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Standard Guide for Using Probability Sampling Methods in Studies of Indoor Air Quality in Buildings[1]

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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.

1.4 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

3. Terminology

3.1 *Definitions*—For definitions of terms used in this guide, refer to Terminology D1356.

3.2 *Definitions of Terms Specific to This Standard:*

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

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

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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—~~samples, v—*physically combining the material collected in two or more environmental samples.

3.2.4 *expected ~~value—~~value, n—*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—~~sample, n—*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—~~parameter, n—*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—~~sample, n—*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—~~frame, n—*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 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—~~sample, n—*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—~~statistic, n—*a sample-based estimate of a population parameter.

3.2.11 *stratified ~~sample—~~sample, n—*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—~~sample, n—*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—~~population, n—*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—~~estimator, n—*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. 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**).

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

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. For example, the United States 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 m^3) 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.