



Standard Guide for Using Probability Sampling Methods in Studies of Indoor Air Quality in Buildings¹

This standard is issued under the fixed designation D 5791; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers criteria for determining when probability sampling methods should be used to select locations for placement of environmental monitoring equipment in a building or to select a sample of building occupants for questionnaire administration for a study of indoor air quality. Some of the basic probability sampling methods that are applicable for these types of studies are introduced.

1.2 Probability sampling refers to statistical sampling methods that select units for observation with known probabilities (including probabilities equal to one for a census) so that statistically defensible inferences are supported from the sample to the entire population of units that had a positive probability of being selected into the sample.

1.3 This guide describes those situations in which probability sampling methods are needed for a scientific study of the indoor air quality in a building. For those situations for which probability sampling methods are recommended, guidance is provided on how to implement probability sampling methods, including obstacles that may arise. Examples of their application are provided for selected situations. Because some indoor air quality investigations may require application of complex, multistage, survey sampling procedures and because this standard is a guide rather than a practice, the references in Appendix X1 are recommended for guidance on appropriate probability sampling methods, rather than including expositions of such methods in this guide.

2. Referenced Documents

2.1 ASTM Standards:

D 1356 Terminology Relating to Sampling and Analysis of Atmospheres²

3. Terminology

3.1 *Definitions*—For definitions of terms used in this guide, refer to Terminology D 1356.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *census*—survey of all elements of the target population.

3.2.2 *cluster sample*—a sample in which the sampling frame is partitioned into disjoint subsets called clusters and a sample of the clusters is selected.

3.2.2.1 *Discussion*—Data may be collected for all units in each sample cluster or, when a multistage sample is being selected, the units within the sampled clusters may be further subsampled.

3.2.3 *compositing samples*—physically combining the material collected in two or more environmental samples.

3.2.4 *expected value*—the average value of a sample statistic over all possible samples that could be selected using a specified sample selection procedure.

3.2.5 *multistage sample*—a sample selected in stages such that larger units are selected at the first stage, and smaller units are selected at each subsequent stage from within the units selected at the previous stage of sampling.

3.2.5.1 *Discussion*—For assessing the indoor air quality in a population of office buildings, individual buildings might be selected at the first stage of sampling, floors selected within sample buildings at the second stage, and monitoring locations (for example, rooms or grid points) selected on sampled floors at the third stage.

3.2.6 *population parameter*—a characteristic based on or calculated from all units in the target population.

3.2.6.1 *Discussion*—The purpose of selecting a sample is usually to estimate population parameters. Population parameters cannot actually be calculated unless data are available for all units in the population.

3.2.7 *probability sample*—a sample for which every unit on the sampling frame has a known, positive probability of being selected into the sample.

3.2.7.1 *Discussion*—The terms *probability sampling* and *random sampling* are sometimes used interchangeably.

3.2.8 *sampling frame*—a list from which a sample is selected.

3.2.8.1 *Discussion*—An ideal sampling frame contains each member of the target population exactly once and contains no units that are not members of the target population. In practice, the sampling frame may miss some members of the target population (for example, new employees in a building) and include some individuals who are not members of the target

¹ This guide is under the jurisdiction of ASTM Committee D22 on Sampling and Analysis of Atmospheres and is the direct responsibility of Subcommittee D22.05 on Indoor Air.

Current edition approved September 10, 1995. Published November 1995.

² *Annual Book of ASTM Standards*, Vol 11.03.

population (for example, individuals who no longer work in the building). However, no member of the population should be listed more than once on the sampling frame.

3.2.9 *simple random sample*—a sample of n elements selected from the sampling frame in such a way that all possible samples of n elements have the same chance of being selected.

3.2.10 *statistic*—a sample-based estimate of a population parameter.

3.2.11 *stratified sample*—a sample in which the sampling frame is partitioned into disjoint subsets called strata, and sample units are selected independently from each stratum, possibly at different sampling rates.

3.2.12 *systematic sample*—a sample selected by choosing one of the first k elements on the sampling frame at random and then including every k th element thereafter.

3.2.13 *target population*—the set of units or elements (for example, people or locations in space and time) about which a sample is designed to provide inferences.

3.2.13.1 *Discussion*—The target population is sometimes referred to as the population or universe of interest.

3.2.14 *unbiased estimator*—a statistic whose expected value is equal to the population parameter that it is intended to estimate.

4. Summary of Guide

4.1 When the objectives of an investigation of indoor air quality include extending inferences from a sample of units to the larger population from which those units were selected, probability sampling methods must be used to select the sample units to be observed and measured. Examples include:

4.1.1 Estimating the distributions of health and comfort symptoms experienced by the employees in a particular building during a specific week.

4.1.2 Estimating the distribution of hourly average concentrations of specific substances in the breathing zone air in a particular building during the working hours of a specific week.

4.1.3 Estimating the relationship between measures of environmental conditions in a building and the health or comfort symptoms experienced by the occupants.

4.1.4 Thus, the study objectives are always a key consideration for determining if probability sampling methods are necessary. Potential objectives for indoor air studies that would require probability sampling methods are discussed explicitly in Section 6.

4.2 Guidance is provided regarding the appropriate probability sampling methods to address these and other goals that require extending inferences from a sample to a specific population. Those sampling methods require construction of a sampling frame from which population elements can be selected. Examples include:

4.2.1 A list of all offices or work stations in a building.

4.2.2 A grid of potential monitoring locations that effectively covers the entire population of interest, and

4.2.3 A list of all persons who work in a specific building.

4.3 Since environmental concentrations usually vary continuously in time, spatial frame units like those listed in 4.2 often must be crossed with temporal units, such as seasons, weeks, days, or hours, to form sampling frame units (for

example, building-seasons, office-weeks, or person-days). Specific issues that must be considered when constructing these types of sampling frames are discussed in Section 7.

4.4 In addition to constructing sampling frames, a randomization procedure is necessary so that units can be selected from the frame with known probabilities. Some basic considerations for and methods of selecting probability samples for studies of indoor air quality are presented in Section 8.

4.5 Finally, Section 9 discusses considerations for statistical analysis and reporting that are peculiar to data collected using probability sampling designs. Special statistical analysis methods are necessary when the sampling design includes stratification, clustering, multistage sampling, or unequal probabilities of selection.

5. Significance and Use

5.1 Studies of indoor air problems are often iterative in nature. A thorough engineering evaluation of a building **(1-4)**³ is sometimes sufficient to identify likely causes of indoor air problems. When these investigations and subsequent remedial measures are not sufficient to solve a problem, more intensive investigations may be necessary.

5.2 This guide provides the basis for determining when probability sampling methods are needed to achieve statistically defensible inferences regarding the goals of a study of indoor air quality. The need for probability sampling methods in a study of indoor air quality depends on the specific objectives of the study. Such methods may be needed to select a sample of people to be asked questions, examined medically, or monitored for personal exposures. They may also be needed to select a sample of locations in space and time to be monitored for environmental contaminants.

5.3 This guide identifies several potential obstacles to proper implementation of probability sampling methods in studies of indoor air quality in buildings and presents procedures that overcome those obstacles or at least minimize their impact.

5.4 Although this guide specifically addresses sampling people or locations across time within a building, it also provides important guidance for studying populations of buildings. The guidance in this document is fully applicable to sampling locations to determine environmental quality or sampling people to determine environmental effects within each building in the sample selected from a larger population of buildings.

6. Study Objectives That Require Probability Sampling Methods

6.1 Inferences beyond the units actually observed in a sample are not rigorously defensible unless the units observed are a probability sample selected from the population to which inferences will be extended. Thus, probability sampling methods are needed whenever inferences will be extended from the units observed in a sample to a larger population. The need for such inferences depends directly on the objectives of the study.

³ The boldface numbers in parentheses refer to the list of references at the end of this guide.

The study objectives may include characterizing a building's occupants using a survey, or characterizing a building's air quality using environmental monitoring, or a combination of both.

6.2 *Occupant Survey:*

6.2.1 A sample of building occupants may be asked to complete a questionnaire or to submit to a physical examination. If the intention is to make inferences from the sample regarding the health and comfort symptoms of all the employees of the building, a census of all building occupants or a probability sample selected from them is required. The occupants would typically be asked about their health and comfort symptoms for a specific period of time (for example, the day that the survey is administered, the previous week, month, or year, and so forth). Developing a valid and reliable questionnaire is a complex process and is not directly addressed by this guide (5).

6.2.2 Specific study objectives that require inferences to a population of building occupants include the following:

6.2.2.1 Estimate the distribution of health and comfort symptoms in a building either before beginning air quality measurements, after implementing remedial measures, or as a measure of the magnitude of a potential indoor air problem.

6.2.2.2 Estimate the distribution of health and comfort symptoms in a building with reported problems and in another building studied for comparison purposes.

6.2.2.3 Estimate the relationship of health and comfort symptoms with worker characteristics, such as age, sex, work location, or type of work performed.

6.2.3 When inferences regarding the occupants of a building are needed, a census of all the building occupants may be necessary. For example, a census of building occupants may be needed to establish statistical differences in occupant comfort or health symptoms between different work areas (for example, floors) within a building. In other cases (for example, estimating the relative frequency of complaints in a building with a large number of workers), a probability sample may provide sufficient precision at less cost.

6.2.4 If the characteristics measured in a questionnaire are temporally dependent (for example, comfort and health symptoms on the day of questionnaire administration), a sample of people and time periods may be needed (for example, a sample of person-days within a given week). Moreover, the survey may need to be replicated across time (that is, repeated in different seasons).

6.2.5 A successful occupant survey requires that a large portion of the sample subjects complete the survey. The Office of Management and Budget usually requires 75 % or more for federally funded surveys. Thus, the success of a survey may depend upon the burden it imposes, pre-survey publicity (for example, newsletters or union endorsements), and follow-up of nonrespondents. The survey should be conducted in such a manner that people are sufficiently motivated to participate but not unduly alarmed about a potential air quality problem. Finally, residual nonresponse is inevitable, and survey data analysis procedures that utilize weighting or imputation to compensate for nonresponse are recommended.

6.3 *Environmental Monitoring:*

6.3.1 Since air quality characteristics generally exhibit both spatial and temporal variability, each air quality measurement (for example, temperature, humidity, or concentrations of specific substances) is generally representative of a specific location and time (or period of time). If the objective is to infer information about the distribution of the measured characteristics (for example, the mean or the range) for a target population of times and places, then probability sampling of both locations and times is required to justify that inference.

6.3.2 Specific study objectives that require inferences to a population of units defined in time and space include the following:

6.3.2.1 Estimate the distribution of hourly average concentrations of specific substances in a building during a specified time frame either before or after implementing remedial measures, or as a measure of the magnitude of a potential indoor air problem.

6.3.2.2 Estimate the distribution of hourly average concentrations of specific substances in a building with suspected problems and in another building studied for comparison purposes. In each case, the target population would be defined as a specific set of building locations crossed with a specific set of time points. Inferences to the population would require that data be collected for a probability sample of the population units.

6.3.3 Temporal variations in air quality must always be considered when designing a survey of a building's air quality. Periodic variations, such as diurnal, weekday/weekend, and seasonal effects can be important. Periodic effects may be caused by periodic variation in activity patterns within the building or environmental factors that affect source strength or ventilation rate. These temporal variations will affect such sampling design characteristics as the definition of the population units and the definition of sample selection strata.

6.3.4 For example, if diurnal effects must be estimated, the temporal dimension of the population units to be measured cannot be greater than 12 h, and the sampling plan must include both daytime and nighttime measurements. If estimating other temporal differences is important (for example, weekday/weekend, high/low wind, before/during/after second-shift), population units must be defined and sampled for each temporal period. The precision for estimates of differences between time periods can be increased by monitoring a single sample of locations during multiple time periods. If concurrent surveys of building occupants and air quality characteristics are required to establish relationships, a separate sample of building occupants may be needed for each time period.

6.3.5 Likewise, the survey may need to be replicated across time to characterize building conditions during multiple seasons. Similarly, if certain air quality problems are perceived to be worse on weekday mornings, surveys conducted on a weekday morning, a weekday evening, and a weekend day may be useful for estimating temporal differences.

6.3.6 Whenever environmental monitoring is being conducted indoors and the outdoor air is a potential source of the substances being monitored, indoor and outdoor air should be monitored concurrently. Constructing a sampling frame for selecting a probability sample of outdoor monitoring locations

may not be feasible. Instead, each indoor monitoring location may be matched to one of a small number of outdoor monitoring sites (for example, one to four) that best represents the outdoor air source for the monitored indoor site.

6.4 Combining an Occupant Survey with Environmental Monitoring:

6.4.1 Air quality characteristics and people's perceptions of the air quality may be measured simultaneously. If the objective is to infer a relationship between the two sets of measurements for a larger population of people, places, and times, then a probability sample of people, places, and times is necessary.

6.4.2 When a survey objective is to estimate the relationship between data collected for building occupants and indoor air monitoring data (for example, between the occurrence of specific symptoms and the concentrations of specific substances), a probability sample of locations and times (for the air quality monitoring and symptom measurement) plus associated people (for example, the people who work primarily at the locations and times being monitored) is needed to support those inferences. In this case, recording symptoms for the same temporal reference periods over which air quality samples are collected is important. See Ref (6) for an example of such an investigation.

6.4.3 A specific survey objective that would require a probability sample of times, locations, and people is the following:

6.4.3.1 Estimate the relationship of health and comfort symptoms with concentrations of specific substances measured in the same times and places as the health and comfort symptoms.

6.4.4 While one may be able to approximate a relationship based on a non-probability sample (for example, locations that approximate the range of health and comfort symptoms or the range of environmental measurements), a population sample is needed if the relationship is to be representative of the entire population. Moreover, if other population characteristics (for example, the distribution of health and comfort symptoms or the mean air concentration) are to be estimated from the same database, a population sample is required.

7. Defining Population Units

7.1 The identification of population units depends on measurement procedures and study objectives. The units in the target population are those units for which measurements will be obtained and which in their aggregate represent the entire universe to which inferences will be extended. For environmental studies, these units usually need to be defined in time and space (7).

7.2 Occupant Survey:

7.2.1 When a survey of the occupants of an office building is needed, defining the population of interest is relatively straightforward. Nevertheless, temporal and spatial effects need to be considered. Questions to be answered regarding the inclusiveness of the population include the following:

7.2.1.1 Does the population include both part-time and full-time workers?

7.2.1.2 Does the population include both temporary and permanent staff?

7.2.1.3 Does the population include all work shifts?

7.2.1.4 Does the population include custodial staff?

7.2.1.5 Does the population include workers in all of the building or only specific areas of the building?

7.2.2 If the data to be collected are time dependent (for example, health and comfort symptoms on a particular day or during the previous week), then the population units have a temporal component, also. Thus, the population units to be sampled may be person-days or person-weeks. The set of days or other time units to be represented by the survey must be explicitly defined. If only one temporal unit is to be represented (for example, one day or one week), no sampling in time is required. Otherwise, sampling in time is necessary to represent the desired population of people and times.

7.3 Environmental Monitoring:

7.3.1 The population units for environmental monitoring usually must be defined in time and space because environmental conditions usually change continuously. A population unit is essentially the unit of time and space that is characterized by a single measurement from a monitoring instrument. Thus, different monitoring instruments may produce measurements for different population units (for example, one provides average concentrations for 6 to 12-h periods while another provides continuous measurements for up to 24 h).

7.3.2 The spatial dimension of a population unit for an air monitoring device may be an envelope of specified volume (for example, 1000 m³) centered at the monitoring device. However, the reliability with which the monitoring device can characterize the air quality in an envelope surrounding itself depends directly on air mixing in the immediate vicinity of the device. Therefore, definition of the spatial population units generally depends on locations of physical boundaries (for example, walls) and on characteristics of the heating, ventilating, and air conditioning (HVAC) system (for example, air handling zones).

7.3.3 The space characterized by a monitoring instrument will not usually have fixed boundaries. Thus, the spatial dimension of a population unit may be somewhat arbitrary. Nevertheless, the spatial population units can be defined by first reviewing the floor plan and the HVAC system of a building to construct a grid of points that, in their entirety, would effectively characterize the entire breathing-zone space of the building if they were all monitored. The spatial population units are then disjoint envelopes centered at the grid points (potential monitoring locations). If the envelopes are of different sizes, statistical analyses must account for these differences.

7.3.4 When a building can be subdivided into rooms or room-equivalents (for example, four room-equivalent areas for an auditorium) such that the air quality in the breathing zone of each room can be characterized by the sample(s) collected using a single air sampling device in each room, the spatial population units may be the set of all rooms or room-equivalents in the building.

7.3.5 Similarly, the temporal dimension of a population unit is the time period characterized by a single measurement. For a continuous monitor, any temporal period ranging from the total time monitored down to the time resolution of the instrument can be characterized in the data analysis phase of

the investigation. Thus, in this case, the temporal dimension of a population unit can be almost any time period suitable for the desired statistical inferences.

7.3.6 Many environmental monitors collect a sample over a specific period of time, called the period of integration, which may be used to characterize the average concentration of a substance during the period of integration. These monitors may have both a minimum and a maximum time period (for example, 6 to 12 h) that can be characterized with satisfactory limits of detection. In this case, the monitoring instrument limits the possibilities for the temporal dimension of the population units. The study goals must be expressed in terms of the population units that actually can be observed and measured. In the previous example, if hourly average or instantaneous concentrations were of interest, either the study goals would have to be expressed in terms of 6 to 12-h averages or a different monitoring instrument would have to be used.

8. Probability Sampling Methods

8.1 Overview:

8.1.1 Two essential ingredients of any probability sampling method are: (1) a sampling frame or list of the elements in the population and (2) a randomization procedure that assigns a positive probability of selection to every unit on the sampling frame. If a simple list of all the elements of the target population does not exist, a multistage probability sampling procedure is usually used. In this case, larger units are selected at the first stage of sampling (for example, study areas within a building) and smaller units are selected at each subsequent stage from within the units selected at the previous stage (for example, workers within sampled study areas). Paragraph 8.2 discusses construction of sampling frames for all types of probability sampling.

8.1.2 Using probability sampling does not mean that all units in the population must be selected totally at random. Instead, the knowledge of engineers, plant managers, and others familiar with a building's operation can be used to partition the sampling frame into subsets, called strata, such that a more efficient sample is obtained by independently selecting a sample from each stratum. Paragraph 8.3 discusses stratification of sampling frames for indoor air studies.

8.1.3 Paragraphs 8.4 and 8.5 introduce two simple methods for selecting probability samples—simple random sampling and systematic sampling. These simple procedures may be sufficient for some indoor air studies. However, more complex probability sampling methods will be more appropriate for many studies. The references listed in Appendix X1 provide in-depth treatment of probability sampling methods.

8.1.4 Because environmental monitoring is often expensive and because precise statistical estimates often require large sample sizes, innovative sampling designs may be necessary for many indoor air studies. Paragraph 8.6 discusses sampling design options that can be considered for reducing survey costs.

8.1.5 If costs or other considerations lead to a total sample size of fewer than 30 observations in time and space, a sample of units purposively selected to be representative of the population of interest is likely to be more appropriate than probability sampling. Probability-based inferences from a

sample to the population from which it was selected require reasonably large sample sizes. When sample sizes are quite small (for example, less than 30), statistical inferences generally cannot be extended beyond the population units actually observed and measured in the study.

8.2 Sampling Frames:

8.2.1 When a sample of the workers in an office building is needed, a list of all the workers in the target population may be compiled and used as the sampling frame.

8.2.2 However, if a building is occupied by several different tenants, a multistage sampling procedure may be necessary. A sample of tenants would be selected from a list of all the building's tenants at the first stage of sampling. A second-stage sample of individual employees would be selected from lists provided by the tenants selected at the first stage.

8.2.3 Creating a sampling frame of locations in time and space for monitoring indoor air quality requires that each unit on the sampling frame be defined in terms of the unit of time and space that can be characterized by a monitoring device, as discussed earlier. Those units might be room-days (where rooms are offices or other areas that can be effectively characterized by a single monitoring instrument), room-hours, grid-point mornings and afternoons, and so forth.

8.2.4 The spatial population units may have natural spatial boundaries, such as the walls of rooms, or they may be a grid of sampling points. If vertical gradients are not of interest, a plane of grid points at a specified height (for example, the breathing zone), may be sufficient. Given the maximum size of the space that can be represented by a single monitoring device, the HVAC design, and the floor plan, a grid of potential sampling points can be established fairly easily for most buildings. Studies that have used random sampling of potential monitoring sites include Refs (6) and (8).

8.3 Stratification:

8.3.1 Stratified sampling refers to partitioning the sampling frame into disjoint subsets and independently selecting a sample from each subset, or stratum. Stratified sampling will usually be appropriate for indoor air studies. The purposes of stratification include the following:

8.3.1.1 Ensuring the representativeness of a sample by guaranteeing that all strata are sampled (for example, all floors of a multi-floor building),

8.3.1.2 Ensuring adequate sample sizes for analyses for individual strata (for example, in offices and in common public areas), and

8.3.1.3 Improving the precision of overall population estimates of means and proportions by forming strata such that environmental parameters are more alike within strata than between strata.

8.3.2 Not only will effective stratification improve the precision of survey estimates, but ineffective stratification generally can be no worse than unstratified sampling. Therefore, stratified sampling is generally recommended for indoor air studies. However, major resources should not be devoted to defining strata unless real gains in precision are expected.

8.3.3 Using different probabilities of selection in different strata is only advisable when estimates with different precision are required for different strata or when prior knowledge of

different sampling costs or variability of environmental measurements make different sampling rates more efficient. Otherwise, the same sampling rate should be used in all strata.

8.3.4 If separate estimates are to be computed for several different areas of a building (for example, different floors or the areas occupied by different tenants), then each such area should be a separate stratum to ensure a sufficient sample size in each area. Within each such stratum, or within the building as a whole, other considerations that can lead to relatively homogeneous strata for improving precision include:

8.3.4.1 Ventilation patterns,

8.3.4.2 Locations of potential sources of the substances being monitored, and

8.3.4.3 Work locations of people with potentially high susceptibilities.

8.4 *Simple Random Sampling:*

8.4.1 Simple random sampling is conceptually the simplest method of probability sampling. A simple random sample is a sample selected so that all possible samples have the same probability of being selected. Selecting a simple random sample within each of several strata may be sufficient for some indoor air studies.

8.4.2 A table of random numbers or a computerized random number generator can be used easily to select a simple random sample. Simply generate or assign a several-digit random number between zero and one to each unit on the sampling frame. Then sort the units in order by the random numbers. The n units associated with the smallest random numbers (or equivalently with the largest) constitute a simple random sample of Size n .

8.5 *Systematic Sampling:*

8.5.1 To select a systematic sample from a sampling frame, use a random number table or a computerized random number generator to select one unit at random from the first k units on the frame, for a suitably chosen value of k . Every k th unit on the frame following the randomly selected unit is also a member of the systematic sample.

8.5.2 Thus, a single random number is sufficient to determine *all* the units in a systematic sample. Alternatively, a systematic sample is a single randomly selected cluster of population units. Because a systematic sample is technically just a cluster sample of size one, a valid estimate of precision (for example, standard error) cannot be computed from a single systematic sample. Therefore, multiple systematic samples (for example, five samples) are recommended so that valid estimates of precision can be computed for survey statistics. Alternatively, a systematic sample is sometimes analyzed as if it were a simple random sample.

8.6 *Multistage Sampling*—If inferences are required for the occupants or environmental conditions in a population of buildings, then buildings would generally be selected with probabilities proportional to some measure of size (for example, number of occupants or occupied square feet) at the first stage of a multistage sample. For example, if buildings were selected with probabilities proportional to the number of occupants and the same number of occupants were selected from each sampled building at the second stage of sampling,

the result would be a two-stage, equal-probability sample of occupants in the specified population of buildings.

8.7 *Cost-Saving Techniques:*

8.7.1 Some techniques that can be used to reduce or control the cost of a statistical survey include:

8.7.1.1 Relaxing precision constraints,

8.7.1.2 Compositing samples, and

8.7.1.3 Using double, or two-phase, sampling techniques.

8.7.2 One may initially begin with a set of study objectives and corresponding precision constraints for several population parameters. If the cost of the survey that would achieve all the precision constraints is too great, relaxing precision constraints may be the most obvious way to reduce the cost of the survey. However, it may not be possible to achieve major cost savings in this way unless precision constraints that have been established for small population subgroups can be eliminated.

8.7.3 When the objective of a monitoring program is to estimate a mean over time or space, or both, the material collected in two or more environmental samples can be combined for laboratory analysis to reduce costs. This procedure, referred to as compositing samples, is only appropriate when the composited samples contain sufficient information to address the study objectives. Compositing samples loses some information (for example, temporal and spatial detail) that can only be obtained from the separate samples. For example, suppose that a study objective was to estimate the mean concentration of inhalable particles for each floor of a multi-story building during a one-week period of time. A set of samplers could be deployed the first day in randomly selected locations on each floor and then moved to new randomly selected locations each day of the week. Each monitor would be collecting a sample that is composited over time and space. Because each composited sample is a sum over time and locations on the same floor, the composited samples would have less variability than the individual location-day samples, and a smaller sample size would be sufficient for obtaining specified precision for the estimated mean concentration of inhalable particles.

8.7.4 Double, or two-phase, sampling refers to collecting information in an initial, inexpensive survey and using that information to refine a later, more expensive survey. The initial, inexpensive survey may be a baseline survey or engineering evaluation of a building. This information could be used to stratify a sample into areas in which indoor air problems are expected to be less prevalent and others in which they are expected to be more prevalent. If a primary objective of the study were to estimate the mean level of a substance in the air, using such strata and sampling each stratum at the same rate could result in a more precise estimate of the mean than using an unstratified sample. Alternatively, such strata may serve as the basis for unequal sampling rates. For example, environmental monitoring might be restricted to the strata expected to represent the *best case* and *worst case* situations. However, because this strategy risks missing the true best and worst cases because of imperfect information for defining the strata, a preferable approach would be to select samples from all strata using different sampling rates. The sampling rates should generally differ by no more than a factor of three.

8.7.5 Another application of double, or two-phase, sampling is to deploy a large sample of inexpensive monitoring instruments at randomly selected locations and co-locate more precise, expensive monitoring instruments at a randomly selected subsample of locations. The mean can then be estimated using a double-sampling regression estimator. The regression relationship between the expensive and inexpensive measurements would be estimated. The double-sampling regression estimator uses the regression predictions of the more expensive measurements for the sample units for which those data were not collected. If there is a high correlation between the measurements produced by the two instruments, the precision of the estimated mean may be almost as great as if the more expensive measurements were obtained for the entire sample.

9. Analysis and Reporting

9.1 Summarizing the data collected in an indoor air study may be fairly straightforward when a census of the building occupants has been conducted. If the population of interest is the current population at the time of data collection, then any observed differences reflect the total population and, therefore, are true differences. No confirmation by statistical significance is necessary. However, if a sample of occupants has been selected, or the current occupants are viewed as a single realization of the long-term population of occupants, then estimation of standard errors and identification of statistically significant differences may be important.

9.2 If building occupants or environmental monitoring locations have been selected with unequal probabilities of selection or using complex sampling design features such as stratification or multistage sampling, proper statistical analysis may be complex. Computing unbiased population estimates requires that each response or measurement be weighted inversely to the sampling unit's probability of selection. Moreover, estimates of precision of survey statistics (for example, standard errors) must account for all features of the sampling design, such as stratification, multistage sampling, and unequal probabilities of selection. In addition, estimates of precision need to incorporate a statistical finite population correction whenever a large portion of the population (for example, more than 10 %) has been selected from any stratum. Most commercially available statistical software packages use procedures that are only applicable for analysis of data collected using simple random sampling from infinite populations. Software packages that have been developed for analysis of data collected from finite populations and using other probability sampling designs are reviewed by Ref (9).

9.3 Even when the overall probabilities of selection are equal, special techniques are needed to correctly estimate standard errors if the sampling design is not simple (unstratified) random sampling. However, when a stratified simple random sample of units has been selected for observation or

measurement, standard statistical analysis methods that assume simple random sampling will generally yield slight overestimates of the standard errors of survey statistics, which would lead to conservative statistical inferences.

9.4 The primary analyses to be conducted should always be decided during the design phase of the study to ensure that the questions asked and the other data collected will be sufficient to support the desired analyses. The results of the initial analyses will usually suggest other analyses of interest. The format of the analyses (for example, specific tables or correlations) will usually be rather specific to the individual studies. However, the analyses will generally include summaries for specific areas of the building and times of day. If the data indicate that air quality problems are greater in some areas or times than others, closer inspection of those areas and times may reveal the source of the problem.

9.5 When analyzing environmental measurements of indoor air quality, one must be aware of the potential effect of measurement errors. If environmental characteristics could be measured without error for every unit in the population, then the resulting distribution of measurements would be the true population distribution. When analyzing environmental data, it is the parameters of this true population distribution (for example, mean, median, and percentiles) that one wants to estimate. However, even assuming that there are no systematic measurement errors, random measurement errors result in an observed distribution (the distribution of all possible measurements) that is flatter and more dispersed than the true population distribution. If the measurement error variability is not negligible relative to the true population variability, sample statistics based on the observed distribution will usually be biased estimates of the corresponding population parameters. Estimates of percentiles far from the median will be most affected. The observed percentiles will lie further from the population median than do the true population percentiles. Statistical techniques are available for estimating parameters of the true population distribution when the observed distribution contains non-negligible measurement error. These techniques require information about the statistical distribution of the measurement errors, which can be developed from quality control data (that is, replicate measurements and standard samples). General techniques for incorporating measurement error in analysis of environmental data are discussed in Ref (10).

10. Resources

10.1 A bibliography of references that discuss the design and analysis of sample surveys is provided as Appendix X1.

11. Keywords

11.1 indoor air quality; probability sampling methods; random sampling; survey sampling

APPENDIX
(Nonmandatory Information)
X1. BIBLIOGRAPHY FOR SAMPLING DESIGN

- X1.1 Cochran, W. G., Mosteller, F., and Tukey, J. W., "Principles of Sampling," *Journal of the American Statistical Association*, March 1954, pp. 13–35.
- X1.2 Cochran, W. G., *Sampling Techniques*, 3rd ed., John Wiley & Sons, New York, NY, 1977.
- X1.3 Hansen, M. H., Hurwitz, W. N., and Madow, W. G., *Sample Survey Methods and Theory*, John Wiley & Sons, New York, NY, 1953.
- X1.4 Kalton, G., *Introduction to Survey Sampling*, Sage Publications, Beverly Hills, CA, 1983.
- X1.5 Kendall, M. G., and Stuart, A., *The Advanced Theory of Statistics, Volume 3: Design and Analysis, and Time-Series*, Hafner Publishing, New York, NY, 1968, pp. 166–238.
- X1.6 Kish, L., *Survey Sampling*, John Wiley & Sons, New York, NY, 1965.
- X1.7 Konijn, H. S., *Statistical Theory of Sample Survey Design and Analysis*, North-Holland and Publishing, London, England, 1973.
- X1.8 Moser, C. A., and Kalton, G., *Survey Methods in Social Investigation*, 2nd ed., Heinemann, London, England, 1971.
- X1.9 Raj, D., *Sampling Theory*, McGraw-Hill, New York, NY, 1978.
- X1.10 Rossi, P. H., Wright, J. D., and Anderson, A. B., eds., *Handbook of Survey Research*, Academic Press, New York, NY, 1983.
- X1.11 Skinner, C. J., Holt, D., and Smith, T. M. F., eds., *Analysis of Complex Surveys*, John Wiley & Sons, Chichester, England, 1989.
- X1.12 Sukhatme, P. V., and Sukhatme, B. V., *Sampling Theory of Surveys with Applications*, Iowa State University Press, Ames, IA, 1970.
- X1.13 Wolter, K. M., *Introduction to Variance Estimation*, Springer-Verlag, New York, NY, 1985.
- X1.14 Yates, F., *Sampling Methods for Censuses and Surveys*, 4th ed., Griffin, London, England, 1981.

REFERENCES

- (1) Gammage, R. B., Hansen, D. L., and Johnson, L. W., "Indoor Air Quality Investigations: A Practitioner's Approach," *Environment International*, No. 15, 1989, pp. 503–510.
- (2) Sterling, E. M., McIntyre, E. D., Collett, C. W., Meredith, J., and Sterling, T. D., "Field Measurements for Air Quality in Office Buildings: A Three-Phased Approach to Diagnosing Building Performance Problems," *Sampling and Calibration for Atmospheric Measurements*, ASTM STP 957, J. K. Taylor, ed., ASTM, 1987, pp. 46–65.
- (3) Gorman, R. W., and Wallingford, K. M., "The NIOSH Approach to Conducting Indoor Air Quality Investigations in Office Buildings," *Design and Protocol for Monitoring Indoor Air Quality*, ASTM STP 1002, N. L. Nagda and J. P. Harper, eds., ASTM, 1989, pp. 63–72.
- (4) U.S. Environmental Protection Agency and the Centers for Disease Control and Prevention, *Building Air Quality, A Guide for Building Owners and Facility Managers*, U.S. Government Printing Office, Washington, DC, 1991.
- (5) Sudman, S., and Bradburn, N. M., *Asking Questions: A Practical Guide to Questionnaire Design*, Jossey-Boss, Washington, DC, 1982.
- (6) Nagda, N., Koontz, M. D., and Albrecht, R. J., "Effect of Ventilation Rate in a Healthy Building," *Proceedings of ASHRAE Conference: IAQ '91—Healthy Buildings*, 1991, pp. 101–107.
- (7) Gilbert, R. O., *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold, New York, NY, 1987.
- (8) Farant, J. P., Baldwin, M., de Repentigny, F., and Robb, R., "Environmental Conditions in a Recently Constructed Office Building Before and After the Implementation of Energy Conservation Measures," *Applied Occupational and Environmental Hygiene* 7:2, 1992, pp. 93–100.
- (9) Wolter, K. M., *Introduction to Variance Estimation*, Springer-Verlag, New York, NY, 1985.
- (10) Fuller, Wayne A., *Measurement Error Models*, John Wiley & Sons, New York, NY, 1987.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org).