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Journal of Hazardous Materials 132 (2006) 1–13

Journal of Hazardous Materials

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Technologies for laboratory generation of dust from geological materials

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Available online 19 January 2006

Abstract

Dusts generated in the laboratory from soils and sediments are used to evaluate the emission intensities, composition, and environmental and health impacts of mineral aerosols. Laboratory dust generation is also utilized in other disciplines including process control and occupational hygiene in manufacturing, inhalation toxicology, environmental health and epidemiology, and pharmaceutics. Many widely available and/or easily obtainable laboratory or commercial appliances can be used to generate mineral aerosols, and several distinct classes of dust generators (fluidization devices, dustfall chambers, rotating drums/tubes) are used for geological particulate studies. Dozens of different devices designed to create dust from soils and sediments under controlled laboratory conditions are documented and described in this paper. When choosing a specific instrument, investigators must consider some important caveats: different classes of dust generators characterize different properties (complete collection of a small puff of aerosol versus sampling of a representative portion of a large aerosol cloud) and physical processes (resuspension of deposited dust versus in situ production of dust). The quantity "dustiness" has been used in industrial and environmental health research; though it has been quantified in different ways by different investigators, it should also be applicable to studies of geological aerosol production. Using standardized dust-production devices and definitions of dustiness will improve comparisons between laboratories and instruments: lessons learned from other disciplines can be used to improve laboratory research on the generation of atmospheric dusts from geological sources.

Keywords: Mineral aerosol; Fugitive dust; Dust generator; Resuspension; Dustiness

1. Introduction

"Dust" in a geological context generally refers to solid inorganic particles emitted into the air directly from the earth's crust by the wind ("mineral aerosol" or "soil dust") or by human activities ("fugitive dust"). Dust generated from surfaces such as unvegetated deserts, agricultural fields, road beds, disturbed lands, and construction and industrial sites, as well as aerosols generated by mineral extraction and processing industries, are significant sources of geologically sourced airborne particulate matter (PM) in many regions. Many investigations associated with PM source apportionments involving dust aerosols have been performed to distinguish the contributions of "geological materials" or "soils" as a broad category within the total particulate burden.

A comparatively small number of studies have used multiple dust parent materials in their "source libraries." Using a limited number of dust source materials makes it more difficult (at best) to quantify the contributions of road dust, wind-eroded dust or particulate emissions from agricultural operations as general categories, much less individual "source emissions sub-types within some of (those) categories" [1]. A relatively large number of source material samples will be generally needed for careful sub-apportionment of the sources of geological dust, given the spatial scales of physicochemical variation of soils and sediments. Obtaining characterizations of dust particles from multiple sites and emission types can provide a "marked improvement" [2] in determining which specific dust sources are present in PM.

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doi:10.1016/j.jhazmat.2005.11.083

Generating, collecting and measuring aerosols in a controlled laboratory setting can be an important tool for determining the emission potentials of different dust sources, measuring the "dustiness" (inherent tendency to produce dust: the dimensionless amount of dust produced from a specific amount of a material under standardized conditions) of different samples, as well as determining the physical characteristics, chemical composition, and/or environmental health and toxicological effects of the particulate matter emitted from specific sites or source materials. However, dust generated in a laboratory setting should be similar in particle size, shape and composition to ambient dust aerosols or at least some component of them, and free of contamination resulting from the (dust generation) process [3]. This paper documents and categorizes the many devices used by various research groups to generate dry powder aerosols in the laboratory with applications to geological dust generation and dustiness testing. It is shown that the myriad of different dust-making techniques and tools and definitions of "dustiness" results in many different results, suggesting a great need for standardization and intercomparison of laboratory-generated airborne PM from geologic media.

2. A review of laboratory dust aerosol generation systems

Dozens of varieties of dust generation/resuspension/sampling chambers have been described in literature; previous reviews of some devices were made by Kaya et al. [3] and Willeke [4] for biomedical applications and by Cowherd and Grelinger [5] for wind erosion and fugitive dust research. Dust generation and dustiness testing instruments have been designed for a wide variety of purposes: for simulating indoor air in dusty manufacturing facilities [6]; for industrial process control [7]; in the pharmaceutical industry (where the objective may be to develop devices such as dry-powder inhalers that maximize the concentration of fine aerosols, for optimal delivery into the respiratory tract) [8–13]; exposing laboratory animals to mineral aerosols for respiratory disease studies [14,15]; preparing samples for chemical analysis [16]; measuring ecophysiological effects of dust accumulation on leaves [17]; simulating solid particle penetration into buildings [18,19]; or even to predict mineral dust accumulation or dispersion on other planets or outer space [20]. Relatively few systems have been strictly utilized for production and investigation of fugitive dusts or mineral aerosol for atmospheric particulate matter research.

2.1. Early dust generators

Among the initial workers to develop their own laboratory apparatus to test the dust-producing ability of substances were Andreasen et al. in Germany [21]. They utilized a long, thin glass tube in which the time required for a given amount of material to fall to the bottom was measured and related to particle sizes using Stokes' law. This research included some of the first investigations of the effects of particle size, humidity and moisture content on the dust-producing ability of a wide variety of materials. Their device can be seen as an early forerunner to an entire class of modern free-fall dust-generation chambers for industrial applications of dustiness testing and particle sizing [22–25], as well as devices with applications to geological dust research [26–29]. Other early dust generators (described in [30]) included devices based on shaking material through a sieve [31,32], as well as the "Wright Dust Feed" [33,34], which used a scraper blade to generate dust from a rotating cylindrical plug of source material.

Most laboratory methods to create mineral dust for particulate matter research (with applications to either indoor or outdoor air) have one feature in common; the eventual requirement of the collection of a physical aerosol sample on a filter medium for gravimetric analysis. Fewer systems reported in the literature have relied on other technologies such as optical sensors [35] or a tapered-element oscillating microbalance (TEOM) [36,37] to measure dust concentrations.

2.2. Utilization and modification of commercial devices

A number of commercial dry aerosol generation devices are available, but they appear to not have been widely used for laboratory studies of dust. A "device for producing a solid aerosol" [38] was eventually commercialized (Palas Aerolsoltechnologie GmbH, Germany) into a "solid particle (dust) disperser," and has been used (for example) to resuspend coal and coal ash particles to expose laboratory mice in a health effects study [39].

Numerous dry dust generation devices have been created by modifying simple, widely available, and/or easily obtainable "commercial off-the-shelf" (COTS) appliances. Miller and Woodbury [40] modified a blender to generate dust from cattle-feedlot soil samples as part of a test of dust emissions under different environmental conditions. The "Dry Particulate Aerosol Generator" described by Ledbetter et al. [41] used an air jet to blow particles off of commercial cotton string wound on standard fishing reels, while the "Automatic Air Pollution Reproducer" [42] was fashioned from laboratory flasks and agitators to supply dust to animals. The "Turntable Dust Feeder" [43] used a rotating cylinder to deliver dust to a turntable's groove where it was picked up by an adjustable aspirator. A "Powder Blower" designed to apply an even coating of powder to the body for medical treatment (DeVilbiss Health Care Division, Somerset, PA, USA) was used by Garcia et al. [44] for laboratory suspension of dust source materials. A jar mill with ceramic media was used by Veranth et al. [45] to generate fine dust aerosols from desert sediments and mine tailings. On a larger scale, a mill mounted next to the inlet of a commercial ventilation system effectively became a "huge dust generator" for measuring aerosol exposure in livestock confinement buildings [46], while talcum powder was funneled into an air compressor to blow dust into an experimental building [19]. A commercial cement mixer was used as a type of rotating-drum dust generator [47].

Although standard COTS equipment can be used or modified to generate airborne dust in the laboratory, most dust-production instruments described in the literature appear to have been individually designed and assembled for a specific laboratory's experiments. The rest of this section will classify and describe many of these systems.

2.3. Classes and considerations for selection of modern laboratory dust-production systems

2.3.1. Sample preparation and collection

The dust generation/resuspension systems in active or recent use can be generally subdivided in two categories with regard to the amount of source sample used, proportion of the fine aerosol collected, and/or the amount of sample preparation required [48].

Some devices suspend a tiny amount of source material and attempt to collect all or as much of the dust emitted as possible in an aerosol sampler; these units generally create dust in discrete "puffs" via direct fluid entrainment of the source sample. Other systems generate a large cloud of dust in continuous "plumes," and aerosol sampler(s) collect only a small and hopefully representative part of it; dust is generally produced in these devices by applying mechanical and/or kinetic energy to the source sample.

Another significant difference between two classes of dust-producing instruments relates to the preparation of source materials prior to emission and collection of aerosols. Some dust-generating systems use sample powders (particularly soils) in more or less the undisturbed, mixed state they exist in nature, while others extensively sieve or otherwise pre-separate the source materials into various size-fractions before aerosolization. One type of system or the other may be the best choice for a given experiment, depending on the specific property or process meant to be measured.

Pre-separation of source material samples, sequential resuspension of different fractions, and complete collection of small "puffs" of dust can be of great value to quantify some parameters. For example, particle size and particle size distribution of a bulk material, as well as factors such as moisture content, density, and particle shape, are known to cause variations in the amount, particle size distribution, and chemical composition of the dust subsequently generated [49–51]. Concentrations of trace substances carried on the surface of airborne soil- or road-derived dust particles, including compounds potentially harmful to crops, livestock or humans, are known to be fractionated with particle size [51–54], especially in the PM10 size fraction of the source material [55,56].

Systems which perform complete aerosol collection by repeated sampling of dust evolved from size-fractionated source materials may provide a better understanding of this chemical fractionation of dust aerosols. Complete collection of all the dust produced from a small sample of source material also reduces concerns about aerosol sampling inefficiencies, which could influence the apparent magnitude of measured emissions [20,57], and provide multiple, replicated, homogenous and reproducible samples for testing specific toxicological hypotheses [45]. To do so, however, one must prepare the source sample very carefully, as incorrectly obtained or too-small analytical samples may not be representative of the bulk properties of the material [58,59]. One must also keep in mind the ability of geological materials, especially silt and sand sized particles, to break apart into finer grains during aeolian processes in the field [60,61].

Other aerosol generating systems create large, continuous plumes of dust by applying energy to a bulk material, then sampling only a (representative) portion of the evolved particles. Such devices may be used to best approximate the samples collected by field aerosol samplers near a dust source area. In the ambient environment, any given aerosol sampler collects only a tiny (but hopefully representative) fraction of what is effectively an infinite cloud of dust advecting at some (often unknown) velocity past a very small sampling device at a point in space. By generating a relatively large "plume" of airborne dust from a relatively large sample of the bulk parent material, then collecting a representative fraction of it, potential inaccuracies in source profiles due to physical and/or chemical heterogeneities in soil, most apparent in small samples [62], will be reduced.

Mineral dust plumes in the atmosphere represent a mix of aerosols generated by area sources generally at least thousands of square meters in size, and dustfall is generally much more chemically homogenous than any small-scale individual dust source material or subsample [52,61]. The larger the dust-source sample, the more likely it will be to represent the average characteristics of the parent material [57]. Soils often exhibit a great deal of natural variability in their physical properties and chemical compositions, even over spatial scales at or below the size of an individual field [63]. This variability is especially apparent in human-modified agricultural systems subject to tillage, irrigation, leveling, use by livestock, and/or amendment with trace-element rich pesticides, herbicides, and/or fertilizers [62,64–66]. Since different chemical elements in soil inherently vary on different spatial scales [67,68], care must be taken so that what may appear to be "diagnostic" ratios between constituents in a small soil sample might actually reflect the spatial scale of sampling more than the chemical variability of the soil itself.

2.3.2. Method of dust generation

Solid inorganic aerosols can be generated in the laboratory in many different ways. Dust can be created from the evaporation of liquid droplets or sprays; this technique has been used to create salt aerosols [69–71] and metallic compounds [72]. Acoustic energy, as used for sonic sieving by soil scientists or ultrasonic dispersion of sediments by geologists [73], or via loudspeakers [74–76] has been used to generate dusts [77–79]. An automated, stepper-motor controlled dry dust generator [80] has been used for epidemiological studies and as one of many ways to simulate dust aerosol exposures for inhalation toxicology laboratory experiments [81–83]. Wind tunnels, which are widely used to study the geophysical and micrometeorological aspects of aeolian processes, have also been used as dust aerosol generators [84–92]. Wind tunnels can recreate the saltation process [27,86], and are thus particularly well adapted to simulate wind erosion of soils and sediments.

Notwithstanding the above techniques, the majority of dust-production instruments can be divided into three classes according to the method by which aerosols are generated [5,48,93,94]:

(A) Fluidization (gas dispersion or ventilation)—in which dust is (re)suspended by direct entrainment into airflow in a tube;
(B) Gravitation (drop or "impact" method)—in which a source sample falls as a discrete slug through the air into or within an enclosed chamber, from which dust is evacuated;
(C) Mechanical dispersion or agitation (rotating drum and similar techniques)—in which the source material repeatedly falls from top to bottom of a horizontal, rotating cylinder or tube and is entrained into airflow.

2.3.2.1. Fluidization. Systems of class (A), gas dispersion/fluidizing bed, have long been used to create aerosols. The fluidization technique was described in 1922 for studies of powdered coal [95], and is still used for such purposes [96]. One of the first modern fluidized bed units, the Laboratory Dust Generator developed by Marple et al. [97] in the 1970s, used a chain conveyor to feed powders into a fluidizing bed system for mineral dust generation to calibrate optical particle counters and aerosol monitors. The fluidized bed method was specified by ASTM (American Society for Testing and Materials) as "a technique to measure the effectiveness of dust control agents for powders" [7]. The ASTM method requires 200 g of material to be placed in the bottom a "fluidizing bed dust chamber" consisting of a capped upright 3-in. diameter tube 18 in. long, with small 7/16 in. holes in the top and bottom caps in which a line of regulated 50 l/min air flows, "puffing/pulling" the dust up into the chamber. The tube is to be clamped to a vibrator running at 29,000 vibrations/min, continuously agitated for 20 min and continuously sampled by an aerosol sampler.

Fluidized bed units of various designs have been used to aerosolize geological materials for a wide variety of applications, from simulating clouds of airborne ash erupted from Mt. St. Helens [30] to aerodynamically separating various fractions of soil for analysis [98]. Rotating-brush dust generators (perhaps a commercial device [38]) were used by Sporenberg et al. [99] to test the particle collection characteristics of cascade impactors and by Pauluhn [100] to generate pesticide-contaminated clay dusts from carpet. A fluidized bed unit was used by Kinsey and Coveney [101] to suspend sieved soil samples; after flowing through a chamber and being discharged by a radioactive source, the particles were collected and size-classified using an Andersen cascade impactor for subsequent mineralogical classification and optical microscopy. Oghiso et al. [102] used a fluidizing bed dust generator to generate silica aerosols for a laboratory-animal toxicological study. Sethi and Schneider [95] reported that fluidization based dustiness testers are attractive in the case of cohesive materials, because the fluidization agent "deagglomerizes the powder."

Several research groups have utilized fluidization devices for dust source apportionment studies. Batterman et al. [103] used a fluidizing bed apparatus to resuspend soil and road dusts to develop representative source profiles for receptor modeling and measure variability of local fugitive dust sources, while Schütz and Sebert [104] used a fluidizing bed aerosol generator to produce samples to investigate the mineralogy of different Saharan dust sources. Another fluidized bed apparatus is part of the DRI Resuspension Sampling System [105] (Fig. 1). This system utilizes dried soil samples pre-sieved into the <38 μm (400 mesh) size fraction. A small quantity (0.1 g) of material is quickly pulsed or "puffed" into a chamber at a flow rate of 45–50 l/min for 5 s every 4 min. The system may run for several minutes to several hours. At most only a few grams of soil are used, and the general objective is to completely sample the incoming air for total characterization of a particular source. The volume of the chamber is approximately 400 l; inside the chamber, aerosols can be sampled simultaneously in the PM10, PM2.5, PM1, and TSP size ranges. The DRI resuspension system has been used to characterize fugitive dusts in Mexico [106], the USA-Mexico border region [107], and Hong Kong [108].

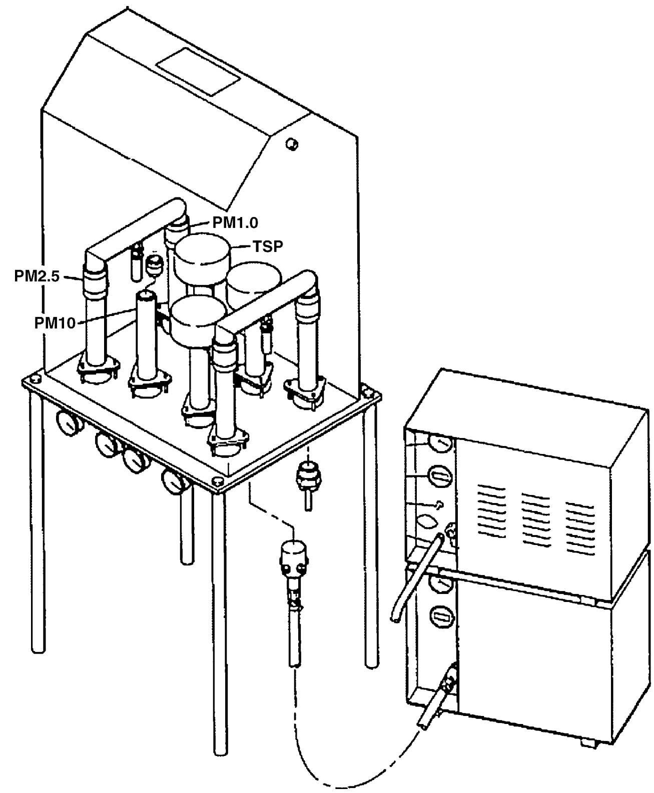

Fig. 1. The DRI resuspension sampling system (after Chow et al. [105]).

Another fluid dispersion system designed to operate with a very small amount of sample (∼1 g or less) is the UC Davis dust resuspension test chamber (Fig. 2) [109], designed to investigate PM10 [110] and PM2.5 [111] emissions from agricultural fields in the San Joaquin Valley of California. This two-part unit consists of dust resuspension and dust collection chambers. The dust collection unit is a painted wooden box with Plexiglas window in front, and has a volume of 92.5 l. A small quantity (usually 1 g) of soil, pre-sieved into a specific size fraction, is converted into fine aerosol by fluidization in the dust generation chamber, which consists of a stainless steel tube with conical taper at both ends and volume of 247.2 cm^3. This dust is precisely "puffed" through the system via air flowing at 3.7 l/m for 15 s every 15 min for total particulate sampling of a size-separated soil sample, utilizing an inlet inside the chamber attached to an IMPROVE aerosol sampler [112]. A similar chamber at Washington State University has been used for studies of wind-eroded dust on the

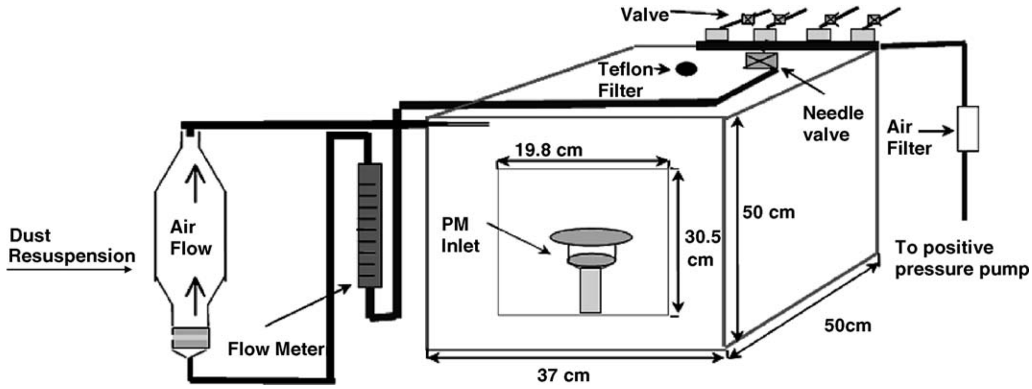

Fig. 2. The UC Davis resuspension test chamber (image courtesy Omar Carvacho).

Columbia Plateau [36], with a TEOM (tapered-element oscillating microbalance) [113] used as the PM10 measurement device.

The dust-producing systems mentioned above are best used for certain types of experiments. If the air in the settling/collection chamber is repeatedly sampled for a sufficiently long time, a nearly complete collection can be made of the aerosols in a given size range resuspended from a specific (but very small) source. This may be important when absolute physicochemical analysis of a particular sample (often pre-sieved into a particular size fraction of the pre-existing source material) is required, or as an input value for a receptor model. This type of device can also measure the complete resuspension potential of a given mass of material, or when counting of a specific number of dust particles is desired [20]. Similar fluidization systems using timed "puffing" pulses of air to transport limited amounts of dust have been utilized in inhalation toxicology studies "to provide a more uniform delivery of material and minimize the amount of starting dust needed" [114].

Most fluidization (class A) devices are often referred to as "resuspension chambers." They simulate the direct (re)suspension ("deflation") of pre-existing, loose, fine particles from a solid surface under static conditions by drag or lift forces. This differs from the other two classes of devices, more properly called "dust generators," which transfer mechanical or kinetic energy to dust source materials, creating aerosols from the abrasion or fracture caused when grains of the source material collide with each other and/or the dust generator. Dust is generally produced in this latter manner during wind erosion of soils by abrasion through the saltation process (particles bouncing onto other particles) [115–117]. For aerosols created in a resuspension chamber by fluidization, the primary mode of energy transfer is between the individual particles of the source material and the input airflow—i.e. solid–fluid. The original particle size distribution of the test substance is not changed [114]. Most fluidization devices or resuspension chambers might be best visualized as simulating the resuspension of previously settled dust at a receptor site downwind of its source, the direct entrainment of dust from a storage pile or a plant leaf [118], or the lifting of material from the earth's surface by a dust devil [119]. Fewer fluidized bed devices are designed to transfer kinetic energy to source materials to generate dust aerosols by mechanical action [97,120]: they typically use small metal balls or "shot" to disagglomerate the source materials into "individual particles by the combination of mechanical impact and microscale turbulent shearing stresses" [120].

2.3.2.2. Gravitation. Dust generation devices of class B (the gravity drop method) generally operate by pouring or dropping a powdery substance into an enclosed volume, advecting dust aerosols out of the chamber, and collecting the suspended material from the diluted flow into an impactor or other sampler. Dust forms in these chambers during turbulent mixing of the source material as it falls, as well as via impaction at the end of the fall [24]. Such devices have long been used in industrial applications in order to compare the relative dustiness of different materials [6]. For example, in a device described by Wells and Alexander [121], several hundred grams of powder was dropped all at once through a box into a receptacle, and a Hexhlet elutriator was used to collect the respirable material. Lundgren and Rangaraj [57] poured large (5 kg) test samples for 1 min some

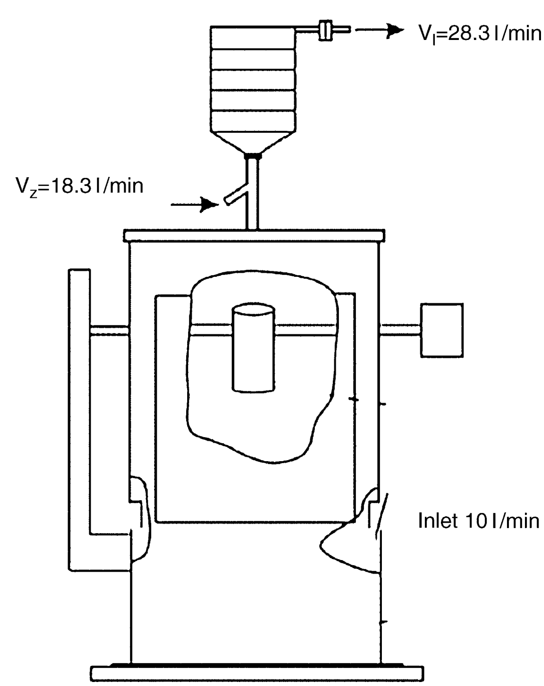

Fig. 3. The MRI tester, after Cowherd et al. [49].

1.5 m into the "Vertical Flow Dust Chamber," a box 0.9 m high and 0.6 m square, from where dust was sampled for 2 min by a high-volume sampler onto a glass fiber filter. The newest dust generator used by the USDA Agricultural Research Service in Lubbock, Texas, a "dustfall tube," [122–126] is a variant of the gravity fall technique in which a mass of soil repeatedly falls from the top to bottom of a 0.5 or 1 m-long tube which oscillates 180° back and forth (in a semicircle) every few seconds.

The MRI tester [49,50,127] (Fig. 3) is a device of class B. It is a complex device that uses 270 cm^3 of sample, vibrating at a very high rate while rotating at 0.8 rpm. The dust source material falls 0.25 m as it slowly pours out onto a metal-covered pad inside a rectangular box, in order to simulate generation of fine particles by impact with a dust-covered receiving surface. The aerosols are evacuated by a 10 l/min airflow, which enters the chamber through side baffles and exits at top, diluted with additional filtered room air, and collected in a multistage impactor or other aerosol sampler. The MRI tester has been used to measure "dustiness," defined for this instrument as the mass of particulate matter collected in the filter at the top of the chamber over the 10 min period which starts as the first material pours out of the cup [5].

2.3.2.3. Mechanical dispersion/agitation. Mechanical dispersion/agitation devices (category C), primarily of the rotating-drum type, are widely used to quantify the dustiness of agricultural and bulk materials and create mineral aerosol samples with application to airborne dust measurement. Rotating-drum systems provide an easy way to test the effects of sample mass, material type, rotation speed, flow rate, rotation time, and humidity on dust emission [128,129].

The rotating-drum technique was specified as a DIN (Deutsches Institut für Normung, the German standards institute) standard for dustiness measurement [130], utilizing the "rotating-pot" Heubach Dust Measuring Appliance [50,131]. A similar system developed at Warren Spring Laboratory in the UK [132] was specified as a British Occupational Hygiene Society (BOHS) standard dustiness testing device [94], and has

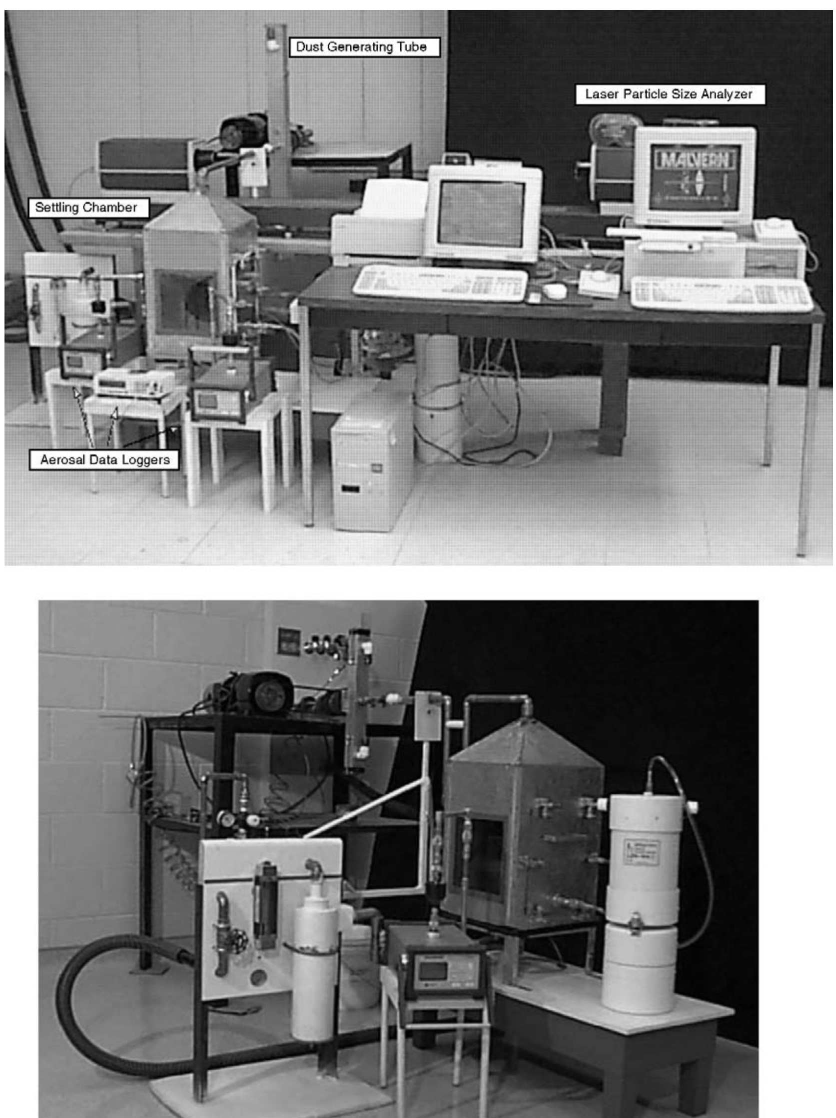

Fig. 4. The Lubbock dust generation, analysis and sampling system.

been extensively used in Europe [93,133]. This dust generation chamber is described as a rotating airtight stainless steel barrel approximately 0.7 m × by 0.3 m in diameter, with removable conical ends and either six [93] or eight [133] bars 0.025 m wide inside the barrel which lift the test material up along the sides as the drum rotates at a speed of 10–60 rpm. Filtered air enters the drum at a flow rate of up to 70 l/min through a 0.03 m diameter hole. Dusty air leaves through a 0.02 m circular opening, eventually passing through a 90 mm membrane filter for aerosol sampling.

Rotating-drum devices have been used extensively for agricultural dustiness testing [93,133,134]. Rotating-drum devices have also been used to evaluate the release of microbes and fungi attached to different solid materials [135,136]. Cooke et al. [137] used a rotating barrel to measure the effect of oil-based additives on dust generation: in their device, an aerosol monitor was placed directly inside the drum and collected dust from directly within the barrel. A small rotating-drum-in-box system was described by Li and Owen [35] for measurement of the production of respirable dust in livestock enclosures. A sample was placed in a small (0.14 m × 0.085 m × 0.04 m) box divided into two compartments; dust was generated from the agitation of a rotating cylinder, suspended by ventilation with compressed air, and measured with a five-stage optical particle counter. Cowherd and Grelinger [5] used this type of device for soil dustiness testing; in each run, 100 g of material was placed in the drum, which was rotated at 30 rpm. The dust-laden airstream was sampled for the first minute of rotation using an Andersen aerosol sampler. The first design of the Lubbock Controlled-Energy Dust Generator [86,122,123,138] also utilized a rotating-drum principle.

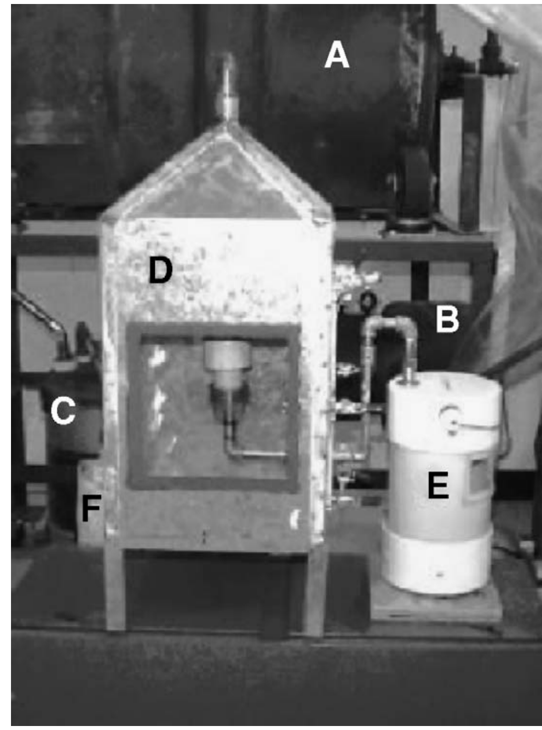

Fig. 5. Controlled energy dust generator: the rotating barrel (A) is controlled by a motor (B). Airflow provided by a blower (C) circulates dust through the system into a settling chamber (D), where fine particles are collected by an aerosol sampler (E). Airflow exits the settling chamber and returns to the blower after passing through a cyclone separator (F), which collects coarse material.

The Lubbock dust generation, sampling and analysis systems (LDGASS) [122–125,139] (Figs. 4 and 5) used by the authors have been designed to simulate wind erosion of soils and sediments under field conditions, collecting a small portion of a large cloud of polydisperse dust aerosol from a relatively large source sample (tens to hundreds of grams of material). The LDGASS consists of three separate modules. In the first, dust is generated by applying energy to a bulk source sample by gravitation or mechanical dispersion. The "dust generation" module of the system originally was comprised of the rotating-barrel Controlled Energy Dust Generator [86,138] (Fig. 5A), conceptually similar to but much larger than the Heubach Dust Measuring Appliance [50,131], a motor-driven "rotating pot." A smaller "dustfall tube" (Fig. 4), of class B (gravitation dust generator), now replaces the rotating-drum CE/DG in the LDGASS. Entrained dust flows into an analysis module of the system, passing through the beam of a laser diffraction particle sizer (Malvern Instruments) located approximately 0.5 m downstream from the exit of the dust generator. Suspended aerosols then flow an additional 0.3 m into a settling module for sampling PM2.5 on an impactor and measuring dust concentration via a forward-scattering nephelometer [140]. The in-line particle analysis and settling/aerosol sampling sections (Fig. 4) were added so that the system could be used in source apportionment studies [122,123].

Gravitation (class B) and dispersion (class C) devices simulate the abrasive breakdown of larger particles to smaller ones by mechanical transfer of kinetic energy to and among the particles of the source material. The energy transfer fragments or crushes the parent material and ejects small pieces (dust particles) into the air [117,138,141,142]. Most soils and sediments, especially in areas suitable for agriculture or construction, consist primarily of coarse agglomerations of fine particles weakly bound together. The processes of saltation (derived from the Latin word for "jump," representing the bouncing, ballistic trajectories of coarse solid particles moving at the base of a layer of flowing air or water) and mechanical disruption by human tools or vehicles (in agricultural fields, construction sites, or a roadbed) cause abrasion, breaking dry soil aggregates by brittle fracture [138,143–146] and releasing them into the atmosphere as dust aerosols [147]. A more thorough physical explanation and review of deagglomeration in the dust generation process is provided by Fonda et al. [20]. The most important mode of energy transfer in devices of classes B and C is solid–solid, as opposed to the fluid–solid interaction of resuspension chambers (class A). Gravitation or dispersion systems, therefore, effectively simulate dust generation at its source (as opposed to dust deposition or resuspension from a downwind receptor site). They can be visualized as recreating wind erosion of a bare land surface, generation of suspended particulate matter from soil by tillage implements or construction tools, or fugitive dust emission by a vehicle travelling on a paved or unpaved road.

3. "Dustiness" and "dustiness indices"

The concept of "dustiness" ("the tendency of dry materials to liberate dust into the air when handled under specific conditions" [48,94]) and the "dustiness index" have long been used to quantify and rank the dust-production potential of various substances in industry. "Dustiness indices" have been developed from tests with many different types of dust-production equipment [131]. As generally defined in industrial hygiene, a "dustiness index" is a dimensionless ratio of the mass of dust (generally in some size fraction evolved from a bulk source sample via given dust-production and dust-collection instruments under standard experimental conditions), to the initial mass of bulk source sample tested, sometimes expressed per unit of testing time [48]. The more complex "size specific dust generation rate" and "total dust generation rate" are also described [148], which could be related to the "dustiness" index used in industrial and pharmaceutical dust studies.

Dustiness indices have also been applied to predict the effects on particulate air quality for materials other than primary geological substances. Lundgren and Rangaraj [57] used a "drop test" in a gravitation-type generator to quantify the fugitive emission potential (dustiness) of chemical fertilizers under different handling conditions and after treatment with various dust suppressants. Breum and co-workers used a dustiness index to describe the potential of cotton [133] and household wastes [135] of different types to emit solid aerosols: waste stored in open paper bags was found to be as much as 45 times more "dusty" than that from plastic bags stored in a closed container.

Dustiness indices have been applied since the mid-1990s to studies of atmospheric particulate matter derived from roadbeds, soils and other geological sources. The controlled-energy dust generator was used to measure a variant of the "total dust generation rate" [148] and describe the potential of different soils in the Southern High Plains of Texas to emit mineral dust by wind erosion [86]. At a conference in June 1997, three different groups of researchers studying emissions of soil-derived dust in three different regions of the USA (the Columbia Plateau [36], the San Joaquin Valley [109] and the Southern High Plains [122]) presented papers in which PM10-related "dustiness indices" were defined in various ways (related to source sample mass, silt content, and/or PM10 collected) via different laboratory dust-production systems.

3.1. Silt content and dustiness

"Dustiness" of soil and sediment has often been considered to be related to its silt content. Investigations of dust in the industrial environment [93,132] found that dustiness was dependent on the proportion of particles <50 μm in diameter, and that maximum dustiness was found at 14% silt, when testing 30 different mixtures of blended coke. Plinke et al. [50] found that "for a given moisture content, finer material produces more dust," but this referred to monodisperse mixtures; a more even mixture of fine and medium silt was found to produce almost as much dust as the individual fractions alone. The United States Environmental Protection Agency's "AP-42" predictive emission factor model for control of open fugitive dust sources [149,150] is based on silt content—here defined as mass fraction of particles <75 μm in diameter.

Several problems exist with the sole use of the ambient silt fraction for dustiness potential and prediction of mineral aerosol emissions, beyond the fact that a source material's dry silt content may not be easily available [110]. The very definition of "silt" is not constant, since geologists, engineers, and soil scientists use different grain-size classifications [151], potentially confusing the correlation of results across disciplines. In addition, the major portion of mineral soils is comprised of groups of weakly cemented particles (aggregates) [144]; a particle which will appear as a sand-sized or even larger grain by dry sieving (or under ambient conditions on the soil surface) may often be a poorly consolidated unit breakable into silt-sized fragments (or even directly into PM10) during conditions of dust production (traffic, tillage, wind erosion) [146,152,153]. Soil aggregates up to 840 μm in size are have long been considered susceptible to wind erosion [154]. According to the experiments of Braunack et al. [143], larger soil aggregates have less tensile strength than smaller aggregates, and are more easily broken; therefore larger clods of soil may more easily release fine particles under brittle fracture. Madler et al. [155] describe numerous tests showing that as "the fragment size distribution shifts to increasingly smaller particles as the specific energy input is increased." Even hard crystals of quartz sand may in some cases be coated by grain cutans ("skins") of secondary minerals (clays, iron oxide, or silica) [156,157], which are scraped or broken off during energetic dust-production processes and released as fine aerosols [158–160].

As opposed to simple resuspension phenomena such as the re-entrainment of settled dust, dust generation processes such as wind erosion and tillage impart mechanical or kinetic energy (impaction or particle separation forces) to soil and sediment grains or aggregates in order to create much smaller aerosols. Not only PM10 but even aerosols to submicron size can be produced in significant quantities, sometimes predominantly, by destruction of large aggregates (when impaction forces exceed particle binding forces) by "sandblasting" and/or abrasive wear of crystalline particles as large as several hundred microns [141,157,158,161–165]. Studies of dust plumes emitted from the northwest sand sea of the Sahara [166] indicate that this might be a major formative mechanism of some dust storms. This may especially be so in the case of soils or sediments with crusted surfaces [142,163,167,168]. Different soils of the same textural class may release significantly different amounts of dust, due to variations of the stability of aggregates, which are shattered into fine aerosols by the energetic process of erosion [122,123]. Soil aggregates of sand size can also be degraded into resuspendable fine particles by other energetic processes such as rainfall [169], as well as freeze/thaw cycles or the growth of salt crystals [164]; the phenomenon of intense dust storms on high winds following hard, "clod-busting" rains or hailstorms is well known in the North American Great Plains. In addition, laboratory experiments have shown that as the energy of impact increases, the size of released aerosols decreases [155]. Therefore, simple resuspension of the dry silt fraction may not properly simulate some important field conditions of dust aerosol production.

4. The need for standardization and comparison

Each instrument designed to create any kind of dust in the laboratory may provide a distinct response (in terms of concentration, chemistry, and/or dispersion of the aerosol generated) to a given sample of source material under given conditions of operation [82,88,121], as well as a unique relationship to actual dust production and exposure in the field [24,50]. Simulated wind erosion aerosols prepared from the same soil samples by four different methods (dry sieving, sonic sieving, fluidization, and mechanical dispersion) were significantly different from each other in elemental composition [88]; some elements showed two-fold greater abundances in aerosol samples generated in a soil-blowing wind tunnel, compared to the aerosols produced by fluidization.

Chung and Burdett [48] discussed several inherent problems caused by the lack of intercomparisons between the variety of dustiness testing techniques and dustiness indices used in industrial hygiene. Many of their findings and conclusions should also be considered applicable with regards to mineral/soil dust-production systems and dustiness terminologies now in use by air quality researchers. The following points made by Chung and Burdett are just as applicable to studies of airborne dust from geological sources:

- A variety of variables (mass, time, volume, airflow rate, type and rate of release, position of filter, etc.) are not kept constant between tests and/or devices, hindering the basis for comparisons.
- There is no unique or uniform definition of "dustiness."
- Different "dustiness indices" are empirical and the results are method-dependent.
- Dust aerosol samples are not always collected in the same or biologically relevant size fractions.

Chung and Burdett [48] reported that the BOHS performed a round-robin intercomparison of 30 samples of 10 materials by six methods. The BOHS working group proposed the development of a standard dustiness index related by

$$\text{Dustiness index} = B(\text{dustiness measured by a given instrument}) + E,$$

where B is a scaling factor for a particular dustiness test method and E is some empirical constant. However, results of the round robin test showed that even these rankings were not reproducible [48,94,170]. The first BOHS report [94] pointed out that there needs to be a practical relationship developed between dustiness test results and actual dust exposures; past intercomparisons [131] have found inconsistent correlations.

It was expected that the round-robin intercomparisons of European dustiness testing devices would "form the basis of further collaborative European research and standardization" for "dustiness as a meaningful industrial hygiene parameter" [48]. With many different laboratory dust-production devices and dustiness indices having been used by air quality researchers, a critical need exists to emulate this approach for studies of geologically derived dust aerosols. One step in this direction was a comparison of the MRI dustiness tester and the DRI resuspension chamber for creating source and ambient profiles from unpaved road surface materials [171].

Interlaboratory, interinstrument experiments have helped calibrate the often-perplexing results provided by different particle-sizing instruments [172,173]. Intercomparisons of this type are also needed to promote the standardization and calibration of different instruments used for the resuspension and/or generation of geologic dust in the laboratory; such data could be used to improve our understanding of the production and environmental impact of mineral aerosols.

5. Conclusions

Simulating natural dust-production processes in a laboratory chamber provides a controlled, practical technique for determining aerosol emission strengths of different geological materials. However, the different modes of operation of different classes of dust generation/resuspension devices mean that different instruments simulate different modes of dust production and collection.

As long as these caveats are kept in mind, individual instruments running under standardized conditions can collect meaningful data on the characteristics of dust from different sources. Any of the dozens of techniques or rationales for dust production in the laboratory might be appropriate, depending on the objectives of the experiment and the design of the instrument. With regard to studies of mineral dust in the ambient atmosphere, investigators might ask themselves which objective is most important to ensure in their laboratory experiments—complete collection of particles in an aerosol sampler after release from a source sample (most fluidization systems), or realistic simulation of the field dust generation process which creates the aerosols to be collected (most gravitation or agitation/dispersion chambers)?

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Acknowledgments

We thank D.W. Fryrear for arranging English translation from papers in German. We thank Patrick O'Shaughnessy and Hilary Inyang for their helpful evaluation of the manuscript. Preliminary reviews of an earlier version of this manuscript by Roy Baker, David James, and several anonymous reviewers are highly appreciated.

References

[1] J.C. Chow, J.G. Watson, D.H. Lowenthal, P.A. Solomon, K.L. Magliano, S.D. Ziman, L.W. Richards, PM10 source apportionment in California's San Joaquin Valley, Atmos. Environ. 26A (1992) 3335–3354.

[2] D.M. Glover, P.K. Hopke, S.J. Vermette, S. Landsberger, D. D'Auben, Source apportionment with site specific source profiles, J. AWMA 41 (1991) 294–305.

[3] E. Kaya, R. Hogg, J.M. Mutmansky, Evaluation of procedures for production of dust samples for biomedical research, Appl. Occup. Environ. Hyg. 11 (1996) 745–750.

[4] K. Willeke (Ed.), Generation of Aerosols and Facilities for Exposure Experiments, Ann Arbor Science Publishers, Ann Arbor, MI, 1980, 597 pp.

[5] C. Cowherd, M.A. Grelinger, The appropriateness of a dustiness test chamber for representation of natural suspension phenomena, in: J.C., Chow, D.M., Ono (Eds.), PM10 Standards and Nontraditional Particulate Source Controls, AWMA Transactions Series TR-22, AWMA, Pittsburgh, 1992, pp. 346–356.

[6] D. Dahmann, G.D. Hartfiel, K. Mocklinghoff, Ein Verfahren zur wirklichkeitsnahen bestimmung der staubungsneigung von schuttgutern (A procedure for the realistic determination of the dust-making inclination of waste), Gefahr. Reinhalt. Der Luft 57 (1997) 503–507.

[7] American Society for Testing and Materials, Test Methods for Effectiveness of Dedusting Agents for Powdered Chemicals. ASTM Designation D-D4331-84, ASTM Committee D22.04 on Workplace Atmospheres, ASTM: West Conshohochken, PA, 1984, 448–452.

[8] M.P. Timsina, G.P. Martin, C. Marriott, D. Ganderton, M. Yianneskis, Drug delivery to the respiratory tract using dry powder inhalers, Int. J. Pharmaceut. 101 (1994) 1–13.

[9] M. Hindle, P.R. Byron, Size distribution control of raw materials for dry-powder inhalers using the aerosizer with the aero-disperser, Pharmaceut. Technol. 19 (6) (1995) 64–78.

[10] R.N. Jashnani, P.R. Byron, R.N. Dalby, Testing of dry powder aerosol formulations in different environmental conditions, Int. J. Pharmaceut. 113 (1995) 123–130.

[11] N.M. Concessio, R. Jäger-Waldau, A.J. Hickey, Aerosol delivery from an active emission multi-single dose dry powder inhaler, Particulate Sci. Technol. 15 (1997) 51–63.

[12] S.P. Newman, W.W. Busse, Evolution of dry powder inhaler design, formulation, and performance, Respir. Med. 96 (2002) 293–304.

[13] S.P. Newman, Dry powder inhalers for optimal drug delivery, Expert Opin. Biol. Ther. 4 (2004) 23–34.

[14] H. Muhle, B. Bellmann, O. Creutzenberg, U. Heinrich, M. Ketkar, R. Mermelstein, Dust overloading of lungs after exposure of rats to particles of low solubility: comparative studies, J. Aerosol Sci. 21 (1990) 374–377.

[15] Y.M. Janssen, J.P. Marsh, M.P. Absher, D. Hemenway, P.M. Vacek, K.O. Leslie, P.J. Borm, B.T. Mossman, Expression of antioxidant enzymes in rat lungs after inhalation of asbestos or silica, J. Biol. Chem. 267 (1992) 10625–10630.

[16] J.R. Morales, M.I. Dinator, F. Llona, J. Saavedra, F. Falabella, Sample preparation for archaeological materials for PIXE analysis, J. Radioanal. Nucl. Chem. Lett. 187 (1994) 79–89.

[17] T. Hirano, M. Kiyota, I. Aiga, Physical effects of dust on leaf physiology of cucumber and kidney bean plants, Environ. Pollut. 89 (1995) 255–261.

[18] S. Lewis, Solid particle penetration into enclosures, J. Hazard. Mater. 43 (1995) 195–216.

[19] Y.C. Chen, E.M. Barber, Y. Zhang, R.W. Besant, S. Sokhansanj, Methods to measure dust production and deposition rates in buildings, J. Agric. Eng. Res. 72 (1999) 329–340.

[20] M. Fonda, M. Petach, C.F. Rogers, J. Huntington, D. Stratton, K. Nishioka, M. Tipo, Resuspension of particles by aerodynamic deagglomeration, Aerosol Sci. Technol. 30 (1999) 509–529.

[21] A.H.M. Andreasen, H. Hofman-Bang, N.H. Rasmussen, Uber das Staubungsvermogen der Stoffe (on the ability to be dusty of materials), Kolloid-Zeitschrift 86 (1939) 70–77.

[22] L. Cheng, Formation of respirable dust at belt conveyor transfer points, AIHA J. 34 (1973) 540–546.

[23] S.L. Sutter, J.W. Johnson, J. Mishima, Investigation of accident-generated aerosols: Releases from free-fall spills, AIHA J. 43 (1982) 540–543.

[24] W.A. Heitbrink, P.A. Baron, K. Willeke, An investigation of dust generation by free falling powders, AIHA J. 53 (1992) 617–624.

[25] J.S. Lanning, M.G. Boundy, D. Leith, Validating a model for the prediction of dust generation, Particulate Sci. Technol. 13 (1995) 105–116.

[26] L.P. Malcolm, M.R. Raupach, Measurement in an air settling tube of the terminal velocity distribution of soil material, J. Geophys. Res. 96 (1991) 15275–15286.

[27] D.A. Gillette, W. Chen, Size distributions of saltating grains: an important variable in the production of suspended particles, Earth Surf. Proc. Landforms 24 (1999) 449–462.

[28] W. Chen, D.W. Fryrear, Aerodynamic and geometric diameters of airborne particles, J. Sed. Res. 71 (2001) 365–371.

[29] W. Chen, Determination of drag coefficients in measuring particle diameters, J. Sed. Res. 73 (2003) 714–719.

[30] J.E. Rutherford, S.W. Horstman, Generation of Mt. St. Helens Dust with a Fluidizing Dust Generator, AIHA J. 46 (1985) 94–96.

[31] W.B. Deichman, A Dustshaker, J. Ind. Toxicol. 26 (1944) 334–335.

[32] L.S. Sonkin, M.A. Lipton, D. Van Hoeson, An apparatus for dispersing finely divided dusts, J. Ind. Hyg. Toxicol. 28 (1946) 273–275.

[33] B.M. Wright, A new dust-feed mechanism, J. Sci. Instrum. 27 (1950) 12–15.

[34] J.A. Graham, F.J. Miller, D.W. Davies, M.E. Hiteshew, L.C. Walsh III, Inhalation studies of Mt. St. Helens volcanic ash in animals. I. Introduction and exposure system, Environ. Res. 37 (1985) 61–71.

[35] X.W. Li, J.A. Owen, A dust segregation rate test system, J. Environ. Sci. Health A 31 (1996) 2533–2545.

[36] A. Busacca, L. Stetler, L. Horning, R. Barry, L. Wagoner, K. Saxton, L.L. Ashbaugh, Development of a PM10 'dustiness index' to assess wind erodibility of soils of the Columbia Plateau, Pacific Northwest, paper presented at the Wind Erosion International Symposium-Workshop, Manhattan, KS, 3–5 June 1997.

[37] N.O. Breum, The rotating drum dustiness tester: variability in dustiness in relation to sample mass, testing time, and surface adhesion, Ann. Occup. Hyg. 43 (1999) 557–566.

[38] L. Molter, W. Molter, F. Munzinger, E. Leopoldschafen, Device for producing a solid aerosol, J. Aerosol Sci. 20 (1989) 5(i).

[39] A. Fernandez, J.O.L. Wendt, R. Cenni, R.S. Young, M.L. Witten, Resuspension of coal and coal/municipal sewage sludge combustion generated fine particles for inhalation health effects studies, Sci. Total Environ. 287 (2002) 265–274.

[40] D.N. Miller, B.L. Woodbury, Simple protocols to determine dust potentials from cattle feedlot soil and surface samples, J. Environ. Qual. 32 (2003) 1634–1640.

[41] A.D. Ledbetter, P.M. Killough, G.F. Hudson, A low-sample-consumption dry-particulate aerosol generator for use in nose-only inhalation exposures, Inhal. Toxicol. 10 (1998) 239–251.

[42] A. Shigematsu, M. Toyohara, T. Iwasaki, A tracer technique for the behaviour of dusts in experimental animal lungs using an automatic air pollution reproducer and a film scintillation counter, Nucl. Inst. Meth. 86 (1970) 279–284.

[43] P.C. Reist, L. Taylor, Development and operation of an improved turntable dust feeder, Powder Technol. 107 (2000) 36–42.

[44] J.H. Garcia, W.W. Li, R. Arimoto, R. Okrasinski, J. Greenlee, J. Walton, C. Schloesslin, S. Sage, Characterization and implication of potential fugitive dust sources in the Paso del Norte region, Sci. Total Environ. 325 (2004) 95–112.

[45] J.M. Veranth, K.M. Smith, A.E. Aust, S.L. Dansie, J.B. Griffin, A.A. Hhu, M.L. Huggins, J.S. Lightly, Coal fly ash and mineral dust for toxicology and particle characterization studies: equipment and meth-

ods for PM2.5- and PM1-enriched samples, Aerosol Sci. Technol. 32 (2000) 127–141.

[46] G.J. Praml, M.H. Zeitler-Feicht, A.L. Hartmann, H. Riedel, Dust exposure of man and animal in swine confinement buildings: benefits of full shift continuous registration, J. Aerosol Sci. 21 (1990) S751–S754.

[47] K.O. Mankell, K.A. Janni, R.D. Walker, M.E. Wilson, J.E. Pettigrew, L.D. Jacobson, W.F. Wilcke, Dust suppression in swine feed using soybean oil, J. Animal Sci. 73 (1995) 981–985.

[48] K.Y.K. Chung, G.J. Burdett, Dustiness testing and moving towards a biologically relevant dustiness index, Ann. Occup. Hyg. 38 (1994) 945–949.

[49] C. Cowherd, M.A. Grelinger, P.J. Englehart, R.F. Kent, K.F. Wong, An apparatus and methodology for predicting the dustiness of materials, AIHA J. 50 (1989) 131–138.

[50] M.A.E. Plinke, R. Maus, D. Leith, Experimental examination of factors that affect dust generation by using Heubach and MRI testers, AIHA J. 53 (1992) 325–330.

[51] M.A. Al-Rajhi, S.M. Al-Shayeb, M.R.D. Seaward, H.G.M. Edwards, Particle size effect for metal pollution analysis of atmospherically deposited dust, Atmos. Environ. 30 (1996) 145–153.

[52] J.E. Fergusson, D.E. Ryan, The elemental composition of street dust from large and small urban areas related to city type, source and particle size, Sci. Total Environ. 34 (1984) 101–116.

[53] A.J. Horowitz, A primer on trace metal sediment chemistry, U.S. Geol. Surv. Water-Supply Paper 84-2227, 1984, 67 pp.

[54] M.A. Al-Rajhi, M.R.D. Seaward, A.S. Al-Aamer, Metal levels in indoor and outdoor dust in Riyadh, Saudi Arabia, Environ. Int. 22 (1996) 315–324.

[55] D.F. Gatz, M.V. Miller, G.J. Stensland, L.C. Chu, Evidence of element fractionation in fine particle size classes of highly erodible soils, in: Particulate Matter/Fugitive Dusts: Measurement and Control in Western Arid Regions, Proceedings of the APCA International Specialty Conference, Tucson, AZ, AWMA, Pittsburgh, 1986, pp. 39–51.

[56] K. Eleftheriadis, I. Colbeck, Coarse atmospheric aerosol: size distributions of trace elements, Atmos. Environ. 35 (2001) 5321–5330.

[57] D.A. Lundgren, C.N. Rangaraj, A method for the estimation of fugitive dust emission potentials, Powder Technol. 47 (1986) 61–69.

[58] T. Allen, Particle Size Measurement, 3rd ed., Chapman & Hall, New York, 1981 (Chapter 1, Sampling of Powders).

[59] B.J. Smith, J.S. White, W.B. Whalley, Simulated aeolian abrasion of Pannonian sands and its implications for the origins of Hungarian loess, Earth Surf. Proc. Landforms 16 (1991) 745–752.

[60] B.J. Smith, J.S. Wright, W.B. Whalley, Sources of non-glacial, loess-size quartz silt and the origins of desert loess, Earth Sci. Rev. 59 (2002) 1–26.

[61] A.J.M. Bory, P.E. Biscaye, A. Svensson, F.E. Grousset, Seasonal variability in the origin of recent atmospheric mineral dust at NorthGRIP, Greenland, Earth Planet. Sci. Lett. 196 (2002) 123–134.

[62] M.C. Wopereis, C. Gascuel-Odoux, G. Bourrie, G. Soignet, Spatial variability of heavy metals in soil on a one-hectare scale, Soil Sci. 146 (1988) 113–118.

[63] A. Castrignano, L. Giugliarini, R. Risaliti, N. Martinelli, Study of spatial relationships among some soil physico-chemical properties of a field in central Italy using multivariate geostatistics, Geoderma 97 (2000) 39–60.

[64] D.K. Cassel, Spatial and temporal variability of soil physical properties following tillage of Norfolk loamy sand, Soil Sci Soc. Am. J. 47 (1983) 196–201.

[65] P. Nkedi-Kizza, L.A. Gaston, H.M. Selim, Extrinsic spatial variability of selected macronutrients in a sandy soil, Geoderma 63 (1994) 95–106.

[66] A.P. Mallarino, Spatial variability patterns of phosphorus and potassium in no-tilled soils for two sampling scales, Soil Sci. Soc. Am. J. 60 (1996) 1473–1481.

[67] A. Weitz, D. Bunte, H. Hersemann, Application of nested sampling technique to determine the scale of variation in soil physical and chemical properties, Catena 20 (1993) 207–214.

[68] E. Earl, J.C. Taylor, G.A. Wood, I. Bradley, I.T. James, T. Waine, J.P. Welsh, R.J. Godwin, S.M. Knight, Soil factors and their influence on within-field crop variability. Part I. Field observation of soil variation, Biosyst. Eng. 84 (2003) 425–440.

[69] V. Dharmarajan, P.W. West, A precise method for the generation of standard metal salt particulates, Anal. Chem. Acta 69 (1974) 43–48.

[70] S. Liu, P.K. Dasgupta, Collection of micrometer and submicrometer size aerosol particles with a packed bead impactor, Microchem. J. 62 (1999) 50–57.

[71] H.M. Chein, D.A. Lundgren, A high-output size-selective aerosol generator, Aerosol Sci. Technol. 23 (1995) 510–520.

[72] J.P. Borra, D. Camelot, J.C.M. Marijnissen, B. Scarlett, New aerosol generator based on the mixing of droplets through electrical forces: production of particles with controlled properties, J. Aerosol Sci. 27 (1996) S181–S182.

[73] M.J. Nuckolls, R.K. Fuller, Sieve analysis of particles smaller than 44 μm in diameter, Soil Sci. 102 (1966) 292–295.

[74] J. Volckens, P.T. O'Shaughnessy, D.R. Hemenway, An aerosol generation system for the production of respirable grain dust, Appl. Occup. Environ. Hyg. 13 (1998) 122–126.

[75] J. Dutkiewicz, S.A. Olenchock, W.G. Sorenson, V.F. Gerencser, J.J. May, D.S. Pratt, V.A. Robinson, Levels of bacteria, fungi and endotoxin in bulk and aerosolized corn silage, Appl. Environ. Microbiol. 55 (1989) 1093–1099.

[76] W.S. Cain, A.A. Jalowayski, M. Kleinman, N.S. Lee, B.R. Lee, B.H. Ahn, K. Magruder, R. Schmidt, B.K. Hillen, C.B. Warren, B.D. Culver, Sensory and associated reactions to mineral dusts: sodium borate, calcium oxide, and calcium sulfate, J. Occup. Environ. Hyg. 1 (2004) 222–236.

[77] P.S. Thorne, Experimental grain dust atmospheres generated by wet and dry aerosolization techniques, Am. J. Ind. Med. 25 (1994) 109–112.

[78] S.J. Reynolds, P.S. Thorne, K.J. Donham, E.A. Croteau, K.M. Kelly, D. Lewis, M. Whitmer, D.J.J. Heederik, J. Douwes, I. Connaughton, S. Koch, P. Malmberg, B.M. Larsson, D.K. Milton, Comparison of endotoxin assays using agricultural dusts, AIHA J. 63 (2002) 430–438.

[79] L. Molhave, T. Schneider, S.K. Kjaergaard, L. Larsen, S. Norn, O. Jorgensen, House dust in seven Danish offices, Atmos. Environ. 34 (2000) 4767–4779.

[80] D.R. Hemenway, K. Boudreau, J. Miller, Retrofitting of a Wright dust-feed, AIHA J. 43 (1986) 874–879.

[81] D.R. Hemenway, S.M. MacAskill, Design, development and test results of a horizontal flow inhalation toxicology facility, AIHA J. 43 (1982) 874–879.

[82] P.T. O'Shaughnessy, D.R. Hemenway, Computer automation of a dry-dust generating system, Inhal. Toxicol. 6 (1994) 95–113.

[83] P.T. O'Shaughnessy, D.R. Hemenway, R.G. Absher, System identification and feedback control of an aerosol production process, Aerosol Sci. Technol. 25 (1996) 292–304.

[84] D.B. Blackford, K. Heighington, The design of an aerosol test tunnel for occupational hygiene investigations, Atmos. Environ. 20 (1986) 1605–1613.

[85] O. Witschger, R. Wrobel, J.R. Fabriès, P. Görner, A. Renoux, A new experimental wind tunnel facility for aerosol sampling investigations, J. Aerosol Sci. 28 (1997) 833–851.

[86] U.B. Singh, Wind erosion: mechanics of saltation and dust generation, PhD Dissertation, Texas Tech University, Lubbock, 1994.

[87] L.C. Chu, G. Stensland, M.V. Miller, D.F. Gatz, Determination of chemical abundance and element ratios of soil aerosols produced by different aerosol generation methods, in: Proceedings of the 77th Annual Meeting APCA, Paper No. 84-22.8, AWMA, Pittsburgh, 1984.

[88] D.F. Gatz, Soil aerosol composition: comparison of source sample generation methods, in: Proceedings of the 88th Annual Meeting AWMA, Paper No. 95-TA38.01, AWMA, Pittsburgh, 1995.

[89] S.J. Page, J.A. Organiscak, Using proximate analysis to characterize airborne dust generation from bituminous coals, Aerosol Sci. Technol. 36 (2002) 721–733.

[90] E. Emets, G. Kolomeytsev, S. Mikheikin, P. Poluektov, A. Smirnov, V. Timonin, Investigation of dust generation processes over radioactive contaminated soil under wind action, J. Aerosol Sci. 29 (Suppl. 1) (1998) 211–212.
[91] M.A.H. Eltayeb, R.E. Van Grieken, W. Maenhaut, H.A.J. Annegarn, Aerosol-soil fractionation for Namib desert samples, Atmos. Environ. 27A (1993) 669–678.
[92] M.A.H. Eltayeb, J. Injuk, W. Maenhaut, R.E. Van Grieken, Elemental composition of mineral aerosol generated from Sudan Sahara sand, J. Atmos. Chem. 40 (2001) 247–273.
[93] K. Hjemsted, T. Schneider, Documentation of a dustiness drum test, Ann. Occup. Hyg. 40 (1996) 627–643.
[94] British Occupational Hygiene Society (BOHS). Technical Guide No. 4, Dustiness Estimation Methods for Dry Materials, Science Reviews Ltd., Leeds, UK, 1985.
[95] S.A. Sethi, T. Schneider, A gas fluidization dustiness tester, J. Aerosol Sci. 27 (1996) S305–S306.
[96] A.C. Lua, Particle characteristics of a stable fluidized bed aerosol generator, J. Aerosol Sci. 23 (1992) 737–739.
[97] V.A. Marple, B.Y.H. Liu, K.L. Rubow, A dust generator for laboratory use, AIHA J. 39 (1978) 26–32.
[98] I.C. Tommerup, D.J. Carter, Dry separation of microorganisms from soil, Soil Biol. Biochem. 14 (1982) 69–71.
[99] F. Sporenberg, G. Ruther, E. Weber, Collection characteristics of inertial impactors, J. Aerosol Sci. 14 (1983) 308–314.
[100] J. Pauluhn, Hazard identification and risk assessment of pyrethroids in the indoor environment, Ann. Occup. Environ. Hyg. 13 (1998) 469–478.
[101] J.S. Kinsey, R.M. Coveney, Mineral characterization of selected soil samples using a dry dispersion technique, Particulate Sci. Technol. 7 (1989) 357–370.
[102] Y. Oghiso, Y. Yamada, Y. Kubota, O. Matsuoka, Pulmonary deposition and effects of inhaled silica particles after short-term exposures in the rat, J. Toxicol. Sci. 11 (1986) 1–13.
[103] S.A. Batterman, T.G. Dzubay, R.E. Baumgardner, Development of crustal profiles for receptor modeling, Atmos. Environ. 22 (1988) 1821–1828.
[104] L. Schütz, M. Sebert, Mineral aerosols and source identification, J. Aerosol Sci. 18 (1987) 1–10.
[105] J.C. Chow, J.G. Watson, J.E. Houck, L.C. Pritchett, C.F. Rogers, C.A. Frazier, R.T. Egami, B.M. Ball, A laboratory resuspension chamber to measure fugitive dust size distributions and chemical compositions, Atmos. Environ. 28 (1994) 3463–3481.
[106] E. Vega, V. Mugica, E. Reyes, G. Sanchez, J.C. Chow, J.G. Watson, Chemical composition of fugitive dust emitters in Mexico City, Atmos. Environ. 35 (2001) 4033–4039.
[107] J.G. Watson, J.C. Chow, Source characterization of major emission sources in the Imperial and Mexicali Valleys along the US/Mexico border, Sci. Total Environ. 276 (2001) 33–47.
[108] K.F. Ho, S.C. Lee, J.C. Chow, J.G. Watson, Characterization of PM10 and PM2.5 source profiles for fugitive dust in Hong Kong, Atmos. Environ. 37 (2003) 1023–1032.
[109] O.F. Carvacho, L.L. Ashbaugh, R.T. Matsumura, R.J. Southard, R.G. Flocchini, Measurement of PM10 potential from agricultural soils using a dust resuspension test chamber, in: Proceedings of the International Conference on Air Pollution from Agricultural Operations, 7–9 February 1996. Kansas City, Midwest Plan Service, Ames, Iowa, 1996, pp. 87–92.
[110] O.F. Carvacho, L.L. Ashbaugh, M.S. Brown, R.G. Flocchini, Relationship between San Joaquin Valley soil texture and PM10 emission potential using the UC Davis dust resuspension test chamber, Trans. ASAE 44 (2001) 1603–1608.
[111] O.F. Carvacho, L.L. Ashbaugh, M.S. Brown, R.G. Flocchini, Measurement of PM2.5 emission potential from soil using the UC Davis resuspension test chamber, Geomorphology 59 (2004) 75–80.
[112] W.C. Malm, J.F. Sisler, D. Huffman, R.A. Eldred, T.A. Cahill, Spatial and seasonal trends in particle concentration and optical extinction in the United States, J. Geophys. Res. 99 (1994) 1347–1370.
[113] H. Patashnick, E.G. Rupprecht, Continuous PM-10 measurements using the tapered element oscillating microbalance, J. AWMA 41 (1991) 1079–1083.
[114] R.N. Shiotsuka, R.S. Kutzman, J.M. Firriolo, R.T. Drew, Use of fluidizing bed aerosol generators to establish a dust mixture of two substances at a fixed ratio for inhalation toxicology studies, AIHA J. 53 (1992) 510–513.
[115] R.A. Bagnold, The Physics of Blown Sand and Desert Dunes, Methuen, London, 1941.
[116] R.A. Bagnold, The flow of cohesionless grains in fluids, Phil. Trans. R. Soc., London Ser. A 249 (1956) 239–297.
[117] R. Greeley, J.D. Iversen, Wind as a Geological Process on Earth, Mars, Venus and Titan, Cambridge University Press, Cambridge, 1985.
[118] P. Rajini, J.A. Last, S.A. McCurdy, R. Lawson, R.J. Southard, K.P. Allamneni, H. Witschi, Lung injury and fibrogenic response to dusts from citrus and grape harvests, Inhal. Toxicol. 7 (1995) 363–376.
[119] D.A. Gillette, P.C. Sinclair, Estimation of suspension of alkaline material by dust devils in the United States, Atmos. Environ. 24 (1990) 1135–1142.
[120] R.F. Boucher, A.C. Lua, A stable, high-concentration, dry aerosol generator, J. Aerosol Sci. 13 (1982) 499–511.
[121] A.B. Wells, D.J. Alexander, A method for estimating the dust yield of powders, Powder Technol. 19 (1978) 271–277.
[122] T.E. Gill, T.M. Zobeck, J.E. Stout, J.M. Gregory, Laboratory generation and measurement of fugitive dust, in: Proceedings of the Wind Erosion International Symposium Workshop, June 3–5, 1997, Manhattan, KS, USDA Technical Publication Series, 1999, 9 pp.
[123] T.M. Zobeck, T.E. Gill, J.E. Stout, M.L. Zhang, A.C. Kennedy, J.M. Gregory, Analysis of laboratory-generated dust suspensions derived from soils and roads, paper presented at ASAE Annual International Meeting, Minneapolis, MN, ASAE Paper No. 972030, August 1997.
[124] Amante-Orozco, A., Fine particulate matter generation under controlled laboratory conditions. PhD Dissertation in Soil Science, Texas Tech University, Lubbock, 2000.
[125] A. Singer, T. Zobeck, L. Poberezsky, E. Argaman, The PM10 and PM2.5 dust generation potential of soils/sediments in the southern Aral Sea Basin, Uzbekistan, J. Arid Environ. 54 (2003) 705–728.
[126] V. Acosta-Martinez, T.M. Zobeck, Enzyme activities and arylsufatase protein content of dust and the soil source: biochemical fingerprints? J. Environ. Qual. 33 (2004) 1653–1661.
[127] C. Cowherd, M.A. Grelinger, Wind erosion emissions of fine particles from limited reservoir surfaces, paper presented at Wind Erosion International Symposium-Workshop, Manhattan, KS, 3–5 June 1997.
[128] N.O. Breum, The rotating drum dustiness tester: variability in dustiness in relation to sample mass, testing time, and surface adhesion, Ann. Occup. Hyg. 43 (1999) 557–566.
[129] K. Hjemsted, T. Schneider, Dustiness from powder materials, J. Aerosol Sci. 27 (1996) S485–S486.
[130] DIN (Deutsches Institut für Normung). Beurteilung des Staubungsverhaltens von festen Stoffen. Bestimmung der Saubungszahl bei Staubentwiklung durch Rotation. (Evaluation of the dustiness of solid materials. Determination of the dustiness number with dust formation by rotation.) DIN Standard 55 992, 1993.
[131] W.A. Heitbrink, W.F. Todd, T.C. Cooper, D.M. O'Brien, The application of dustiness tests to the prediction of worker dust exposure, AIHA J. 51 (1990) 217–223.
[132] R.W. Higman, C. Schofield, M. Taylor, Bulk material dustiness, an important property—its measurement and control, paper presented at the Fourth International Environ. & Safety Conference, St. Albans, UK, 1984.
[133] N.O. Breum, E.M. Nielsen, Dust content of cotton-quality control in terms of airborne dust and endotoxin—a pilot study, Gehahr. Reinhalt. der Luft 56 (1996) 389–392.
[134] N.O. Breum, B.H. Nielsen, M. Lyngbye, U. Midtgard, Dustiness of chopped straw as affected by lignosulfonate as a dust suppressant, Ann. Agric. Environ. Med. 6 (1999) 133–140.
[135] N.O. Breum, B.H. Nielsen, E.M. Nielsen, U. Midtgard, O.M. Poulsen, Dustiness of compostable waste: a methodological approach to quan-

tify the potential of waste to generate airborne micro-organisms and endotoxin, Waste Manage. Res. 15 (1997) 169–187.

[136] A.M. Madsen, L. Martensson, T. Schneider, L. Larsson, Microbial dustiness and particle release of different biofuels, Ann. Occup. Hyg. 48 (2004) 327–338.

[137] J.B. Cooke, H.H. Perkins Jr., N.F. Getchell, Controlling dust in agricultural products with additives, Cereal Foods World 23 (1978) 554–556.

[138] U.B. Singh, J.M. Gregory, G.R. Wilson, T.M. Zobeck, Dust emission from a controlled energy environment, paper presented at ASAE International Summer Meeting, Kansas City, MO, ASAE Paper No. 944041, June 1994.

[139] T. Zobeck, A. Amante-Orozco, Effect of dust source clay and carbonate content on fugitive dust emissions, in: Proceedings of the 10th International Emissions Inventory Conference, U.S. Environmental Protection Agency, Denver, CO, May 2001, 13 pp.

[140] P. Lilienfeld, Nephelometry, an ideal PM- 2.5/10 method? in: Particulate Matter: Health and Regulatory Issues, AWMA International Specialty Conference Proceedings VIP-49, AWMA, Pittsburgh, 1995, pp. 211–225.

[141] D.A. Gillette, Production of dust that may be carried great distances, in: T.L., Péwé (Ed.), Desert dust: origin, characteristics, and effect on man, Spec. Pap. 186, Geol. Soc. Am., Boulder, CO, 1981, pp. 11–26.

[142] D.A. Gillette, J.A. Adams, D. Muhs, R. Kihl, Threshold friction velocities and rupture moduli for crusted desert soils for the input of soil particles into the air, J. Geophys. Res. 87 (1982) 9003–9015.

[143] M.V. Braunack, J.S. Hewitt, A.R. Dexter, Brittle fracture of soil aggregates and the compaction of aggregate beds, J. Soil Sci. 30 (1979) 653–667.

[144] E.L. Skidmore, D.H. Powers, Dry soil-aggregate stability, energy-based index, Trans. ASAE 46 (1982) 1274–1279.

[145] E. Perfect, B.D. Kay, Statistical characterization of dry aggregate strength using rupture energy, Soil Sci. Soc. Am. J. 58 (1994) 1804–1809.

[146] E. Perfect, Fractal models for the fragmentation of rocks and soils: a review, Eng. Geol. 48 (1997) 185–198.

[147] Y. Callot, B. Marticorena, G. Bergametti, Geomorphologic approach for modelling the surface features of arid environments in a model of dust emissions: application to the Sahara desert, Geodinam. Acta 13 (2000) 245–270.

[148] M.A.E. Plinke, D. Leith, M.G. Boundy, F. Löffler, Dust generation from handling powders in industry, AIHA J. 56 (1995) 251–257.

[149] U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors, USEPA AP-42, Office of Air Quality Standards, Research Triangle Park, NC, 1985.

[150] C. Cowherd, G.E. Muleski, J.S. Kinsey, Control of open fugitive dust sources, Final Report to US Environmental Protection Agency, Contract No. 68-02-4395, Project No. 8985-14, Midwest Research Institute, Kansas City, MO, 1988.

[151] R.V. Dietrich, J.T. Dutro Jr., R.M. Foose (Eds.), AGI Data Sheets for geology in the field, laboratory and office, 17.1 (Grain-size scales used by American geologists), 17.2 (Grain-size scale used by engineers), 17.3 (Grain-size scale used by soils scientists), 2nd ed. American Geological Institute: Falls Church, VA, 1982.

[152] S.C. Alfaro, J.L. Rajot, W. Nickling, Estimation of PM20 emissions by wind erosion: main sources of uncertainties, Geomorphology 59 (2004) 63–74.

[153] Y. Shao, Simplification of a dust emission scheme and comparison with data, J. Geophys. Res. 109D (2004) D10202, 1–6.

[154] W.S. Chepil, Soil conditions that influence wind erosion, USDA Tech. Bull. 1185, U.S. Dept. Agric., U.S. Govt. Printing Ofc., Washington, DC, 1958.

[155] M. Madler, W. Koch, F. Lange, K. Husemann, In situ aerodynamic size classification of aerosols in the size range between 0.1 and 100 μm for dustiness tests and powder characterization, J. Aerosol Sci. 30 (1999) 451–465.

[156] R. Brewer, Cutans: their definition, recognition and classification, J. Soil Sci. 11 (1960) 280–292.

[157] D.H. Krinsley, J.C. Doornkamp, Atlas of Quartz Sand Surface Textures, Cambridge University Press, Cambridge, UK, 1973.

[158] L. Gomes, G. Bergametti, G. Coude-Gaussen, P. Rognon, Submicron desert dusts: a sandblasting process, J. Geophys. Res. 95 (1990) 13927–13935.

[159] S.C. Alfaro, A. Gaudichet, L. Gomes, M. Maille, Modeling the size distribution of a soil aerosol produced by sandblasting, J. Geophys. Res. 102 (1997) 11239–11249.

[160] S.C. Alfaro, A. Gaudichet, L. Gomes, M. Maille, Mineral aerosol production by wind erosion: aerosol particle sizes and binding energies, Geophys. Res. Lett. 25 (1998) 991–994.

[161] W.S. Chepil, Properties of soil which influence wind erosion: II. Dry aggregate structure as an index of erodibility, Soil Sci. 69 (1953) 403–414.

[162] D.A. Gillette, T.R. Walker, Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of west Texas, Soil Sci. 123 (1977) 97–110.

[163] L. Hagen, Soil aggregate abrasion by impacting sand and soil particles, Trans. ASAE 27 (1984) 805–808.

[164] K. Pye, Aeolian Dust and Dust Deposits, Academic Press, London, 1987.

[165] B. Chatenet, B. Marticorena, L. Gomes, G. Bergametti, Assessing the microped size distributions of desert soils erodible by wind, Sedimentology 43 (1996) 901–911.

[166] P. Rognon, G. Coude-Gaussen, G. Bergametti, L. Gomes, Relationships between the characteristics of soils, the wind energy and dust near the ground, in the western sandsea (N.W. Sahara), in: M. Leinen, M. Sarnthein (Eds.), Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport, NATO Advanced Sci. Inst. Ser. C, Math. & Phys. Sci., 282, Kluwer, Dordrecht, 1989, pp. 167–184.

[167] T.A. Cahill, T.E. Gill, J.S. Reid, E.A. Gearhart, D.A. Gillette, Playa crusts, saltating particles and dust aerosols at Owens (Dry) Lake, California, Earth Surf. Proc. Landforms 21 (1996) 621–639.

[168] D. Goossens, Effect of soil crusting on the emission and transport of wind-eroded sediment: field measurements on loamy sandy soil, Geomorphology 58 (2004) 145–160.

[169] D.A. Gillette, Threshold friction velocities for dust production in agricultural soils, J. Geophys. Res. 93 (1988) 12645–12662.

[170] British Occupational Hygiene Society (BOHS). Progress in dustiness estimation, BOHS Technology Committee Working Group on Dustiness Estimation. Ann. Occup. Hyg. 32 (1988) 535–544.

[171] C. Cowherd, M.A. Grelinger, Resuspension of fine particles using a dustiness test chamber, in: Proceedings of the 90th Annual Meeting, AWMA, Paper 97-RA118.03, AWMA, Pittsburgh, 1997.

[172] J.P.M. Syvitski, K.W.G. Leblanc, K.W. Asprey, Interlaboratory, interinstrument calibration experiment, in: J.P.M. Syvitski (Ed.), Principles, Methods, and Application of Particle Size Analysis, University of Cambridge Press, Cambridge, UK, 1991, pp. 174–193.

[173] F.M. Etzler, M.S. Sanderson, Particle size analysis: a comparative study of various methods, Particle Particle Syst. Characteriz. 12 (1995) 217–224.