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Design and validation of a passive deposition sampler

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Abstract

A new, passive particle deposition air sampler, called the Einstein–Liroy Deposition Sampler (ELDS), has been developed to fill a gap in passive sampling for near-field particle emissions. The sampler can be configured in several ways: with a protective hood for outdoor sampling, without a protective hood, and as a dust plate. In addition, there is an XRF-ready option that allows for direct sampling onto a filter-mounted XRF cartridge which can be used in conjunction with all configurations. A wind tunnel was designed and constructed to test the performance of different sampler configurations using a test dust with a known particle size distribution. The sampler configurations were also tested *versus* each other to evaluate whether or not the protective hood would affect the collected particle size distribution. A field study was conducted to test the sampler under actual environmental conditions and to evaluate its ability to collect samples for chemical analysis. Individual experiments for each configuration demonstrated precision of the sampler. The field experiment demonstrated the ability of the sampler to both collect mass and allow for the measurement of an environmental contaminant *i.e.* Cr⁶⁺. The ELDS was demonstrated to be statistically not different for Hooded and Non-Hooded models, compared to each other and the test dust; thus, it can be used indoors and outdoors in a variety of configurations to suit the user's needs.

Background and introduction

Outdoor particle deposition air sampling has been performed through various approaches to assess the health impact of particulate matter in outdoor ambient or indoor air. Collected samples can be analyzed to determine their chemical and/or biological composition and the

particle size distribution within the samples. Passive deposition samplers are an option for air sampling involving low frequency events because they do not require a power source, but instead rely on physical forces of deposition, interception and attraction to collect and retain particles.¹

One of the earliest passive particle deposition samplers was the dust bucket.^{2,3} The bucket is placed outside with a small volume of water inside. Due to the open and wide inlet, matter is freely collected within the bucket. This matter may be comprised of more than just particulates and can include insects and rain-water. After sampling, the contents of the bucket are then dried, weighed, and if needed, undergo further analysis.^{4,5} There could be interferences, *e.g.* insect collection; thus, the data collected are at best semi-quantitative.

Another technique is the deposition plate which is best suited for use indoors on undisturbed surfaces.^{5,6} Dust settles on the plate, which can remain in place for extended periods of time in a secure location. The drawback to the deposition plate is that it does not have a housing that can protect it outdoors.^{7–10}

Wagner and Leith developed a passive aerosol sampler (the Wagner–Leith sampler).⁹ After experimenting in a wind tunnel designed specifically for the sampler, Wagner and Leith found that the Wagner–Leith sampler showed a coefficient of variation of 18.1% for PM_{2.5} and 32.2% for PM₁₀.¹⁰ Ott and Peters developed and tested six different shelters for the Wagner–Leith sampler. This shelter, called the Flat-Plates shelter, allowed coarse particles to reach the sampler and simultaneously minimize rain infiltration.¹¹ Yamamoto *et al.* developed a personal air sampler called the personal aeroallergen sampler (PAAS).¹² The PAS-GP-II was developed by Tao *et al.* to monitor PAHs in both gaseous and particle forms.¹³ The Ferm sampler consists of a polypropylene container with a 37 mm hole in the lid and it was found that the vertical position resulted in the collection of fine particles on the filters as well as ions resulting from gas phase compounds that reacted with those particles.¹⁴ Lin *et al.* presented a passive sampler consisting of a circular chamber with angular outlets open to wind in a 360 degree design.¹⁵

The passive Einstein–Lioy Deposition Sampler (ELDS), which is the subject of this research, was constructed to improve on existing passive sampling methods. For example, in contrast to most of the other samplers it was tested for particle size collection efficiency in the size range of <1.0 µm to >20 µm in a controlled wind tunnel system where particles with a known distribution were released into the tunnel. The particulate matter was collected without a carrier fluid to improve transport, sampler setup and removal, and allow for quantitative measurement of mass and analysis of the particle size distribution through optical microscopy. Standard 37 mm filters were used, which allowed for ease of deployment and use of standard chemical, *e.g.* metals, analysis techniques. A rain shield (hood) was added and can be removed as needed, and all parts of the sampler besides the filters can be cleaned and reused in subsequent deployments. The ELDS can be set up as a single unit or multiple units can be deployed at once, either grouped together or spread out over a wide area. If a researcher wishes to sample over a wide surface area, several ELDS units can be set up to collect mass on multiple filters, while still using standard filter media. The sampler improves upon previous methods by providing a characterized, validated

device that can collect particulates on standard filters with little interference and high ease of deployment and analysis.

Rationale

Particulate matter contributes to lung irritation, asthma, chronic bronchitis, and irregular heartbeat.¹⁶ Risk of lung cancer may be increased with exposure to PM, particularly in combination with smoking, second-hand smoke, and other lung exposures such as occupational exposures.¹⁷ The elderly and children are particularly susceptible or vulnerable to particulate matter.^{18,19} The environmental effects of PM include haze and dust deposition that can contribute to surface soiling, acidification and corrosion, and eutrophication.¹⁴ Particles can deposit on both indoor and outdoor surfaces and be re-suspended into the air over time.^{2,20} Deposition can also contribute to water and surface contamination.^{7,8}

A well-characterized, covered, and easily operated particle dry-deposition sampler is an important tool for looking at the local transport and deposition of fine, coarse, and inhalable particles. The successful development of a deposition sampler, capable of collecting inhalable particles emitted on or entrained from nearby roadway sources, open fields and piles, as well as indoor environments will assist in examining public and environmental health problems. The results can be used for inhalation and ingestion/dermal exposure and risk assessment.

Materials and methods

The following sections describe the materials and methods used to test and characterize the deposition sampler. Included are the sampler and wind tunnel designs as well as the experimental methods including setup and functions of each component of the device.

Sampler design

The ELDS is shown in Fig. 1a and a schematic of the sampling base is shown in Fig. 1b. Particles are allowed to freely deposit on the base, which can hold up to four 37 mm filters, housed separately in open-faced sampling cassettes. The number of filters was based on a practical consideration: four 37 mm filters are the maximum amount that can fit on the base. The sampler is built around a core consisting of a threaded rod that is wrapped in Teflon tape to avoid any metal contamination. The threaded rod allows all parts to be bolted to the core and allows for the varying of the height of the base relative to the bottom edge of the funnel, which protects the samples from rain. The sampling cassettes and base are contained within a single piece of Delran plastic, to minimize static charge. The design of the base and sampling cassettes also allows for filters to be preloaded in the laboratory and transferred from the field by a technician without handling the filters outside the laboratory setting. This procedure minimizes contamination prior to and after placing the sampler in the field. It also allows for the easy placement of filters in the open-faced ELDS base and replacement of the base assemblies to facilitate return of samples for analysis. This platform provides for long-term passive sampling as bases can be easily exchanged on one sampler, thus there is no need to transport the entire sampler back to the laboratory and/or remove filters in the field.

The ELDS cassettes were designed to allow for unobstructed airflow across the surface to maximize sampling effectively. The filter fasteners are 45 mm in diameter at their widest point and 2 mm in thickness, leaving 28 mm of diameter of the filter exposed. The thickness of the fastener and the diameters were chosen to effectively secure the filter in place but still allow it to be open to the air for particle deposition. The 40 mm wide and 3 mm deep well allow the filter to sit slightly recessed from the surface. The filter sits on Delran filter support, which can be pushed out through a hole at the bottom of the ELDS base. The filter support also has a 2 mm notch cut into it, to allow the filter to be easily gripped and removed after sampling. The entire filter base measures 120 mm across.

A protective hood can be used with the sampler to protect the filters from rain and other precipitation. The hood is 147 mm at its widest and the edge of the hood is located 30.2 mm above the top of the filter base. This was not changed during experimentation but is designed to be variable and movable on the threaded rod. Any changes to the filter base to hood gap size for the Hooded version of the ELDS have not been characterized beyond 30.2 mm. The sampler was tested both with and without the hood in place (Hooded and Non-Hooded).

An X-ray Fluorescence (XRF) cartridge-ready side of the sampler (the underside) was also designed and implemented for the sampler. Using the underside of the sampler, two filter areas were modified to allow an XRF cartridge to be slid into place and held there with a filter holder similar to the holders on the top-side of the ELDS. A large screw near the outer edge of the sampler holds the cartridge in place. After sampling, the filter can be weighed in the cartridge and placed directly into an XRF machine for analysis.

The sampling base is compact and can be used as a single unit (with manually moveable parts), which allows for easy changing and replacing in the field. It is small and light and can be easily and quickly deployed. The supporting pieces (Teflon tape, center rod, nuts, and bolts) can be easily purchased making the construction and replacement relatively simple. Hooded and Non-Hooded versions of the ELDS were tested to examine the ability to sample both outdoor and indoor environments.

Characteristics of the test dust

The test dust used to examine particle deposition onto the sampler in the wind tunnel was Fine Arizona Test Dust, Powder Technology, Inc, Burnsville, MN.²¹ The dust consists primarily of silicon dioxide (68–76%) and aluminum oxide (10–15%) with other minerals making up the remaining percentages. Particle sizes of the test dust ranged from 0.711 to 52.4 microns and were determined by the manufacturer using a Coulter counter.^{18,22} The dust has a fairly even mass distribution of each particle size, so there is a greater number of smaller particles.¹ The most important reason for using the Arizona Test Dust was that the particle size range of the dust included fine, coarse, and supercoarse particles.^{19,20}

The smallest particle size bin measured using the Coulter counter (data provided by Powder Technology, Inc.) for the test dust was 0.711 μm . Using optical microscopy, particle sizes as small as 0.610 μm were detected on the ELDS. For distribution comparison, all particles found to be smaller than 0.711 μm on sampling filters were reclassified as 0.711 μm .

Wind tunnel design

The wind tunnel was constructed out of a 3.05 m long PVC pipe purchased from an air conditioning supply company. A schematic of the wind tunnel is pictured in Fig. 2. The pipe diameter measures 0.51 m with an inner diameter of 0.48 m. A standard fan controlled by a variable transformer (or variac) pulled air through the system and was attached to the outlet of the pipe with screws and sealed along the edge. The fan was attached to the variac, which was capable of lowering the fan speed to achieve real-world typical wind speeds that range from 0.045 m s^{-1} to 4.5 m s^{-1} ($1\text{--}10 \text{ mi h}^{-1}$).^{23,24} The inlet of the wind tunnel system drew in ambient air from the surrounding laboratory. Airflow laminarity was maximized with a honeycomb, created from 20.3 cm long tubes bunched together and packed behind the filter that protects the inlet. A flexible 0.51 m diameter plastic tube was attached to the fan and can be placed into a nearby fume hood to function as the wind tunnel exhaust. The wind tunnel itself was operated at 0.65 m s^{-1} (650 cm s^{-1}) which is approximately 1.45 mi h^{-1} , a speed below that of windy conditions. A port at the apex of the wind tunnel is situated at 5.10 times the inner diameter of the wind tunnel (2.46 m) from which the deposition sampler can be attached and hung. This distance was purposely selected as wind tunnels usually achieve a stable flow at a distance of 5 to 7 diameters from the inlet.²⁵ The test dust was injected into the tunnel using a Wright Dust Feeder (WDF) at the top of the tunnel near its inlet. The wind tunnel was operated at a Reynolds number indicative of turbulent flow conditions with a Reynolds number of 21 900 and a velocity of 0.65 m s^{-1} . The turbulent flow caused particle mixing throughout the entire path traversed inside the wind tunnel, and allowed particles of all sizes to come into contact with the ELDS sampling base. Without mixing, most of the fine particles would not have travelled far enough in the tunnel to come in contact with the ELDS sampling base. Conversely, the very large particles could settle too quickly without reaching the sampler. A port was also placed on one side of the wind tunnel at a 90 degree angle to the deposition sampler port and was used to attach an active air sampler, which was utilized to detect the output of the particle generator. The aforementioned ports were also used to determine wind velocity inside the tunnel using a velocimeter. An additional, larger port, which can open, close, and lock, was placed on the side of the wind tunnel opposite to the active sampler port and behind (downwind) the samplers. It was used to place the samplers inside the tunnel and to vacuum and clean the wind tunnel after each sampling run of 250 minute duration.

Wright Dust Feeder

The Wright Dust Feeder (WDF) is a powder dispersion device used in controlled emission studies to introduce dust of various particle sizes to a variety of systems.²⁶ To use the WDF, dust is tightly packed into a cylinder. For the reported research, the small dust cylinder of the WDF was used, which has a volume capacity of 5 cm^3 .²⁶ During operation of the WDF, the packed dust rotates against a sharp metal edge within a hollow shaft that extends into the cylinder. Dust is scraped off the bottom of the cylinder by the metal edge in the presence of airflow that is delivered to the space just below the shaft. The WDF must be used with an inlet flow rate of 25 L min^{-1} to insure complete disaggregation of the test dust.²⁶ The inlet air carries the scraped dust down a tube for release into the target system. Pressurized airflow of 25 L min^{-1} , monitored with a rotameter, was fed through the dust feeder and dust

and air were injected into the system through a 0.32 cm tube opening into a funnel that measured 5.40 cm at its widest point.

The WDF dust output rate is not constant, and the variability may affect the particle size distribution of the test dust. This is possibly caused by incomplete disaggregation of the packed dust.^{27,28} This is likely due to small differences in how tightly the dust is packed for each run. Further, clogging can temporarily disrupt the emission rate. In such circumstances, it is likely that the particle size distribution is slightly altered and will tend toward emitting more larger particles than originally expected due to the agglomeration of smaller particles.

Wind tunnel deposition experiments

The configurations tested in the wind tunnel were a Hooded and Non-Hooded version of the ELDS. All dust experiments were completed according to the following procedure. The passive sampler was loaded with pre-weighed, 37 mm PTFE (Teflon) filters. The Wright Dust Feeder small dust cylinder (diameter = 1.35 cm) was packed tightly with dust to within approximately 1.5 cm of the opening. The exact level of dust is not important as long as the dust cylinder is tightened to insure contact with the dust scraping mechanism. Laboratory pressurized air (25 L min⁻¹) was attached to first a rotameter and then the Wright Dust Feeder. The passive sampler of a particular configuration was attached inside the tunnel, and the variac and fan settings were set to achieve the desired air speed of 0.65 m s⁻¹, which was measured by a digital velometer.

An active sampler was set to a flow rate of 3.5 L min⁻¹ and attached inside the tunnel to collect a representative dust sample. The inlet was positioned perpendicular to the air stream, as the active sampler was meant to collect a representative sample of mass but not under isokinetic conditions. Isokinetic sampling was not necessary for this step as the purpose of the active sampler was to collect a “grab sample” to monitor the mass output of the WDF. The active sampler was not used to characterize particle size abundance.

Each sampling experiment consisted of eight 30 minute experiments plus a 10 minute add-on at the end to achieve 250 minutes of passive sampling. During each 30 minute run, a new active sampler was operated for 10 minutes to estimate dust mass during each session, to account for the inherent variable nature of the Wright Dust Feeder. After 30 minutes, the Wright Dust Feeder was repacked with dust and reset, and the passive sampler was rotated 90 degrees, counter-clockwise, to achieve a more even particle distribution across the four filters. Electrostatic deposition of particulates was evident on the wind tunnel and walls. To minimize re-suspension, in between experiments the wind tunnel was vacuumed and all samplers and cartridges were cleaned. Wet cleaning methods were not used based on the results of the results of a re-suspension and particle infiltration test that indicated that the dry cleaning methods were sufficient.

Re-suspension particle infiltration into the wind tunnel

The smallest particle size bin measured using the Coulter counter (data provided by Powder Technology, Inc.) for the test dust was 0.711 μm . Using optical microscopy particle sizes as small as 0.510 micrometers were detected on the ELDS. For distribution comparison, all particles found to be smaller than 0.711 μm on sampling filters were reclassified as 0.711

µm. A test was conducted inside the wind tunnel to test for particle infiltration from room air and re-suspension of test dust after cleaning. In all, only six particles were found using optical microscopy, on two filters over one 4 hour test. Therefore, the ambient and re-suspended dust contribution to the detectable concentration of dust within the wind tunnel was negligible. The results also indicate that the fine particles found on sampling filters were either originally present in the test dust or generated by the WDF.

Passive sampler preparation (Hooded and Non-Hooded configurations)

The 37 mm PTFE (Teflon) filters used in both the active and passive samplers were pre-weighed in a temperature and humidity controlled weighing room (21 °C, 31–39% relative humidity) and then stored in individual filter cases prior to their use. The entire cassette and its individual components were cleaned with alcohol swabs prior to placement of the filters. After the sampler's base components were reassembled (filter supports cleaned and placed back into base) the filters were placed on top of the supports and the filter locks were screwed into place. The filter location was noted (location A, B, C, or D) on the underside of the filter cassette.

Jersey City, NJ field experiment

A field experiment was conducted in Jersey City, New Jersey at the Garfield Avenue Chromium Remediation Site. Jersey City has a long history with chromium, beginning in the early 1900s. From 1905 to 1976, chromite ore was processed in Jersey City to convert trivalent chromium to hexavalent chromium (Cr^{6+}) which is a more soluble form of the element.²⁹ The waste that resulted from this process was used as landfill for nearby construction projects, resulting in over 160 contaminated waste sites around Jersey City.^{29,30} Though many sites have been remediated or are currently undergoing remediation, the risk of exposure to chromium continues to exist in Jersey City. This is especially of concern during remediation work, when previously buried stores of chromium have the potential to become re-suspended in the local air.

While trivalent chromium is a necessary trace element required by humans in very small amounts, the hexavalent form is toxic. Depending on the exposure duration and concentration, chromium(VI) can cause lung cancer, gastrointestinal bleeding, kidney or liver failure, ulcers, skin and mucosal irritations, and perforated septums.^{29,31} Children are especially at risk due to their playing habits and behaviors, which can include inadvertent ingestion of chromium(VI) and an increased percentage of metal uptake from the digestive system to the bloodstream.³² Ingestion may occur when children touch contaminated surfaces and then place their hands, toys or food into their mouths. Surface loading of environmental contaminants can demonstrate the potential risk of exposure for children in a home.^{3,33–35}

For this experiment, two Hooded samplers were placed in the same location over three sampling periods. The location was near a known hexavalent chromium waste site that was actively undergoing remediation. The aim of field testing was to conduct sampling before and during site remediation for a two-part study. However, due to a spike in chromium levels, work was temporarily stopped on the site.³⁶ Because of this event, it was possible to

collect samples using the ELDS after work on the site had stopped. The field tests were also conducted at a time when there was an opportunity to compare the ELDS data to chromium values measured by onsite active samplers. The data collected by the active samplers are published in a monthly report. This report was used to compare the variability in chromium levels over the full course of the site remediation.³⁶ Additionally, a nearby NOAA weather station measured 10.32 in (26.21 cm) of precipitation over the field sampling period.³⁷ This precipitation provided the opportunity to test the ELDS under rain conditions.

Work at the chromium remediation site had to be stopped if Cr^{6+} levels are shown to reach the site's "actionable level" of 49 ng m^{-3} of air, set by the New Jersey Department of Environmental Protection.³⁸ This situation occurred during the study. Dust-suppression measures are routinely used to minimize dust re-suspension, and therefore chromium re-suspension. These measures include water misting and spraying of dust-suppression materials, tarps placed on excavated dirt, and limiting trucks to paved areas only.³⁸ Despite these efforts, the site did reach its actionable level over the course of the study, providing a unique opportunity for study. This opportunity will be further discussed.

Particle size analysis

Particles collected on each filter were analyzed using a Zeiss Imager.A1 microscope, which has transmitted and reflected light options. Analysis was done to allow for direct comparison between the particle size distribution collected by the samplers and the known size distribution of the Arizona Fine Test Dust. $40\times$ magnification and the dark field were used to avoid filter interference. Transmitted light was used and the light setting was 90% of the total available light. At least one-hundred images, corresponding to one-hundred fields of each filter, were taken and later analyzed using ImageJ, an image analysis program by the National Institute of Health.³⁹ During analysis, images were discarded if they showed filter "noise", in which pieces of the filter can be seen (due to incomplete saturation with mineral oil). This was corrected for by limiting particle size counting to $0.51 \mu\text{m}$. Filter noise, representing the filter characteristics showing through the image, usually presented about $1/10^{\text{th}}$ of this size. Images were processed using the following method: the size of the sampling field was set using a reticule. After that, the background was cleared and the images set to 8 bit resolution. Next, a threshold was obtained that included all particles but minimized noise. Lastly, all particles were enumerated and sized electronically and the data were stored in a spreadsheet.

Particle statistics

The particle size statistical analysis was divided into two areas of comparison: accuracy, which encompassed comparisons between different sampler configurations (Hooded and Non-Hooded) and the test dust, and precision, which encompassed comparisons between the individual experiments within each sampler configuration. The tests were designed to evaluate the ability of the different sampler configurations to accurately represent the test dust, and the ability to reproduce results.

Each wind tunnel experiment (4 for Non-Hooded, 3 for Hooded wind tunnel samplers) provided four filters with mass for analysis. Two were randomly chosen from each base for

particle size analysis. The particle size distributions of these two filter samplers were pooled together to form the particle distribution dataset for each run. For instance, the particle size distributions of the two filters from Hood 1 (the first Hooded sampling run) were pooled together to form the dataset “Hood 1”. This dataset was then compared to the Hood 2 and Hood 3 runs for the precision analysis. To compare the different sampler configurations with the test dust, all the datasets from each individual configuration were pooled. For example, Hood 1, Hood 2, and Hood 3 were pooled to form the dataset “Hooded”. The pooled distribution was then compared to the “Non-Hooded” and “test dust” datasets.

The comparison was made using the chi-square test, since it compares the entire distribution, rather than a central tendency or variance as each distribution was highly skewed toward right-tails. The chi-square test allowed for analysis over the whole distribution, which was important for determining the efficacy of the sampler configurations to accurately represent the test dust. To be able to use the chi-square goodness-of-fit test, it was necessary to divide the particle size distributions into bins of equal particle diameter size ranges. Optimal bin size was decided upon using Scott's formula:^{40,41}

$$h = \frac{3.49s}{n^{1/3}} \quad (1)$$

where h is the bin width, s is the standard deviation, and n is the sample size. In order to choose a bin width that would represent all the data, the “Hooded” and “Non-Hooded” datasets were temporarily combined and “ n ” and “ s ” were found from this pooled data. The test dust was not included because the information for the test dust was provided by the manufacturer in a percentage format already in size bins (not in a raw data format that would provide a more accurate standard deviation); because of this, “ n ” was unknown for the test dust. Eqn (1) yielded a bin width of 0.280 mm, which was small enough to still represent the dataset.

For quality control, the main datasets (Hooded, Non-Hooded, and Test Dust) were also tested using other bin assignment methods. These methods allow the user to choose the number of bins, which in turn translate to bin widths. The first method was Sturges' (equation):⁴²

$$k = 1 + 3.3(\log_{10} n) \quad (2)$$

where k is the number of bins needed and n is the sample size. This method yielded a bin size of 2.272 μm , which caused some information loss in the finer details of the particle size distributions. The last method test was Doane's (equation):⁴⁰

$$k = 1 + \ln n + \ln \left(1 + \gamma \sqrt{\frac{n}{6}} \right) \quad (3)$$

where k is the number of bins needed, n is the sample size, and γ is the kurtosis of the distribution. This method yielded a bin size of 1.893 μm , which is still too large to

accurately represent the fine details of the distributions. While Sturges' and Doane's methods are useful for quality control, Scott's method was the best for placing the data into size bins while still maintaining the details of each size distributions.

Results

Wind tunnel experiment results

The wind tunnel experiment results are provided as graphical representations and statistical results for the measured particle size distributions obtained from two filters selected from each run. Table 1 lists all wind tunnel experiments and the statistical comparisons. The XRF side of the sampler was a late addition and not characterized for particle size, though the mass results can be seen in Table 2.

The actual particle size distribution of the test dust (from manufacture) and the size distributions for the Hooded and Non-Hooded sampler experimental results are shown in Fig. 3 and 4. These show that the percent abundance of particles within each size bin (Scott's method) is similar across the distributions measured for the Hooded and Non-Hooded samplers, and the test dust. Differences were recorded at the tails due to fluctuations in particle counts, but this accounted for less than 0.2% of the entire particle size distribution. The test dust and Hooded sampler configuration show a greater number of fine particles than the Non-Hooded configuration. Despite this difference, the shapes of the two sampler configuration's particle size distributions are more similar to each other than the test dust. This may be due to slight changes to the test dust particle size distributions caused by the actions of the Wright Dust Feeder during operation; an observation also made by Akiyama *et al.*, and Liden *et al.*^{27,28}

The particle size distributions of the Hooded and Non-Hooded samplers were compared statistically to each other and to the test dust using a chi-square goodness-of-fit test at the 0.05 significance level. An alpha value of less than 0.05 would indicate that the distributions are statistically different and did not likely result from the same, original source. An alpha above 0.05 indicated that the distributions are statistically not different. Using Scott's optimal bin method, it was found that the *p*-value resulting from the comparison of the three size distributions was 1.000 (see Table 1) indicating that the Hooded, Non-Hooded, and test dust particle size distributions are statistically not different and not significantly modified during generation or collection by each sampler. For quality assurance, a chi-square goodness-of-fit test was also performed on the same data using both Sturges' and Doane's optimal bin size methods. The *p*-value was 0.996 for Sturges' method and 1.000 for Doane's method. Both these values support the observation that the Hooded, Non-Hooded, and test dust particle size distributions are statistically not different. These results further indicate that the Hooded sampler configuration does not produce any size selection bias compared to the Non-Hooded configuration and the test dust.

Hooded sampler experiments

The particle size distributions showed a high degree of similarity except at the tails, which represent a difference of less than 0.5% for the entire particle size distribution. Hood 3

showed a greater number of fine particles than the other two experiments, and therefore a slightly less numbers of larger particles, indicating that there may have been some incomplete disaggregation of the test dust for Hood 1 and Hood 2. This possibility was also mentioned by Akiyama *et al.* and Liden *et al.*^{27,28}

The three sampling experiments of the Hooded sampler configuration were compared using the chi-square goodness-of-fit test. The *p*-value was found to be 1.000, indicating that the particle size distributions of the three experiments are statistically not different. This result demonstrates the precision of the Hooded sampler. Using non-binned data, the precision value was calculated to be 0.06 based on the mean particle diameter. Thus, the sampler is able to obtain repeatable results over multiple tests.

Non-hooded sampler experiments

The four Non-Hooded sampler configuration experiments differ in their amounts of detected fine particles (<2.5 μm), which ranged from 38 to 56% percent abundance of the total distribution. These differences are reflected by the percentages of measured larger particles. The greater the number of smaller particles, the less the percentage of larger particles. This again can be attributed to differences in disaggregation in the Wright Dust Feeder for individual runs. The four sampling experiments of the Non-Hooded sampler were compared in the same way the runs of the Hooded sampler were. Again, the *p*-value was found to be 1.000, indicating that the particle size distributions of the four Non-Hooded sampling experiments are statistically not different. These results show that like the Hooded version of the ELDS, the Non-Hooded sampler demonstrates precision and is able to obtain repeatable results. Using non-binned data, the precision value was calculated to be 0.21 based on the mean particle diameter.

Field experiments

The Cr^{6+} air concentrations obtained in $\mu\text{g m}^{-3}$ of air by the site-remediation team's active air sampler in Jersey City are shown Table 3. In addition, the ELDS results are also in Table 3, in units of $\mu\text{g Cr}^{6+}$ per g of collected mass. The information about the type of individual onsite active sampler is not available, so it was not possible to convert the air concentration to a surface area concentration. The ELDS measure surface deposition, not air concentration, and the onsite samplers were used as a reference instead of a direct comparison. Review of the ambient air data showed that during remediation the amount of Cr^{6+} present in the air was double that of the pre-remediation levels. After remediation was halted, the levels of Cr^{6+} dropped to just below pre-remediation levels. Deposition data for the ELDS show a similar pattern, but with an even greater increase in Cr^{6+} during remediation. After remediation began, chromium levels on the ELDS filters, represented as $\mu\text{g m}^{-2}$, measured an increase by a factor of 4.9 times, then dropped by more than half of the pre-remediation level after remediation stopped. The amount of chromium in dust also increased during the remediation period, suggesting that chromium levels in the ground were higher in areas where soil was removed. The concentration of Cr^{6+} in dust more than doubled during the remediation period and dropped to approximately a third of the initial pre-remediation value after work was halted.

Discussion

The results of the wind tunnel and field experiments demonstrate that the ELDS sampler is an effective tool for sampling dry deposition. The controlled wind tunnel experiments characterized the particle size collection capabilities of the sampler. The results showed that the sampler collects a representative sample of particle size distribution of the dust that was presented to it during the laboratory experiments. The field test demonstrates the ability of the sampler to collect quantitative data in an outdoor, real-world situation. The deposited dust collected by the ELDS filters were successfully analyzed for total mass and chromium content in a laboratory, by gravimetric and chemical analyses, respectively.

The wind tunnel provided for controlled environments and selection of a test dust with a known distribution, in particular one that ensured that there were particles above 0.5 μm , to examine a wide range of particle sizes. In addition, the experiments with test dust in the wind tunnel gave the opportunity to have repeated experiments completed under the same conditions. The chi-square test results of the three Hooded experiments and the four Non-Hooded experiments show that all the experiments conducted for each individual sampler were comparable to each other and collected particle size distributions that were statistically not different. This provided confidence that when using the ELDS for atmospheric deposition experiments the results would be interpretable and reflective of the levels of PM in the surrounding air.

The Hooded and Non-Hooded versions of the sampler yielded similar particle size distributions. There was an early concern because it was thought that the hood could physically block particle sedimentation (gravitational settling) as particles settled from the air. In addition, it was thought that it could be possible that Brownian motion (the interaction of fine particles within air molecules) could cause smaller particles to stay suspended within the hood. Because the Hooded and Non-Hooded samplers' particle size distributions were found to be not statistically different, it can be concluded that the protective Hood did not alter the test dust particle size distribution collected on the ELDS filters. This is an important finding because it means that the ELDS is not just a reliable sampling tool, but also versatile. The sampler can be used with or without the hood, or even as a dust plate, used without the central support. This can be concluded because the Non-Hooded version, which is open to the elements, collects particle size distributions that are statistically not different from the Hooded version. When compared to a water surface sampler, the ELDS is a more user-friendly option as there are no moving parts or replacement needed during sampling unless filters need to be replaced. In that case, the base can be removed by simply unscrewing it and attaching a new base with pre-loaded filters. There is no need to transfer dust from one medium to another to determine the mass collected, which is necessary in other deposition samplers such as the dust bucket and dust fall collection trap, where dust in collected water needs to be transferred to a filter medium or condensed for analysis.

Wagner and Leith¹⁰ developed a wind tunnel to test their sampler. Their test dust ranged in size from 0.6 to 9 μm and their wind tunnel speeds ranged from 1.5 to 5 m s^{-1} .¹⁰ They compared the mean value of the particle sizes found on their sampler to the mean value collected in a cascade impactor. Their data were binned into nine size bins and the main

statistical comparison was the coefficient of variation (CV) which is the standard deviation divided by the mean.¹⁰ Three samplers were tested during each experiment to test precision and it was found that the CV varied amongst size ranges, having a CV of 18.1% for PM_{2.5} and a CV of 32.2% for PM₁₀.¹⁰ This sampler was tested only for fine and coarse particles, size ranges that are typically sampled for with active and passive samplers. The ELDS is different in that it was successfully tested for fine, coarse, and supercoarse particles, covering a wide range of particle sizes. In addition, the ELDS was tested using smaller size bins which more accurately reflect the actual size distribution.

Ott and Peters also tested the Wagner and Leith sampler in a wind tunnel to test different shelters for their sampler.¹¹ They compared the particle sizes collected in the Wagner–Leith sampler to a dichotomous sampler. They compared the PM_{10–2.5} ratio of the passive and dichotomous samplers, with a ratio of 1 indicating that the samplers are equal, additionally they compared the CV.¹¹ They selected their “Flat Plates Shelter” for field experiments after it was found to have the lowest ratio of 1.04 and the lowest CV of 13.4%.¹¹ Field tests showed a PM_{10–2.5} ratio ranging from 1.11 to 1.49 and a CV ranging from 3.4–20.8% over eight tests.¹¹ The shelter for the ELDS was tested for all size ranges concurrently and over a wider more closely defined size range. The results indicated that the ELDS can be used to successfully collect a wide range of particles.

Lin *et al.* tested their sampler in a wind tunnel to test whether wind direction could be ascertained after observing the deposition of particles inside separate channels within their sampler.¹⁵ They found that wind speeds inside the sampler were at least halved throughout each channel, which aided in PM deposition.¹⁵ While there are not 360 channels relating to every wind direction, it is useful for determining the general direction of particulate influx. The sampler was not characterized for the full particle size distribution, as wind direction was the focus of research. Lin's sampler and the ELDS are very different samplers. While Lin's sampler relied on deposition from wind flow through a channel, the ELDS is open which facilitates gravitational settling across the entire base.

For the Jersey City field study there were three main sampling periods, “pre-remediation”, “remediation”, and “halted”. The active sampler on site showed an air concentration of chromium increased to 1.9 times the initial level during the “remediation” phase of the experiment. These data were found by averaging the chromium level found for each day within each of the three time periods. After, the chromium levels fell by a factor a 1.9 during the “halted” phase, effectively returning to the “pre-remediation” level. The ELDS measures deposition, or surface area concentration, and Cr⁶⁺ levels of the deposited dust were measured and compared to the total mass collected. Thus, the data differ from the active sampler evaluation method in that they were not averaged, but evaluated for the cumulative total loading. Over the three sampling periods, the “remediation” phase showed a 2.2 factor increase in Cr⁶⁺ dust concentration (µg Cr⁶⁺ per g dust) as compared to the “initial phase” and a 6.5 factor drop from the “remediation” to the “halted” phase. While the factor increase for the “remediation” phase is similar to the active sampler, the “halted” phase shows a greater drop in chromium. These results from the ELDS are not only an indication of air concentration but also an indication of the increase of Cr⁶⁺ concentration in deposited dust over the remediation time period. These values likely reflect increasing Cr⁶⁺ in the exposed

site soil over the remediation period. As the upper layers of soil were removed, the Cr⁶⁺ contaminated layers were revealed as a new surface. The ELDS can be used over varying time periods as long as there is a measurable amount of dust mass on the filters. In this field study, it was used to measure long-term (approximately 3–6 weeks at a time) deposition.

The ELDS measured chromium surface deposition ($\mu\text{g m}^{-2}$) for the time periods mentioned above. During the “remediation” phase, Cr⁶⁺ levels increased by a factor of 4.9 from the “initial” phase and decreased by a factor of 10.5 from the “remediation” to the “halted” phase. This is a better indication of the long-term impact of chromium on the neighborhood around the site, and indicated that chromium was likely accumulating on surfaces in the neighborhood over the “remediation” time period. Long-term accumulation on surfaces can affect air concentration if re-suspension occurs and can also cause Cr⁶⁺ and other contaminants to be tracked into homes by pets and people.⁴³ For instance, Cr⁶⁺ could have settled on roads, sidewalks, lawns, and front porches. Cars driving on roads could stir dust into the air, increasing deposition on other surfaces. Cr⁶⁺ on walking surfaces can be tracked into homes on shoes. Dry deposition on surfaces is important for understanding the long-term accumulation impact of particulate matter and the contaminants and chemicals that make up that matter.

Previous studies in Jersey City have sought to quantify Cr⁶⁺ exposure as it relates to residents and households in the area. A study by Liroy *et al.* that examined chromium in household dust found that levels ranged from 3.25–320 ng cm⁻² in indoor wipe samples and 1.0–12 ng cm⁻² in vacuum samplers.^{33,44} The results of the Jersey City ELDS experiment are 1.78 ng cm⁻² for outdoor samples, which differ from indoor environments that are subject to different cleaning habits, accumulation of dust, and varied exposure to the outdoors. The metric of Cr dust concentration ($\mu\text{g Cr per g dust}$) has also been shown to have a statistically significant relationship to Cr levels in urine.⁴⁵ Thus, the samples may be useful in long-term biomonitoring studies for long lived agents.

Based upon the field and laboratory results the ELDS can be used both inside and outside to measure the flux of contaminants such as chromium, pesticide, and lead from the outdoor to the indoor environment. A typical placement of a dust plate-like device is to place it on surfaces that people often come into contact with on a daily basis or to place them at varying heights to measure the gradient of dust in a room.² Placing the ELDS, for instance, on a table, would allow the cumulative surface loading of dust and contaminants on that table to be measured while still allowing that table to be kept clean and used. Studying the gradient of dust over the height of a room can provide important exposure information for children, who often play on the floor and studies have shown that dust accumulation is greater closer to the floor.²

The ELDS was not tested under high wind conditions, which could cause re-suspension of particulates. Future research considerations can include variable wind speeds and variable heights between the filter base and the edge of the hood. Additionally, larger hood sizes can be tested, though a larger hood will likely serve as a barrier to particle deposition.

The ELDS can be easily deployed and uses standard (easily purchased) 37 mm filters. This is important if deposition data are needed in an emergency situation or a situation for which a power source is not an option or impractical. The samplers can be quickly placed around an area of interest and then analyzed later in a laboratory without maintenance needed in the interim period.

Conclusions

The Einstein–Lioy Deposition Sampler is a versatile, dry-deposition, passive, particulate sampler. It is simple, does not require electricity, and can be used to sample for particulate matter and solid chemicals and elements. It does not require a power source, which allows the sampler to be used anywhere. In addition, there are no moving parts, so very little setup and maintenance is needed when using the device.

The sampler has been tested and characterized in a wind tunnel against a dust with a known particle size distribution: Fine Arizona Road Dust. It was shown that the sampler is both accurate and precise in collecting a known particle size distribution. It is precise because both configuration distributions found from the individual experiments of each configuration were shown to be not different.

Field tests at the Cr⁶⁺ remediation sites demonstrated the performance of the sampler in a real-world situation. The ELDS measured the rise and fall in chromium near a known chromium waste site during and after remediation. Mass was collected and retained on Teflon filters over the sampling periods. The ELDS could be transported to and from the sampling site with ease.

For instance, samplers placed around a residence and inside can be compared to analyze the amount of dust deposited indoors compared to outdoor deposition. These data can indicate the amount of infiltration from outdoors to indoors and are important when evaluating the health and safety of residents near known waste sites and contamination over time due to accidents or terrorism attacks.

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Abbreviations

ELDS	Einstein–Liroy Deposition Sampler
PM	Particulate Matter
PM₁₀	Particulate Matter 10 micrometers or smaller in diameter
PM_{2.5}	Particulate Matter 2.5 micrometers or smaller in diameter
XRF	X-Ray Fluorescence
WDF	Wright Dust Feeder
PTFE	Polytetrafluoroethylene (Teflon)
CV	Coefficient of Variation
Cr	Chromium
Cr⁶	Hexavalent chromium

Environmental impact

The Einstein–Lioy Deposition Sampler (ELDS) provides a new means to collect surface deposition samples through passive deposition. The sampler does not require any power source to operate, as it is completely passive. In addition, it utilizes four 37 millimeter filters of any type, allowing for the use of standard filter analysis procedures. The ELDS can be used in multiple configurations: suspended from a support with a protective hood for outdoor use, suspended from a support without the protective hood, and as a dust plate. The ELDS has been shown in laboratory tests to collect particle size distributions representative of the surrounding environment. It can be used both indoors and outdoors for a variety of sampling needs.

Fig. 1.
 (a) The ELDS sampler shown in the Hooded configuration. (b) Schematic of the ELDS sampler base showing the diameters of the components.

Fig. 2.
Wind tunnel design including wind velocity and measurements.

Fig. 3.
Graph depicting the particle size distributions of the test dust and the Hooded and Non-Hooded sampler configurations.

Fig. 4. Graph depicting the particle size distributions of the test dust and the Hooded and Non-Hooded sampler configurations at the tails.

Table 1

Results of the wind tunnel experiments

Wind tunnel experiments					
Sampler configuration	Data acquisition	Chi-square value	p-value	Significance	Conclusion
Hooded	Pooled data from Hood 1–3	14,323	1,000	Not statistically significant	The particle size distributions are statistically not different
Non-Hooded	Pooled data from Non-Hooded 1–4				
Arizona Fine Test Dust	Manufacturer provided				
Hood 1	Pooled data from 2 filters of the run	16,458	1,000	Not statistically significant	The particle size distributions are statistically not different
Hood 2	Pooled data from 2 filters of the run				
Hood 3	Pooled data from 2 filters of the run				
Non-Hooded 1	Pooled data from 2 filters of the run	29,918	1,000	Not statistically significant	The particle size distributions are statistically not different
Non-Hooded 2	Pooled data from 2 filters of the run				
Non-Hooded 3	Pooled data from 2 filters of the run				
Non-Hooded 4	Pooled data from 2 filters of the run				

Table 2
XRF mass data demonstrating the ability of the XRF ELDS component to collect and retain mass

	Average filter gain (mg)	Standard deviation	Coefficient of variation
XRF 1	0.17	0.01	0.01
XRF 2	0.65	0.06	0.10

Table 3

Chromium results from Jersey City three-part field test. The 30 day value was found by dividing by the days in the field and multiplying by 30. It is a reference value only because particulates did not necessarily deposit in even intervals

Dates in field	Total days	Active sampler Cr(VI) ($\mu\text{g m}^{-3}$)	ELDS average ($\mu\text{g Cr(VI)}$ per g dust) for time period	Std dev.	$\mu\text{g g}^{-1}$ corrected for 30 days (reference only)	ELDS average Cr(VI) deposition ($\mu\text{g m}^{-2}$)	Std dev.
5/27/10–6/29/10 Pre-remediation	33	8.70×10^{-3}	1.52	0.70	1.38	3.64	1.21
6/29/10–9/13/10 Remediating	45	1.64×10^{-2}	3.40	0.93	2.27	17.77	5.37
9/12/10–10/4/10 Halted	21	8.50×10^{-3}	0.52	0.56	0.74	1.70	1.96