gravimetric analysis. The sampler operates at a nominal flow rate of 113 L min^{-1}. Suspended particles in ambient air enter the inlet and then are accelerated through multiple impactor nozzles. Particles larger than 10 μm AD are separated from the rest by inertial effects as the accelerated jets are deflected in the lower plenum. The combine airflow flows down the vent tube to the filter, a 102-mm fiber-glass filter. The Graseby-Andersen (G-A) PM$_{10}$ inlet was tested by McFarland and Ortiz (1982) in a large aerosol wind tunnel at Texas A&M University, with the results presented in Fig. 9. The G-A PM$_{10}$ inlet design does meet the EPA PM$_{10}$ cutpoint D$_{50}$ of 10.0±0.5μm. The G-A PM$_{10}$ inlet provides a useful reference-sampling inlet for the PM$_{10}$ component in ambient air samples, and was used for that purpose in this project.

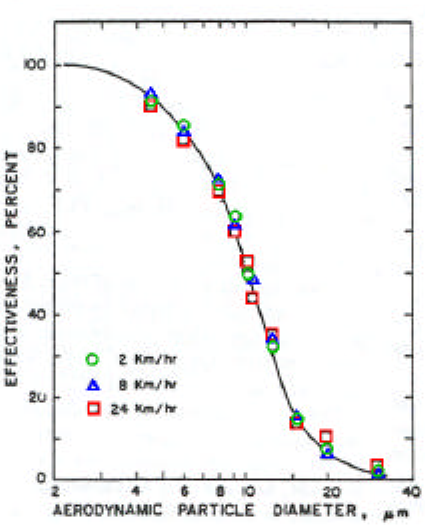

Figure 9. Effectiveness vs particle AD as a function of wind speed for the G-A PM10 inlet. Adapoted fromMcFarland and Ortiz (1982).

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[3] Andersen Instruments, 500 Technology Court, Smyrna, GA 30082

5. ECAM Inlet

The Los Alamos Accident Response Group (ARG) program has, over the past several years, sponsored development of a new environmental continuous air monitor (ECAM) to provide radiological air monitoring for accident responders at the scene of an accident involving a nuclear weapon, no matter what the ambient conditions might be. The instrument design is based on the Laboratory-designed plutonium alpha-CAM (Canberra Industries Alpha Sentry CAM), with the addition of a special inlet, and on-board vacuum blower and data communication capabilities. The special inlet has been designed to meet several objectives: first, the inlet must be capable of maintaining excellent aerosol collection performance in high wind conditions; second, the inlet must be protected from precipitation to prevent damage to the detector and the filter; and third, the inlet should provide size-selective separation of particles in the sample such that the large particle components of ambient dusts are removed to help prevent sample burial and interference with the alpha-radiation detection process. To achieve good inlet performance in high wind as well as calm, the design must decelerate the airflow as it enters the inlet without at the same time introducing distortions in the particle size distribution present in the free stream. This is accomplished by and omni-directional array of six modified shrouded probes making up the inlet. As seen in Figure 10, the nozzles of the probes are recessed inside shroud cells, which provide the needed

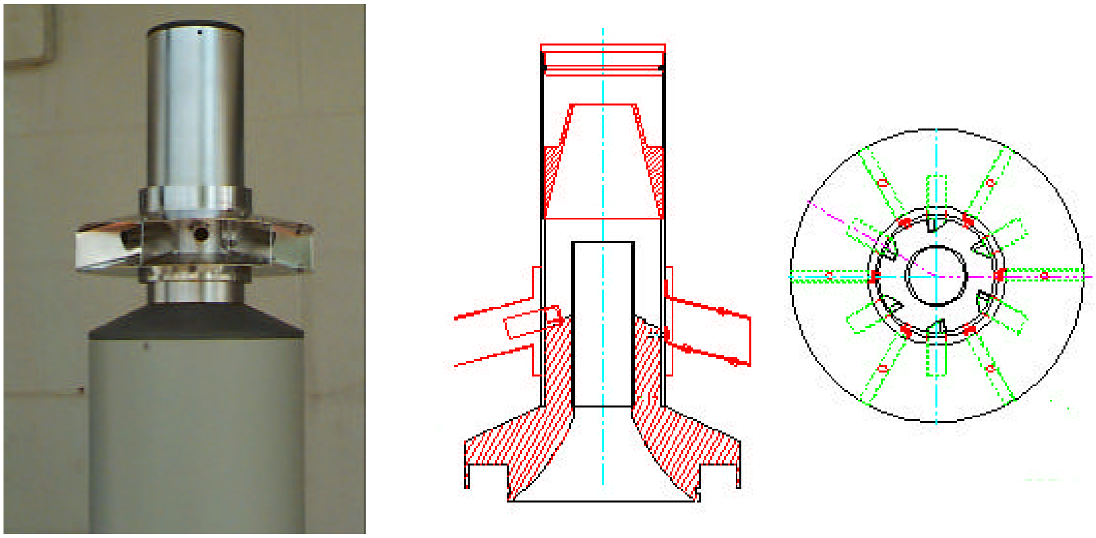

Figure 10. ECAM inlet

deceleration as airflow impinges on the inlet, and also provides protection from rain. The shrouded probe concept has been shown to provide excellent aerosol transmission efficiency regardless of velocity and particle size. Each of the six nozzles discharges into the base of an inverted cyclone. The cyclone design parameters as such that the 50% transmission cut point is at 10-µm aerodynamic diameter. Note in the cross-section drawing that there is a small conical trap at the top of the cyclone that is meant to capture large particles removed from the sample by the induced cyclonic flow. The exact configuration of the trap was still under development at the time of these tests, and a temporary design was installed for evaluation. The output of the inlet passes out of the base through the cyclone outlet tube down into the CAM head attached below.

III. Methods

A. Field Testing

The initial filed test of relative collection efficiencies of selected inlets was performed in the vicinity of the 46-m meteorological tower at the LANL TA-54 site.

Site Description

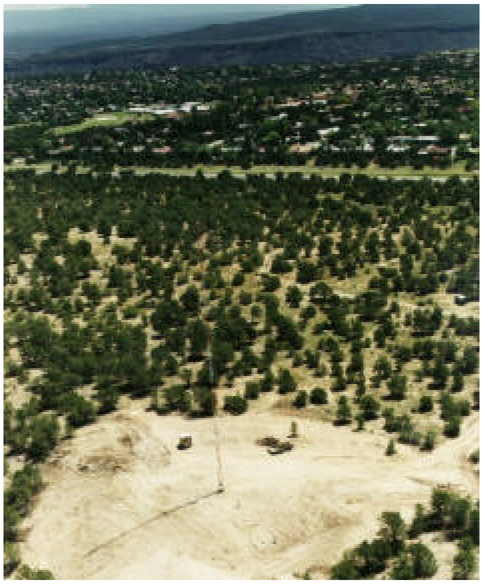

Figure 12. Bird view of the TA-54 site.

The TA-54 station is located in a clearing just off the eastern tip of Mesita del Buey on the Pajarito Plateau at longitude of 106° 13' 22.1", latitude 35° 49' 32.8" and elevation of 1996.3 m (6548 ft) above sea level. The terrain drops 15 m into Canada del Buey to the north and drops 10 m into Pajarito Canyon to the south. To the east-southeast, the terrain drops gently about 75 m to the eastern edge of White Rock Canyon. The station is shown in Fig. 12 looking southeast toward the residential area of White Rock. The eastern escarpment of White Rock Canyon can be seen near the top of the photo. The photograph presents the site during construction of the meteorological tower. Since then, the natural vegetation has returned to the area around the tower. Beyond the clearing, pinion and juniper trees of several meters height cover a most of the surrounding area. The plateau tilts at about 1.5 degrees to the east-southeast in the vicinity of this station.

During the test period (March 2 - May 4, 2000) the average wind speed at the site was 3 m s^{-1} with gusts up to 17 m s^{-1}, and total precipitation 43.2 mm. The wind conditions during each test are listed in Table 3 and Fig 13. The schematic diagram of the site is presented in Fig. 13 and actual view of the test site in Fig. 14.

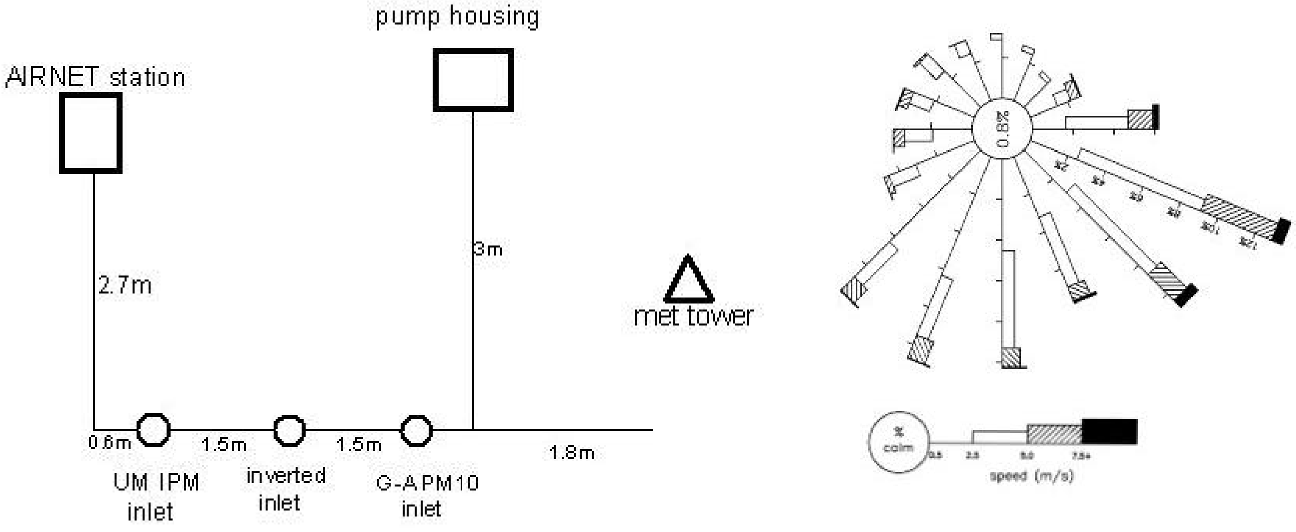

Figure 13. Plain view of the test site and the wind rose for test period

Figure 14. View of the experimental set up at the TA-54test si

designed to compare inlet efficiencies of the several types for ambient aerosols relative to each other. No reference sample was collected as a basis for comparison. Several configurations of inlets were tested for three one-week-long sampling periods. The first arrangement consisted of the UM IPM, the inverted 102-mm and AIRNE-station inlets (Fig. 15). In the next configuration the 102-mm inverted inlet was replaced with a 47-mm inverted inlet equipped with the filter type routinely used by ESH-17 in the AIRNET-station (Fig 16). To establish comparison against the PM$_{10}$ standard, the G-A PM$_{10}$ inlet replaced the inverted one (Fig. 17). The UM IPM and G-A inlets were operated using 102-mm Gelman A/E filters. The filters were collected weekly using methodology specific for individual inlet.

A summary of operational parameters of all tested inlets are presented in Table 1.

Figure 17. G-A, UM IPM and AIRNET inlets

Table 1. Operational parameters of tested inlets

Inlet	Filter type	Nominal Flowrate L min^{-1} (cfm)
UM IPM	102-mm Gelman[4] A/E (glass fiber)	113 (4)
102-mm Inverted	102-mm Gelman A/E	113 (4)
47-mm Inverted	47-mm Gelman A/E & Dynatech polypropylene	85 (3)
G-A inlet	102-mm Gelman A/E	113 (4)
AIRNET station	47-mm Dynatech polypropylene	113 (4)

Airflow to any two of the inverted, UM IPM, and G-A inlets, when operational, was provided from a single high capacity oil-less vacuum pump located in a separate housing (see Fig.14). AIRNET-station airflow was provided from a built-in oil-less pump with exhaust to the outside. For consistency and to avoid additional biases, the actual flow rate to all samplers was measured at the beginning and at the end of sampling period with the same, calibrated flow meter[5]. After approximately 170 h of sampling and after 24-h delay for humidity equilibration, filters were analyzed gravimetrically on calibrated balances with precision of 0.001g. AIRNET-type filters were analyzed by New Mexico Department of Health Scientific Laboratory Division Air & Heavy Metals Section. Filters from UM IPM, Inverted, and G-A inlets were analyzed in LANL ESH-4 HPAL facilities using ANSI traceable Mettler Precision Balance PM1200[6]. Duration of sampling in hours was taken from a timer built into AIRNET station. Meteorological conditions: average wind speed, maximum gust, and soil moisture for the test, were obtained from an automatic data logging station operated by ESH-17. The average weekly mass concentration C, was calculated as,

$$C\ (\mu g\ m^{-3}) = \frac{(Wg - Wt)}{V_a \times \Delta Time}, \tag{2}$$

where, Wt and Wg is the tare and gross weight of the filter in grams, V_a is the actual volumetric flow rate in $m^3\ min^{-1}$ calculated as an average of the flow rates measured at the beginning and at the end of sampling, and ?Time is elapsed time in minutes.

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[4] Gelman Sciences, 600 South Wagner Road, Ann Arbor, MI 48103

[5] SAIC RADeCO Model C-828 S/N 1909

[6] Mettler-Toledo, Inc. 1900 Polaris Parkway Columbus, Ohio 43240

B. High Velocity Aerosol Wind Tunnel Testing

Wind tunnel setup

A high velocity portable wind tunnel (Fig 18) was used in the study for inlet testing. The tunnel was designed and built at the USDA/ARS Palouse Conservation Field Station near Pullman, WA (Pietersma *et al*., 1996) as part of a soil erosion project. It is 13.4 m long and has a working section 7.3 m long, 1.2 m high and 1.0 m wide. Power is supplied by a 33-kW gasoline industrial gas engine, which drives a 1.4-m industrial axial vane fan (Joy Series 1000 Model 54-26) (Fig 19). Variable-pitch blades and variable engine speed allow the wind speed to be set manually. Using 13 available engine speeds, the velocity can be adjusted from <2 to 20 m s^{-1}. There is a transition from the fan inlet height to the ground level (Fig. 20). Intensive flow conditioning is an option in this wind tunnel. Fan-induced turbulence and swirl can be eliminated using 2 perforated plates, a honeycomb and a small mesh screen spaced over a distance of about 2 m.. For these tests however, flow conditioning was limited in orders to achieve the highest wind speeds.

Figure 18. USDA/ARS portable wind tunnel adapted for inlet testing

Figure 19. Wind tunnel motor and axial vane fan

Figure 20. Tunnel transition to the ground level

Detailed flow profile information in the tunnel is obtained using a Pitot tube sensors arranged in a six by six array, oriented orthogonal to the flow near the tunnel outlet. Guidance on the degree of uniformity of the flow profile can be found in the 40CFR53**.**42 (US EPA 1999b)**:** ”… *The wind speed in the wind tunnel shall be determined during the tests using an appropriate technique capable of a precision of 5 percent or better (e.g., hot-wire anemometry). The mean wind speed in the test section of the wind tunnel during the tests shall be within 10 percent of the value specified in table D-2. The wind speed measured at any test point in the test section shall not differ by more than 10 percent from the mean wind speed in the test section….*”. Even though these tests were not intended to generate data for an EPA certification, they were used as guidance.

Test aerosols were delivered to the tunnel upstream of the fan with offset-feed auger box (see Fig 21). The aerosol injection was done from six drop-tubes spread across the wind tunnel inlet (see Fig 19) to help in deagglomeration of the test particles, and to obtain uniform aerosol mixing in the air stream. Uniformity of the air velocity profile and aerosol concentration profile were good as shown in Fig. 22 and 23. The velocity profile was obtained at six heights and six locations across the tunnel at the test section. Aerosol profiles were taken in the center of the tunnel test section at 30, 60 and 90 cm above floor.

Figure 21. Offeset-feed auger box

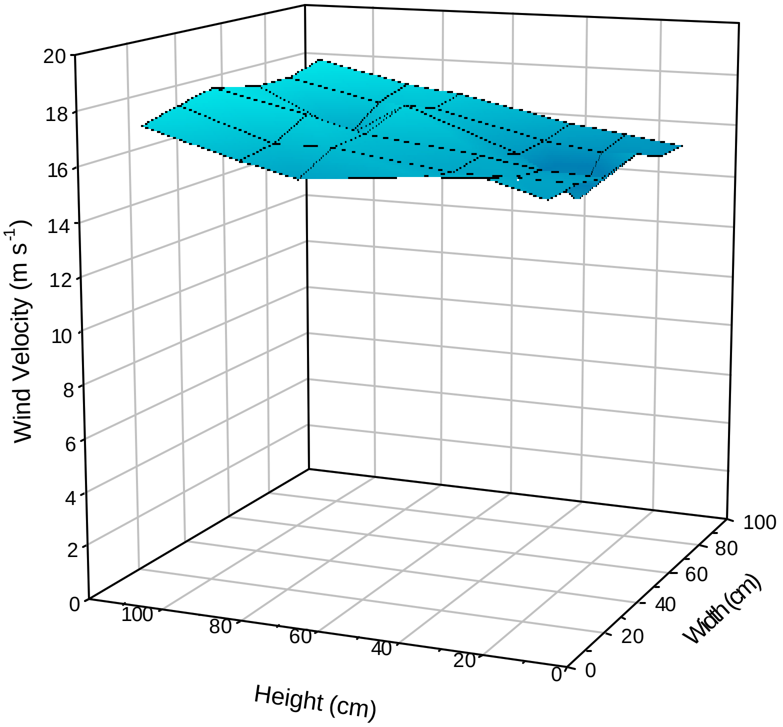

Figure 22. Velocity profile in the wind tunnel for u=17 m s^{-1}

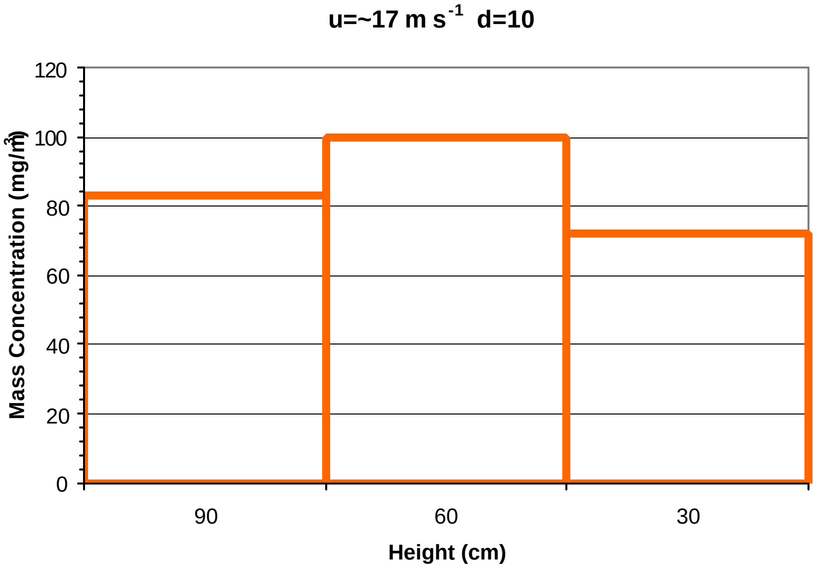

Figure 23. Center-line vertical aerosol concentration profile of 10 µm particles and at a wind speed of ~17 m s^{-1}

For the experiments the outlet of the tunnel was modified by building 3 m x 3 m extension to accommodate large samplers and to avoid excessive blockage. The design of the extension is shown schematically and as built in Fig. 24.

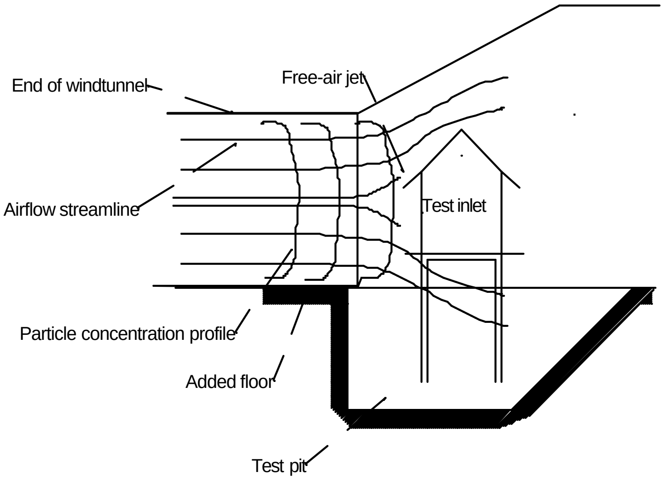

Figure 24. Tunnel extension for testing large inlets

Test aerosols

To obtain values of sampler efficiency as a function of different size aerosol particles and wind speed conditions, large quantities of mono-disperse test particles were needed. Environmental impact considerations (the wind tunnel exhaust to the open environment without filtration) restricted the type of test aerosols for used in this evaluation to nontoxic, natural particles. As contaminated soil particles are of primary concern for the LANL, we decided to obtain test particles in the form of ground and size classified soils. A commercial particulate vendor[7] was identified and contracted to prepare 200 lb each of narrowly distributed (approximately 5-, 10-, and 30- µm) red kaolin clay soil particles. The system used for test particle preparation is shown in Fig. 25. Soil samples were grounded using the RSG "Ultra Fine Grinding" Mill (seen on the left) and classified with ASC air classifiers. The UFG mill introduced by RSG in 1999 is used to grind mineral samples as small as 2-µm particle diameter. To classify soil particles according to their aerodynamic sizes the RSG used their patented Advance Classification System (ACS).

Figure 25. The RSG, Inc**.** system (UFG mill and ACS-005 air classifier) used in soil test particle preparation (courtesy of RSG. Inc)

The RSG, Inc. performed size analysis on each soil sample with their Microtrac X-100 system that uses tri-laser diffraction analysis[8]. The results of the analysis for 5-, 10-, and 30-µm soil particles are presented in Fig. 26.

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[7] RSG, Inc.119 Crews Lane, Sylacauga, AL 35150

[8] Microtrac Inc. at 148 Keystone Drive, Montgomeryville, PA 18939

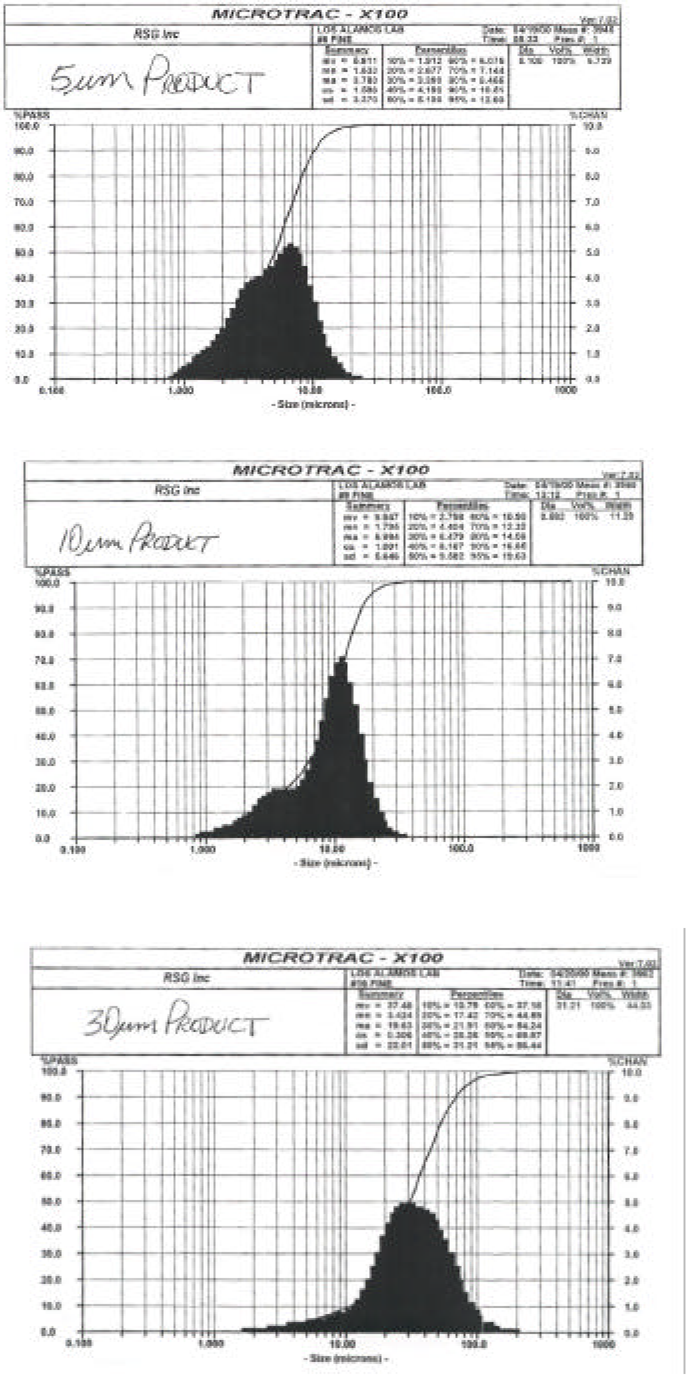

Figure 26. Results of Microtrac analysis of grinded soils samples used for inlet testing

Independent verification of the test soil particles size distribution was performed by Lovelace Respiratory Research Institute (LRRI) using API Aerosizer[9]. The Aerosizer is equipped with a dual laser beam optical sensor system for time-of-flight measurements and integral air flow control systems. Results of the analysis are presented in Fig. 27.

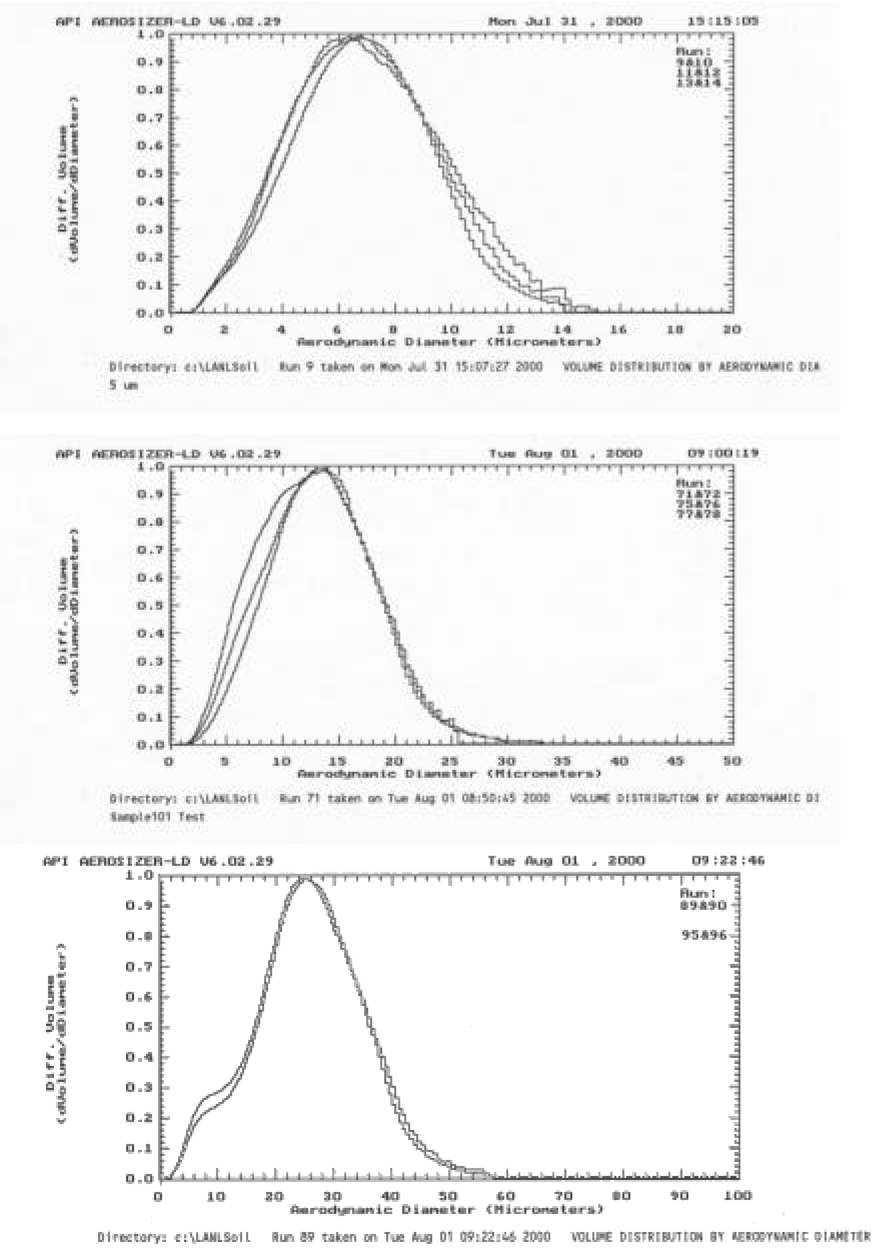

Figure. 27. Size distributions for 5, 10-, and 30-µm test soil particles measured with API Aerosizer.

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[9] TSI Incorporated Particle Instruments Division/Amherst 7 Pomeroy Lane, Amherst, MA 01002-2905

Numerical results of the test soil particles aerosizing are presented in Table 2.

Table 2. Results of test soil particle analysis using API Aerosizer

Nominal Diameter (µm)	**Volume Median Aerodynamic Diameter (µm)**	**GSD (µm)**	**Mean Diameter (µm)**	**Mean GSD (µm)**
5	6.49	1.51		
	6.49	1.50		
	6.57	1.54		
			6.52	1.51
10	12.94	1.46		
	11.97	1.54		
	12.55	1.51		
			12.49	1.50
30	24.03	1.56		
	24.41	1.56		
	23.46	1.59		
			23.97	1.57

Comparing the results of the size distribution analysis carried with the Microtrac and API Aerosizer, some differences are noticeable, especially for larger particles. For the nominal size of 10-µm diameter, the Microtrac analysis yielded a diameter 26% smaller than the API Aerosizer results. For the nominal size of 30-µm, the Microtrac overestimated the size by 36%. These differences could be attributed to different measuring techniques: light scattering versus time-of-flight, and are indication of difficulties in aerosol size distribution measurements. The light scatter techniques used in the Microtrac instrument represents more closely the physical diameter (PD) of the aerosol particles, whereas the API Aerosizer measures aerodynamic diameter (AD). These two are related via Equation 2:

$$\frac{AD}{PD} = \sqrt{\frac{\rho_p}{\rho_w}} \qquad (2)$$

where ?$_p$ is the density of test particles (soil, 2.3 g cm^{-3}) and ?$_w$ is the density of water 1 g cm^{-3}.

Shrouded Probe – Reference Sampler

In order to determine the effectiveness of each inlet tested in the aerosol wind tunnel it was necessary to obtain an unbiased reference sample of the test aerosols. It was essential that this sample be collected rapidly and accurately regardless of the particle size being generated and of the wind velocity in the wind tunnel. The shrouded probe (McFarland *et al*., 1989) provides precisely the sampling performance for these tests. The shrouded probe is designed specifically to address some of the problems associated with representative sampling in air streams of varied velocity and direction (Fig. 11). The shrouded probe exhibits near-constant sampling efficiency over a wide range of wind speeds and for particle AD range spanning <1 µm to 20 µm (Huebert *et al*., 1990). Internal wall losses are very low, which eliminates the need to recover significant portions of the sample after each run. The shrouded probe operates at a single design sample flow rate, unlike isokinetic probes, and therefore there is no need for control and monitoring of sampling rate.

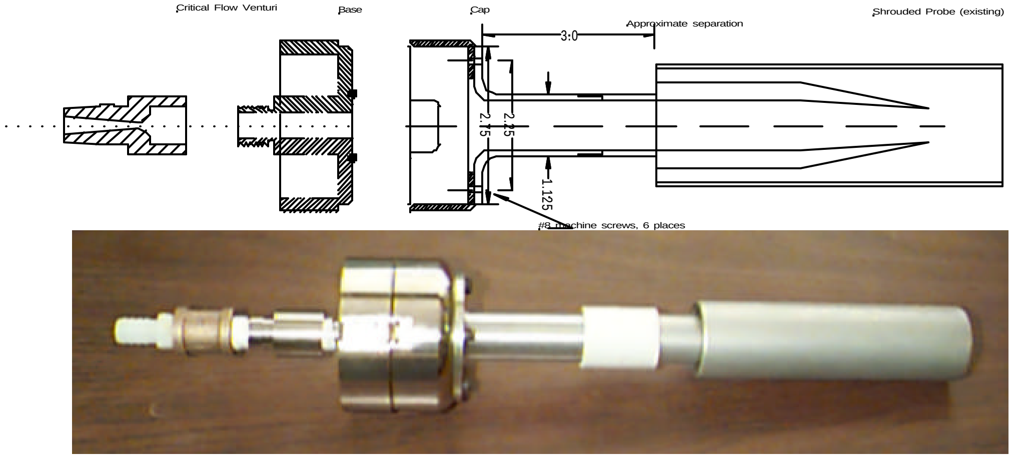

Figure 11. Cross-section and physical realization of a shrouded probe (McFarland *et al*. 1989) connected to quick-change filter cartridge (center) and critical orifice (left).

Shrouded probes were extensively tested (McFarland *et al*., 1989; Huebert *et al*., 1990) for their performance under extreme conditions showing excellent sampling efficiency. For this project five special shrouded probe-quick-change filter cartridge-critical orifice assemblies were constructed and used to collect reference (free air stream) samples in the wind tunnel experiment. The built-in critical flow venturi sets the nominal flow rate to 57 L min^{-1}.

IV. Results

Field Test Intercomparisons (Relative)

The comparison of relative performance of different inlets under ambient conditions at TA-54 site is presented in Table 3. The table contains weekly averages of aerosol particle mass concentration and wind speed, as collected in tested inlets and by a propeller anemometer on a tower at 12 m. The test were carried out between March 2-May 5, 2000.

Table 3. Summary of inlet performance field test. Each test involved simultaneous sampling for approximately 170 h under ambient aerosol conditions.

Test No	Inlet	Mass Concentration (mg m^{-3})	Average Wind Speed (m s^{-1})	Soil moisture (%)
1	UM IPM 102-mm Inverted AIRNET	9.8 8.2 5.1	2.6	7.2
2	UM IPM 102-mm Inverted AIRNET	10.3 4.3 3.7	2.5	8.2
3	UM IPM 102-mm Inverted AIRNET	43.5 20.8 15.4	3.3	10.2
4	UM IPM 47-mm Inverted AIRNET	10.6 7.7 5.3	2.5	15.6
5	UM IPM 47-mm Inverted AIRNET	5.1 6.4 4.1	2.8	15.8
6	UM IPM 47-mm Inverted AIRNET	16.8 12.6 10.2	3.2	13.6
7	UM IPM G-A inlet AIRNET	16.3 2.4 10.0	3.8	10.7
8	UM IPM G-A inlet AIRNET	15.9 2.5 11.0	3.3	7.8
9	UM IPM G-A inlet AIRNET	16.7 3.2 9.8	3.1	8.1

Graphical comparison of the relative inlet performance under different inlets configurations is presented in Fig. 28 in terms of weekly averages of mass concentrations. Performance was represented by the total mass of ambient aerosols collected, regardless of size.

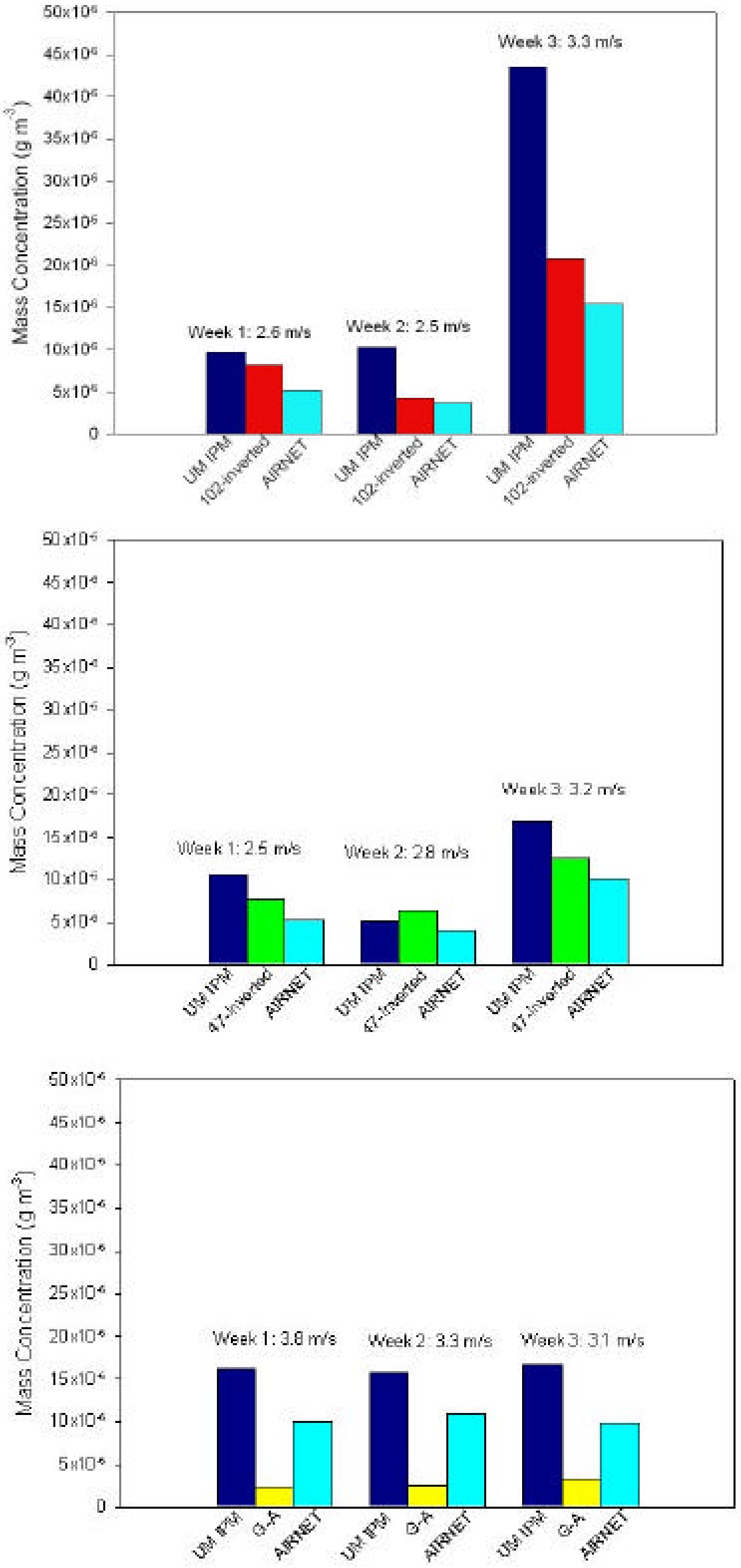

Figure 28. Comparison of performance of individual inlets under ambient aerosol. conditions. Weekly averages of wind speed are listed above the bars.

Wind tunnel tests

The wind tunnel tests were made between June 19 - 23, 2000. Three selected inlets: AIRNET, UM IPM, and ECAM were tested for their collection efficiency with 5-, 10- and 30-µm test soil particles and three wind speeds of approximately 12-, 15-, and 17-m s^{-1}.

Each test consisted of 3 or 5 min runs. Test particles were collected on a filter and at an air flow-rate specific for the tested inlet. Test particles were collected simultaneously with a shrouded probe placed in the flow for use as the reference (free stream) aerosol particle concentration. Each run was repeated 2-3 times to enable statistical analysis of the outcome results.

Figure 29. Shrouded probe (left) and Pitot tube (right) used to collect reference values

The reference probe was position 60 cm above the wind tunnel floor and inside the original wind tunnel, along with the Pitot tube used for air velocity measurements. The reference sampler and Pitot tube is shown in Fig. 29. The Pitot tube output was interfaced with a 21X Campbell Scientific datalogger providing 1-min air velocity averages. The datalogger software allowed for on-line monitoring of air velocity, to detect and correct any problems with the Pitot tube clogging.

Before a test, the numbered and pre-weighted filters were loaded into the sampler under test and into shrouded probe cartridge. The pre-test weighing was done just before the test on ANSI traceable Mettler Precision Balance AE100 (latest calibration June 2000). The same balance was used to obtain the post-test mass of the filter. The balance was located in an adjacent building and filters were transported to minimize losses of collected soil particles. Filters were later stored for further analysis if necessary, e.g. for uniformity of filter coverage.

The samplers (AIRNET, ECAM, UM IPM) were positioned in the extension section of the wind tunnel, 60 cm from the original end of the tunnel in the free jet regime. The AIRNET, ECAM, and UM IPM samplers undergoing testing are illustrated in Fig 30, 31, and 32.

Figure 30. Test of the AIRNET sampler in the wind tunnel

Figure 31. Test of the ECAM sampler in the wind tunnel

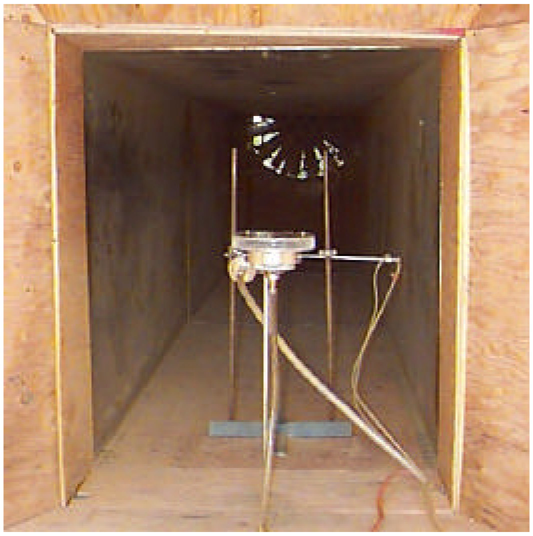

Figure 32. Test of the UM IPM sampler in the wind tunnel

RESULTS AND DISCUSSION

The aerosol inlet performance was evaluated under ambient aerosol conditions at LANL, as well as under the controlled conditions of the high-velocity wind tunnel in ARS, Pullman. This approach was suggested in the EPA draft document (EPA 1999c) stating that "…*Mark et al. (1992) reviewed the attributes of wind tunnel testing, and noted that tests using controlled conditions are a necessity to determine whether an aerosol sampler meets a basic set of established performance specifications. Hollander (1990) suggested that sampler performance criteria should be evaluated in controlled outdoor tests, given the inability of wind tunnels to accurately mimic the influences of outdoor meteorological conditions on sampling...*"

During the ambient tests the aerosol size distribution was not monitored, so only the relative performance of the inlets one to another can be evaluated. Results of ambient conditions experiments presented in Table 3 and Fig. 27 show that under low wind conditions (up to 3.8 m s^{-1} weekly average) the UM IPM inlet using 113 L min^{-1} flow-rate captured the largest mass, with the open face filter the second largest, and the AIRNET station the third largest mass. Similar patterns were repeated for all weekly tests. The PM_{10} G-A inlet, which is a size selective inlet with 50% cut off point for 10-µm particles, restricted penetration of larger particles and thus collected significantly less mass. The AIRNET station performance as an aerosol inlet (as defined here) was slightly below that of the inverted open-face inlets. However, they are still being used as low cost solution, for example in the WIPP Environmental Monitoring Project (Carlsbad Environmental Monitoring & Research Center 2000). The UM IPM inlet, specifically designed to overcome the deficiency of the inverted open-face inlets, has shown performance above other inlets.

The relative performance difference between inlets varied depending on ambient atmospheric conditions. From Table 3 it can be seen that UM IPM inlet measured aerosol concentrations up to 3 times higher than the AIRNET or the inverted filter holder inlet. However, the relatively low wind conditions encountered in these tests are only a limited sample of wind speeds experienced in the LANL environment. There are situations, when environmental sampling has to be done under higher wind velocities, like those experienced during recent Cerro Grande and Hanford fires, when high winds resuspended contaminated soils.

The controlled test, performed in the high velocity wind tunnel with test particles of selected sizes overcomes the limitations of highly variable, uncontrolled ambient testing with uncharacterized aerosols. The 5-, and 10-µm diameter particles represented the respirable fraction and 30-µm the resuspendable fraction. The results of the wind tunnel experiments are summarized in the Tables 4, 5, and 6 and presented in forms of sampler efficiency curves for three inlets in Figs. 33, 34, and 35. The sampler efficiency was derived as an average of the ratios between the aerosol particle mass concentration measured by the tested inlet (sampled mass concentration) to the reference mass concentration measured by the shrouded probe. The error bars on the graphs represent ±1 standard deviation (SD).

Table 4. Results of wind tunnel experiments for the ECAM sampler

Wind Speed (m s^{-1})	Nominal Particle Diameter (µm)	Reference Mass Concentration (mg m^{-3})	Sampled Mass Concentration (mg m^{-3})	Ratio (%)	SD
12.5	5	97.2	23.1	23.8	1.2
	10	58.3	8.3	14.2	1.9
	30	34.7	1.8	5.2	4.9
14.7	5	116.6	23.2	19.9	1.4
	10	67.3	13.4	19.9	2.4
	30	37.4	2.2	5.9	1.7
16.6	5	117.6	19.1	16.2	0.5
	10	174.0	22.5	12.9	1.5
	30	68.0	1.0	1.5	1.6

Table 5. Results of wind tunnel experiments for the UM IPM sampler

Wind Speed (m s^{-1})	Nominal Particle Diameter (µm)	Reference Mass Concentration (mg m^{-3})	Sampled Mass Concentration (mg m^{-3})	Ratio (%)	SD
12.5	5	91.5	110.6	120.9	21.6
	10	86.0	53.9	62.7	15.3
	30	39.8	20.4	51.3	1.8
14.7	5	89.3	104.4	116.9	18.7
	10	83.3	41.3	49.6	14,4
	30	35.6	18.7	52.5	13.4
16.6	5	124.3	166.2	133.7	7.5
	10	88.9	25.1	28.2	0.7
	30	62.1	28.6	46.1	6.3

Table 6. Results of wind tunnel experiments for the AIRNET sampler

Wind Speed (m s^{-1})	Nominal Particle Diameter (µm)	Reference Mass Concentration (mg m^{-3})	Sampled Mass Concentration (mg m^{-3})	Ratio (%)	SD
12.5	5	118.8	92.3	77.7	5.2
	10	69.4	57.2	82.4	4.5
	30	42.0	70.0	166.7	22.7
14.7	5	104.8	90.1	86.0	8.2
	10	63.1	39.2	62.1	12.6
	30	36.4	85.9	236.0	49.6
16.6	5	51.2	62.0	121.1	34.5
	10	54.3	39.3	72.4	2.1
	30	22.6	45.6	201.8	14.0

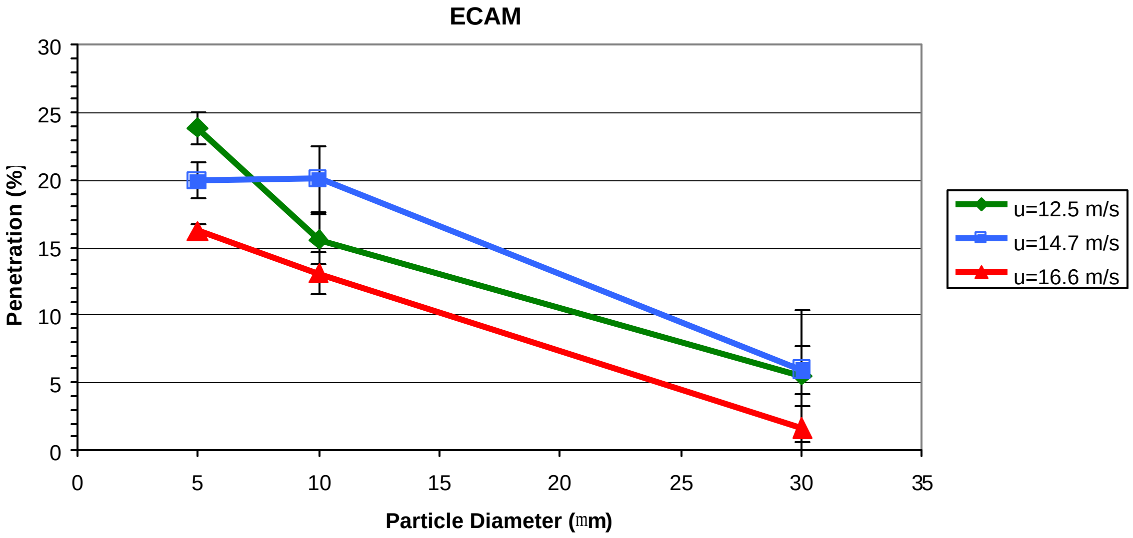

Figure 33. Penetration curves for the ECAM sampler for three wind speeds u=~12, ~15, and ~17 m s^{-1}.

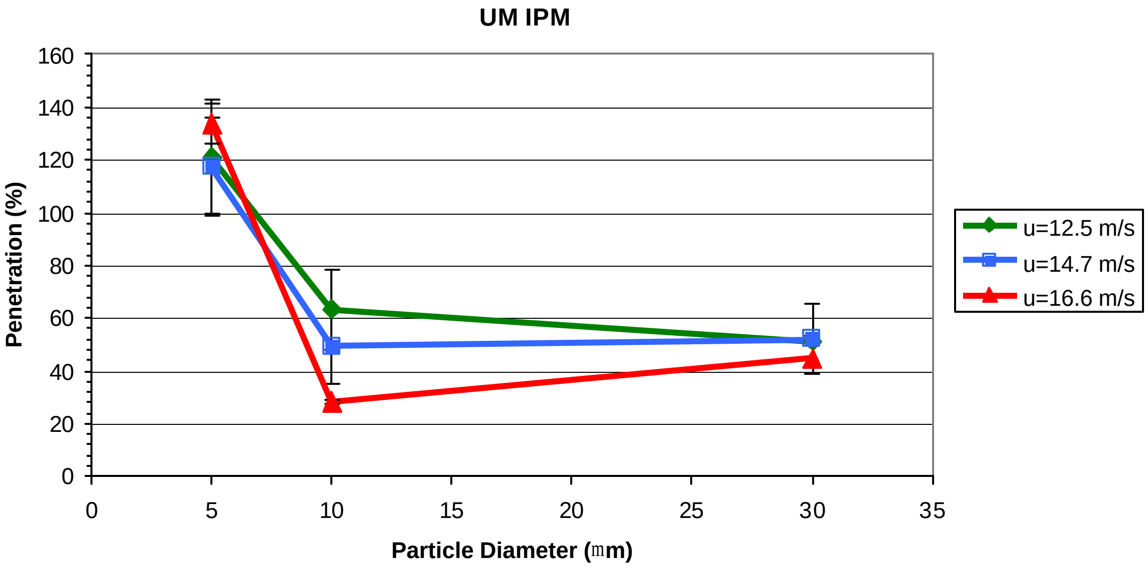

Figure 34. Penetration curve for the UM IPM sampler for three wind speeds u=~12, ~15, and ~17 m s^{-1}

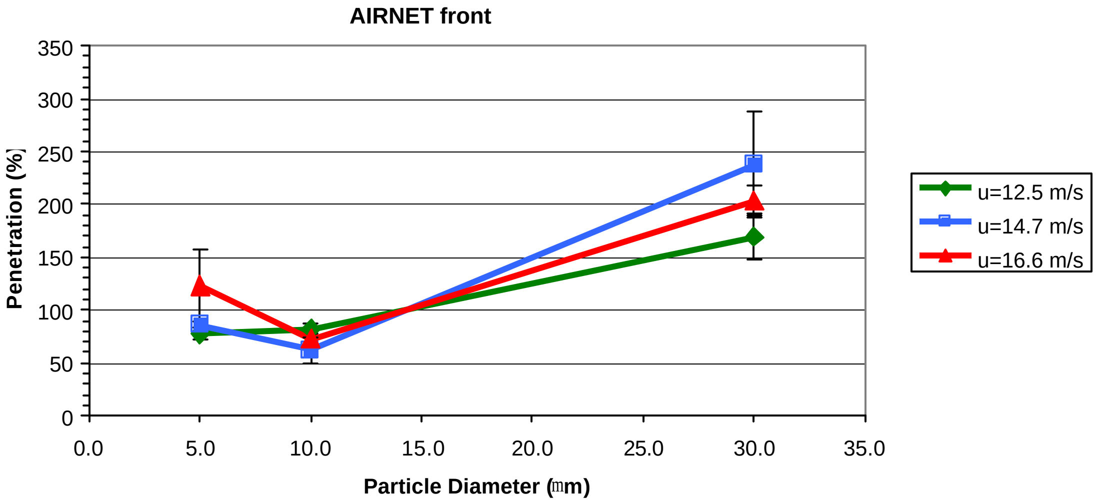

Figure 35. Penetration curve for the AIRNET sampler with the internal filter holder facing the flow stream for three wind speeds u=~12, ~15, and ~17 m s^{-1}

Several observations can be made based on the data presented in the foregoing penetration curves. First, with regard to the ECAM data, it is clear that the test design did not perform as respected for a design goal of a D_{50} cut-point of 10 µm. A possible explanation for this unexpected outcome is that the addition of the experimental dust trap cone changed the cyclone properties such that the cut-point was moved back to less than 5 µm AD. The shape and position of this cone are clearly sensitive design parameters. Further investigation of the critical design parameters of this element of the cyclone are planned for future work on this inlet. A an earlier study with slightly different version of the ECAM inlet (Murray Moore personal communication, June 2000) at lower wind velocity of 6.7 m s^{-1} showed that this inlet has regular penetration curve with around 60% penetration for 10-µm particles. With the version of inlet used in this study it was found that for wind speeds above 10 m s^{-1} the penetration drops to around 20%. For this high wind speeds there was still finite probability for 30-µm particles (penetration values around 5%) to penetrate the ECAM inlet.

The UM IPM sampler has been tested by its designers Liu and Pui (1981) for 8.5-, 11.0- and 13.4-µm diameter at low wind speeds. In their paper the penetration efficiency was over 100% for particles of 8.5-, 11.0- and 13.4-µm diameter at wind speed of 0.6 m s^{-1}, and dropped to 90% for 8.5 and 11.0-µm particles and to 80% for 13.5-µm at wind

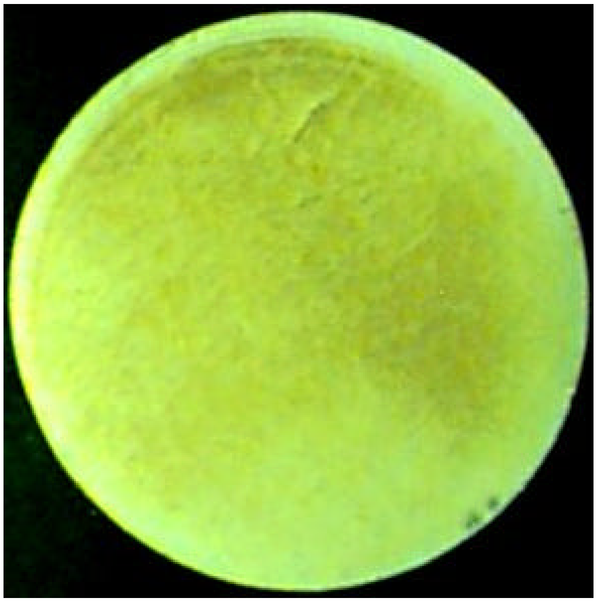

Figure 36. 102-mm filter used in one of the tests showing non-uniform coverage

speed of 2.8 m s^{-1}. No higher wind velocity was tested. Our high velocity tests have shown similar inlet behavior for all tested wind speeds with sharp drop in penetration from 5- to 10-µm diameter particles from 120-130% to 30-60% and then constant for 30-µm diameter particles. These values are below theoretical predictions of the ideal “hole-in-an-infinite-wall” inlet by Zebel (1978). Zebel’s predicted aspiration efficiency of circular inlet of 9.2 cm diameter for particles 15-µm aerodynamic diameter was 100% at low wind speed, decreasing to 90% at a wind speed of 6.9 m s^{-1} and 80% at 15.8 m s^{-1}. In our case inlet diameter was 11.6 cm and for particles10-µm AD at wind speeds of 12.5- 14.7- and 16.6 m s^{-1} aspiration efficiency was about 63%, 49% and 28%, respectively. Similar observation of decrease in aspiration efficiency for larger particles (13.4-µm) and higher wind speeds was made by the designers of the original IPM inlet (Liu and Pui, 1981). They observed as well a decrease in aspiration efficiency of their inlet larger than that predicted by Zebel’s (1978) theory. Their suggested explanation of the discrepancy was that the actual flow field at the inlet is more complicated than that assumed by Zebel. Our experiments, using solid particles (in contrast to Liu and Pui, 1981 who use liquid particles), have shown another property of the UM IPM inlet shown in Fig. 36. The deposition pattern of a 10-µm AD test aerosol on the 102-mm filter is showing strong directional dependence with higher loading on the downwind side (top of the picture) of the inlet. This was also observed on some field samples.

The louvers of the AIRNET sampling station housing an open face filter act as air inlets to the interior space. The ambient low wind velocity conditions of the field test created sampling conditions inside the housing very similar to those outside. The similar performance of AIRNET and inverted open face filter sampler is therefore not unexpected. However, under high wind conditions in the wind tunnel, the AIRNET sampler exhibited about 96% efficiency for 5-µm particles and about 60% efficiency for the respirable fraction represented by 10-µm particles, but overestimation of concentration for 30-µm particles for all wind speeds tested. The overestimation ranged from 170% for ~12 m s^{-1}, 237% for ~15 m s^{-1} and 204% for ~17 m s^{-1} wind speeds. The explanation of this phenomenon could be that the AIRNET housing inlet is sampling subisokinetically and therefore large particles are impacted through the louvers into the AIRNET housing with higher efficiency than smaller size particles. Therefore, the open face filter sampler inside is sampling from atmosphere containing a higher concentration of large particles than outside the housing. This hypothesis is supported by results from penetration tests carried out with the open face filter located inside AIRNET housing facing the air flow, being parallel to it and opposing it. The results of such tests are presented in Fig. 37 and 38.

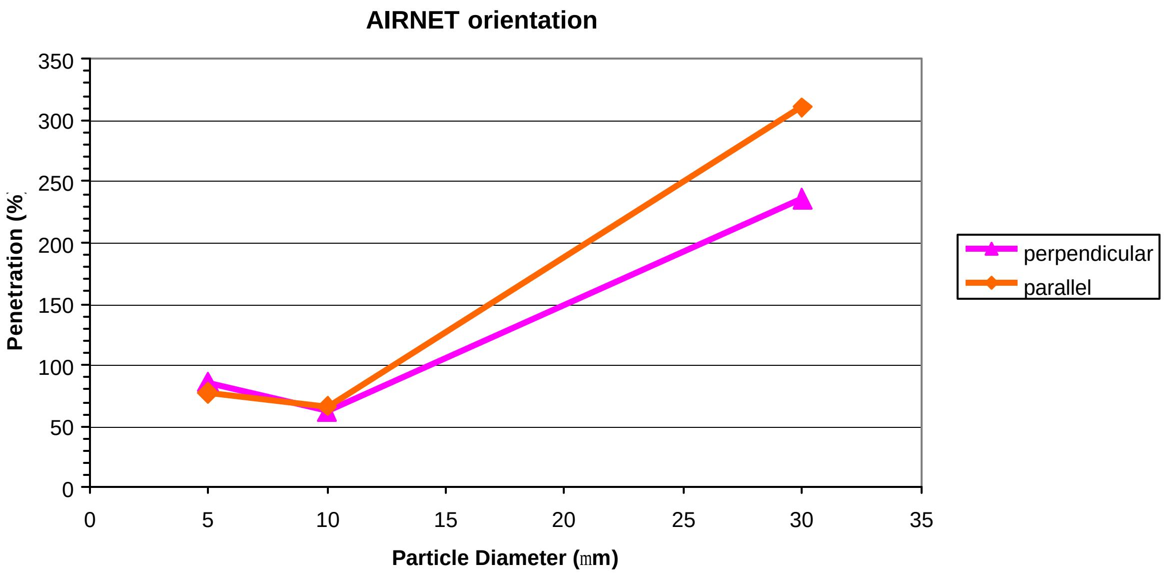

Figure 37. Comparison of penetration vs particle diameter for the AIRNET sampler with the internal filter holder perpendicular to and parallel to the flow stream for wind speeds of ~15 m s^{-1}

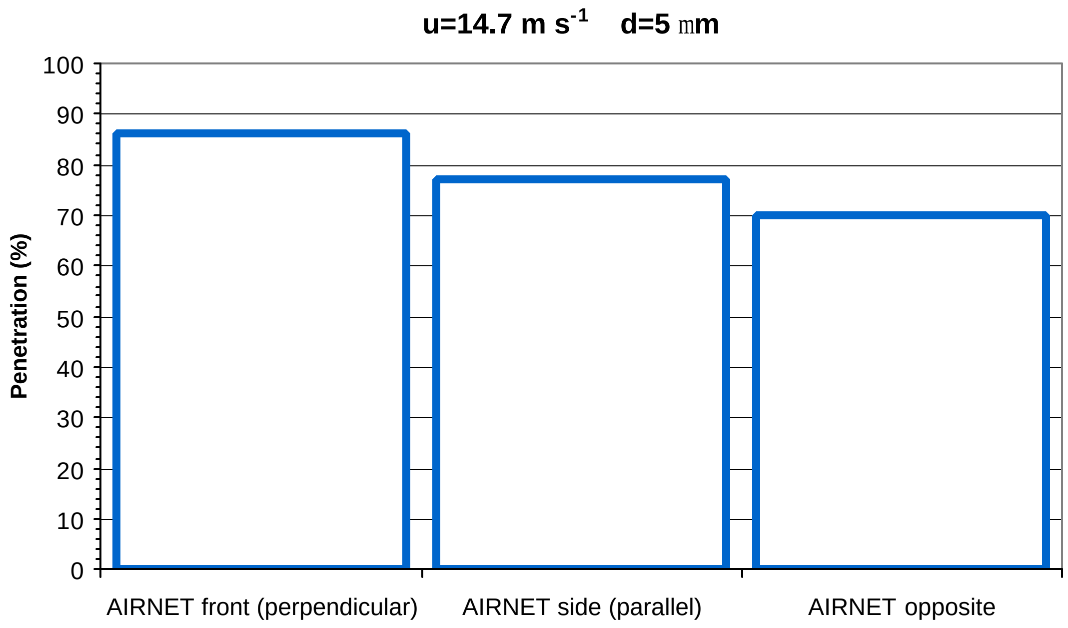

Figure 38. Penetration efficiency of 5-µm particles for different orientation of the AIRNET housing with respect to the wind tunnel flow.

There was a 21% decrease in penetration of 5-µm diameter particles into the filter of the AIRNET sampler when the internal filter holder was facing the flow versus the situation where the sampler was rotated 180 degrees.

CONCLUSIONS

A number of different types of ambient sampler inlets were tested in this project, each with a different intended role and application. All the inlets must operate in ambient environmental conditions that are sometimes unfavorable to good sample collection. As a result, certain design compromises have been made to accommodate the intended use under adverse conditions. The simplest inlet of all is a simple filter holder. But when it is operated in an inverted condition to protect the filter from rain and gravitational settling of large particles onto the exposed filter, performance is affected, with smaller ambient mass concentrations estimated in the LANL field trials compared with a protected, upright filter holder as in the UM IPM sampler design (Figure 27).

Higher ambient wind velocities, which while not common, do occur and are associated with critical resuspension and transport processes, required a different test approach which was provided in this study by a high velocity wind tunnel. Both the effects of increasing wind speed and increasing particle size were evaluated. The results show that while wind speed increases do have a significant effect on collection efficiency, the largest effect was that due to increasing particle size. The UM IPM sampler is supra-efficient for particles in the 5 μm size range (penetration > 100%), but then for particles between 10 and 30 μm diameter, the efficiency drops to between 20% and 40%, depending on wind velocity. It would appear that a significant fraction of particles above a critical size simply move through the capture zone of the inlet with sufficient inertia that they are able to cross the curving flow streamlines induced by the sample flow into the filter and avoid capture. This is a well-known phenomenon that leads to sub-isokinetic sampling in the case of sample extraction probes facing into a flow field with a *lower* inlet velocity than the free-stream velocity. Under such conditions, inertia tends to carry more large particles into the inlet than would be expected from the free-stream concentration. Here, since the inertial trajectories are parallel and away from the filter, the effect is to actually cause *fewer* of the larger size particles to be captured. It may be that the addition of a deflection cone on the upper plate, as has been used in some other designs, would remedy this problem by causing the parallel flow lines to diverge toward the filter slightly, and thus change the inertial trajectory toward the collection surface (Fig. 39).

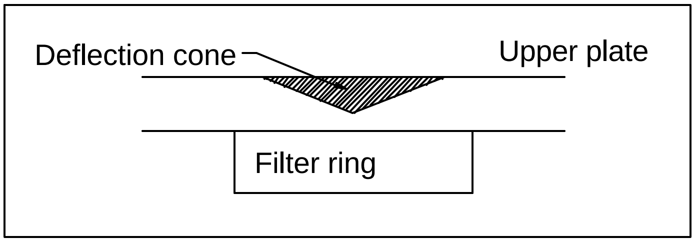

Figure 39. Modification of the UM design to improve high wind velocity collection efficiency for large particles

With regard to the ECAM sampler, as has been previously noted, the design of the large particle trap needs further design work, or perhaps only better placement in the cyclone relative to the outlet tube, to move the cut point up to the design target of 10 μm AD.

As with all of the samplers tested, the AIRNET sampler is particle size and wind speed sensitive. In the wind tunnel experiments, it collected virtually all of the small particles (~96% average efficiency for 5-µm particles), more than 50% of the 10-µm particles (which is comparable to EPA equivalent PM_{10} sampler), while oversampling for large particles. Therefore, particulate matter mass concentrations would be conservatively estimated at least for the higher wind speeds (>10 m s^{-1}) that occurred during the experiment.

Results obtained during this 1-year project suggest the need for further, more detailed studies if the full knowledge of the aerosol inlets used in the LANL is to be accumulated. The extreme condition may be experience during accidents with transportation of nuclear materials or natural disaster like fires. The results of environmental surveillance, even if it is carried on longer time scales (weeks) can be distorted by short-term extreme conditions (high winds) if the response of the sampler is unknown.

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