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Standard Guide for Air Sampling Strategies for Worker and Workplace Protection[1]

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1. Scope

1.1 This guide describes criteria to be used in defining air sampling strategies for workplace health and safety monitoring or evaluation. Sampling criteria such as duration, frequency, number, location, method, equipment, and timing are all considered.

1.2 Where air sampling is prescribed by law or regulation, this guide is not intended to take the place of any requirements that may be specified in such law or regulation.

1.3 Guidance for surface sampling strategies for metals and metalloids is provided in Guide D7659.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

D4840 Guide for Sample Chain-of-Custody Procedures

D7659 Guide for Strategies for Surface Sampling of Metals and Metalloids for Worker Protection

E1542 Terminology Relating to Occupational Health and Safety

2.2 *ISO Standards:*[3]

ISO 7708 Particle Size Fraction Definitions for Health-Related Sampling

ISO/IEC 17025 General Requirements for the Competence of Testing and Calibration Laboratories

EN 1540 Workplace Exposure—Terminology

3. Terminology

3.1 For definitions of terms relating to occupational health and safety, see Terminology E1542.

3.2 For definitions of terms relating to atmospheric sampling and analysis, see Terminology D1356.

3.3 *Definitions:*

3.3.1 *alarm sampler*—sampling device that produces an alarm (audible, visible, or both) when the concentration of a substance exceeds a pre-set value.

3.3.2 *exposure (by inhalation)*—situation in which a chemical or biological agent is present in the air that is inhaled by a person. **EN 1540**

3.3.3 *occupational exposure limit*—upper bound on the acceptable concentration of a hazardous substance in workplace air.

3.3.3.1 *Discussion*—Typically established by national authorities in efforts to protect workers' health.

3.3.4 *professional judgment*—application and appropriate use of knowledge gained from formal education, experience, experimentation, inference, and analogy. **D7659**

3.3.4.1 *Discussion*—The capacity of an experienced professional to draw correct inferences from incomplete quantitative data, frequently on the basis of observations, analogy, and intuition.

3.3.5 *sampling excursion*—duration of time during which active sampling is not being performed, typically between two durations of active sampling.

4. Significance and Use

4.1 This guide describes standard approaches used to formulate air sampling strategies before actual air sampling occurs.

4.2 For most workplace air sampling purposes, and for the majority of materials sampled, air sampling strategies are matters of choice. Air sampling in the workplace may be done for single or multiple purposes, such as health impact, hazard or risk assessment, compliance assessment, or investigation of

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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] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

complaints. Problems can arise when a single air sampling strategy is expected to satisfy multiple diverse purposes.

4.2.1 Proper consideration of limitations of cost, space, power requirements, equipment, analytical methods, training and personnel result in a best available strategy for each purpose.

4.2.2 A strategy designed to satisfy multiple purposes must be a compromise among several alternatives, and will not be optimum for any one purpose; however, the strategy should be appropriate for the intended purpose(s).

4.2.3 The purpose or purposes for sampling should be explicitly stated before a sampling strategy is selected in order to ensure that the sampling strategy is appropriate for the intended use. Good sampling practice, legal requirements, cost of the sampling program, and the utility of the results may be markedly different for different intended sampling purposes.

4.3 This guide is intended for use by those who are preparing to evaluate air quality in a work environment of a location by air sampling, or who wish to obtain an understanding of what information can be obtained by carrying out air sampling.

4.4 This guide should not be used as a stand-alone document to evaluate any given airborne contaminant(s).

4.5 This guide cannot take the place of sound professional judgment in development and execution of any sampling strategy. In most instances, a strategy based on a standard practice or method will need to be adjusted due to conditions encountered in the field. Documentation of any professional judgments applied to development or execution of a sampling strategy is essential.

5. Air Sampling—General

5.1 Results from air sampling are but one of many sources of information about workplace health and safety of conditions. Air sampling should not be used to the exclusion or absence of other pertinent information.

5.2 Bioassay and biomonitoring results, clinical observations, visual observation, quality and process control data, and material balance studies, where applicable, should always be used in conjunction with air sampling data.

5.3 Qualitative agreement among separately obtained sources of information will typically increase confidence in the interpretation of workplace hazard or risk assessments. Disagreement among information sources or data should be cause for concern, and will result in investigation into the source(s) of disagreement.

6. Purposes for Air Sampling

6.1 *Risk Evaluation*—To estimate the expected, or maximum, or both contaminant concentrations in the workplace. The information obtained is used to recommend worker protection requirements and to assess the probability of sensitization or hypersensitivity reactions.

6.2 *Exposure Estimation*—To measure the actual concentrations of contaminant to which one particular worker is exposed. The concentrations measured may or may not be hazardous. In many cases, it is sufficient to show that any exposures are less than half of applicable limits or standards. It may be necessary to show that an exposure does not exceed an applicable limit value within a stated degree of confidence.

6.3 *Exposure Documentation*—To provide the data base necessary for epidemiological studies, when the existence of a health hazard is postulated. It is similar to exposure estimation, but is focused more on job categories or job titles, rather than on an individual worker, and requires the use of instruments and methods that minimize the likelihood of obtaining results that are below the limits of detection.

6.4 *Facility Characterization*—To determine the levels of the analyte or analytes of interest within a facility at an initial or baseline point, during or after process operations, or as part of facility decommissioning.

6.5 *Selection of Engineering Controls*—To determine, for contaminants that are not totally contained, the collection or capture efficiencies of control devices necessary to bring specific contaminant concentrations below applicable limits at specific locations.

6.6 *Evaluation of Engineering Controls*—To measure the quantities of contaminants passing or escaping from a control device due to leaks, wear, damage, inadequate maintenance, overloading, or accidents.

6.7 *Selection of Personal Protective Equipment*—To determine the protection factor required for personal protective equipment in order for a person to work in a contaminated or potentially contaminated area for a specific period of time.

6.8 *Selection of Bioassay or Biomonitoring Procedures, or Both*—To determine the applicability of bioassay methods that estimate an individual's total dose or body burden of a material and biomonitoring methods that estimate an individual's rate of exposure or rate of uptake of a material.

6.9 *Compliance with Regulations and Standards*—To obtain the measurements required to satisfy legal requirements, or to determine if exposures in the workplace are below legal limits.

6.10 *Source Identification*—To single out the contribution of each of many potential sources of contamination, based on each contaminant's unique characteristics and other factors, such as emission fluctuations, wind direction and variability, dispersion conditions, and the presence or absence of distinct trace materials.

6.11 *Process Control*—To ensure that the process being monitored is proceeding according to design, that valuable materials are not being lost through leaks or side reactions, and that only those effluents expected, in the quantities expected, are being produced. This type of sampling can be used to detect and halt process changes before hazardous air concentrations are produced.

6.12 *Education and Taining*—To educate workers in the importance of sound control practices (for example, engineering controls, personal protective equipment, good housekeeping).

6.13 *Investigation of Complaints*—To resolve concerns expressed by workers, management, or other stakeholders.

7. Air Sampling Plans—General Considerations

7.1 Sampling plans should be fit for the intended purpose or purposes. In general, this means that the outcome of the sampling campaign will be a set of data that meets data quality objectives and can be evaluated to provide the intended information. The intended purpose or purposes should be explicitly stated before evaluating sampling options or selecting a sampling strategy. Sampling should, to the extent practicable, be representative of the exposure being assessed.

7.2 Principles of good practice, as well as applicable regulatory or legal requirements, should be considered and addressed during development of the sampling plan.

7.3 Limitations of the sampling plan should be considered and addressed. These include, but may not be limited to, the following:

7.3.1 Ability to collect samples at desired sampling locations;

7.3.2 Resource limitations such as time, cost, equipment, or trained personnel;

7.3.3 Ability of the analytical laboratory to detect and report the analyte or analytes of interest in the given sample matrix, with the required data quality objectives at the anticipated concentration range; and

7.3.4 Ability to evaluate the data, especially from a statistical perspective.

7.4 Due to one or more of the limitations described in 7.3, it may be necessary to develop a single sampling plan intended to accomplish multiple purposes (see 6.2). When this is the case, conflicts may emerge with one or more of the criteria given in Sections 9 – 11, and compromises will typically be required to optimize the overall sampling strategy. When this occurs, the resulting strategy may not be optimal for any one purpose.

7.5 Whether to collect a single sample, or a set of samples, is a key decision. Collection of a set of samples, rather than a single sample, is normally recommended for proper data evaluation. A set of samples, rather than a single sample, is normally required in the following instances:

7.5.1 When a comparison of “hot spots” to background locations is needed;

7.5.2 When required to meet regulatory requirements;

7.5.3 When a statistical evaluation of the data is needed.

7.6 The following are examples of when a single sample may be appropriate:

7.6.1 When physical limitations, such as collecting a sample on a small item or accessibility limitations, prevent the collection of multiple samples;

7.6.2 When multiple operations are being performed simultaneously; in this instance, it may not be possible to collect more than one sample per operation.

7.7 In cases where sampling is performed in response to an emergency or other urgent situation, the sampling plan typically will be based primarily on professional judgment, since planning time is at a minimum.

7.8 The sampling plan should include appropriate quality assurance measures that will provide documentation, throughout the sampling event and subsequent collection and evaluation of data from the samples, that appropriate quality standards have been met.

7.9 Documentation of how the sampling plan was developed is of great benefit in the event that issues arise in collecting or analyzing the samples, or in evaluating the data. Considerations include, for example, whether the sampling plan was statistically based.

8. Factors Affecting Air Sampling

8.1 Some of the factors affecting contaminant air concentrations include the velocity and direction of air movement, contaminant sinks, movement of personnel and equipment, source strength, and distance from the source. Small differences in location can have major influences.

8.1.1 The volume of air movement affects dilution of the contaminant(s). The more air that passes the source of contaminant per unit of time, the lower the contaminant concentration per unit volume is likely to be.

8.1.2 The direction of air movement determines areas of heaviest exposure downstream, and may prevent any exposure upstream. Variation indirection of air movement determines the total area exposed. Where there is slow air movement, eddy currents, or air recirculation, there may be an increase in air contaminant concentration with time (or pockets of higher contaminant concentrations).

8.1.3 Contaminants may be lost in a variety of sinks. Aerosol particles are subject to gravitational settling; vapor contaminants can condense on surfaces or aerosol particles; gases can be adsorbed on various surface and particles; and all can react with each other, surfaces, or normal air components.

8.1.4 Movement of personnel and equipment can change local air flow patterns significantly. Movement tends to increase the number and size of eddy currents present, can re-suspend settled aerosols, and can deflect contaminants away from local exhaust ventilation, such as hoods.

8.1.5 The rate and velocity of contaminant evolution also affects local air movement. Large or high velocity emissions can overwhelm local airflow, while small or low velocity emissions have a smaller effect. High concentration emissions, emissions with compositions that differ significantly from surrounding air, or emissions whose temperatures vary significantly from surrounding air, or combinations of these factors, , may resist mixing with the air for considerable times and distances downwind.

8.1.6 Distance from the emission source is an important factor. Contaminants usually become more dilute with distance from the source. Samples taken outdoors usually show more variation with distance from the source compared to those taken indoors, due to the greater air volume to consider, greater variations in air temperature, air pressure, wind speed, wind direction, and precipitation washout. Outdoor samples can also be distributed and diluted over a much greater range of vertical and horizontal distance. Even indoor contaminant concentrations may vary more than two orders of magnitude between floors and ceilings, or between two locations more than a meter

apart in any direction (**1**, **2**).[4] Samples taken from within the open face of local exhaust ventilation, with the sample inlet facing into the moving air, will almost always indicate higher concentrations than the same type of sample taken at or beyond the edge of the opening (**3**).

8.2 It is essential that air samples be taken as close as possible to the location of interest, as determined by the purpose of sampling.

8.2.1 Samples taken for the purpose of selection of engineering controls, evaluation of engineering controls, source identification, or process control should usually be taken downwind of the source, and as close to it as possible.

8.2.2 Samples taken for the purpose of risk evaluation, exposure estimation, selection of personal protective equipment, selection of bioassay or biomonitoring procedures, and investigation of complaints should be taken within the breathing zone of the person affected.

8.2.3 Where a worker's activities cause the emission of a contaminant, breathing zone samples will usually indicate concentrations up to one order of magnitude higher than nearby fixed location samples (**2**, **4**).

8.2.4 If the worker's activities do not cause emission, then breathing zone samples will usually indicate concentrations the same as, or lower than, nearby fixed location samplers (**1**). The worker's exposure will usually be lower than the concentration indicated by fixed location samplers, if the worker is in and out of the contaminated area and does not affect emissions.

8.2.5 When personal breathing zone samples are appropriate but do not provide adequate sensitivity, fixed or portable samplers with higher sensitivities must be used and should be placed at about breathing height above the ground or floor.

8.3 Alarm samplers are a special case. They may produce false (as well as true) alarms.

8.3.1 Use of a large number of alarm samplers should be avoided. When used, they must be placed where there is a high probability they will warn personnel of a contaminant or control equipment failure that results in hazardous contaminant air concentrations.

8.3.2 A good practice is to place indoor alarm samplers in or very near exhaust ventilation. They may not sample the highest concentrations at this location, but they are more likely to be exposed to some increase in concentration if a release occurs anywhere in the room.

8.3.3 Outdoor alarm samplers should be placed far enough downwind of potential sources to allow mixing eddies to diffuse the plume enough to detect the contaminant(s) at the sampler.

8.4 Samples taken for compliance purposes should use the rules of good practice to the maximum extent possible, while complying with all specific regulatory requirements. The user may also sample in additional locations, with additional types of samplers, or with additional analytical methods, as necessary.

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

9. What to Sample

9.1 For most sampling purposes, the contaminant(s) of concern should be sampled using collection apparatus and media that will not alter the composition(s) or concentration(s) of the contaminant(s).

9.2 Appropriate analytical methods that are fit for purpose will be used to determine the results that can be obtained.

9.3 In some cases, such as source identification, selection of engineering controls, and evaluation of engineering controls, a marker material other than the contaminant of interest may be sampled with greater ease or sensitivity, or both, as long as the marker material concentration is proportional to the contaminant source strength.

10. How to Sample

10.1 Sampling procedures are dependent upon the type of sampling equipment available, analytical methods employed, and the purpose(s) of sampling. Other factors, such as staff training and available resources, may also be important.

10.2 Sampling instruments can influence sampling strategy, due to their size, space requirements, and mass. For example:

10.2.1 *Vertical Elutriator*—used in cotton dust sampling is too large to be placed on the worker.

10.2.2 *Dosimeter Badge*—can be placed on the individual, over the entire shift, with little or no complaint from nor hinderance to the worker.

10.2.3 *Detector Tubes*—designed for taking very short term samples.

10.2.4 *Personal Sampling Pumps*—designed for either long-term or short-term sampling, or both.

NOTE 1—Many sampling instruments are capable of collecting more than one contaminant simultaneously.

10.3 Selection of appropriate air sampling media is essential. Considerations for selection of sampling media include the following:

10.3.1 Suitability for the application;

10.3.2 Compatibility with the analyte or analytes of interest;

10.3.3 Suitability for the analytical method which will be used.

10.4 Analytical methods affect sampling strategy by placing limits on minimum and maximum collection durations for each sample. Also, multiple contaminants may have to be sampled separately, on different collection media. Even for materials sampled in the same medium, separate samples may be necessary, due to different methods of sample preparation and analysis in the analytical laboratory.

10.5 The purpose of sampling will profoundly affect how sampling is carried out.

10.5.1 Selection and evaluation of engineering controls, selection of respiratory protection or bioassay/biomonitoring techniques, or both, source identification, and process control samples are not usually correlated to health standards.

10.5.2 Risk evaluation, exposure estimation, exposure documentation, and compliance samples are usually compared

to health standards, such as the applicable occupational exposure limit (OEL), and are usually best collected with personal samplers.

10.6 For sampling of particulate matter, many OELs invoke a size-selective sampling criterion, based on conventions in ISO 7708. Where applicable, such criteria should be considered in selection of the sampling instrument.

10.7 In addition, the potential for a fraction of the sampled particulate to deposit on interior walls of some sampling devices should be taken into account; see references (**5-7**) for more information.

11. When to Sample

11.1 Air sampling shall be carried out when required by law or regulation.

11.2 Air sampling is typically done when there is a probability that any individual will be exposed to significant airborne concentrations of a hazardous material, and when there is an analytical method for determining the quantity of the hazardous material on/in a sampling medium.

11.3 The following five considerations are important in deciding when to sample.

11.3.1 *Type of Operation*—In practice, most operations generate conditions that are combinations of two or three of the following:

11.3.1.1 *Repetitive Operations,* such as production lines, where the same operation or cycle of operations is carried out day after day, with very little change.

11.3.1.2 *Non-repetitive or Irregular Operations,* such as maintenance or construction, where each operation is essentially unique.

11.3.1.3 *Enclosed Operations or Processes,* where there is little or no human contact with any hazardous material present, unless a leak or spill occurs.

11.3.2 *Start Time*—Sampling is best initiated at the time the risk of significant exposure or release begins, or as soon as feasible thereafter. In most cases, sampling should start at the beginning of a work shift, or at the beginning of the first cycle capable of producing significant exposures or emissions.

11.3.3 *Duration of Sampling*—Influenced by many things including:

11.3.3.1 *Purpose of Sampling on Duration*—If the purpose of sampling is to determine compliance with a standard, then the sampling duration shall be the same as that specified in the standard (**8**). Most OELsare based on an 8 h exposure, but some are based on 10 h. Most ceiling OELs and short term exposure limits (STELs) are based on 15 min exposures, but some are based on 5, 10 or 30 min exposures.

11.3.3.2 *Equipment Limitations*—Samples should not be so large that they overload the collector, but should, whenever possible, be large enough for the analyte or analytes of concern to be detected by an analytical method that is fit for purpose.

11.3.3.3 *Characteristics of the Operation Sampled*—Brief periods of high exposure, followed by periods of significantly lower exposure, might be sampled only during the peak exposures. Full shift samples would be adequate for repetitive operations with relatively constant exposure levels. Alarm samplers might be run continuously.

11.3.3.4 *Statistical Considerations*—When more than one sample must be taken, the duration of each sampling period should be held constant, because the variability of a sample is a function of its duration (**9**). That is, longer sampling durations result in smaller confidence limits for the mean, while shorter durations result in larger confidence limits, on the average, assuming sampling durations do not vary in step with cycles in the operation. If different sampling durations must be used for multiple samples of the same process or operation, then each sample must be weighted in proportion to its duration when calculating the mean.

11.3.3.5 *Practical Considerations*—It is often not practical to run personal samplers beyond one shift, or to run static samplers beyond 24 h. In some cases, it may satisfy the purpose of sampling to show that the concentration sampled did not exceed a percentage (for example 10 %) of any applicable OEL.

11.3.4 *Number of Samples*—Factors that should be considered include:

11.3.4.1 *Purpose of Sampling*—For compliance with a regulation or standard, the minimum number of samples required may be specified in the standard.

11.3.4.2 *Equipment Limitations*—The duration of the operation sampled, and the minimum and maximum feasible durations for a single sample, determined by limitations of the sampling and analytical methods, set outside limits on the number of samples that can be taken. For example, an 8-h workshift could be sampled with one 8-h sample, two 4-h samples, four 2-h samples, or eight 1-h samples, depending on the characteristics of the equipment available.

11.3.4.3 *Characteristics of the Operation Sampled*—For relatively constant exposures, fewer samples are needed. Cyclic or irregular exposures should initially be sampled during each identifiable phase of the operation, in order to gain understanding of the pattern of exposure.

11.3.4.4 *Economics*—Consider the minimum number of samples required to accomplish the purpose for sampling. It is preferable to add one or more samplers than to have too few samplers for the task(s) at hand.

11.3.4.5 *Staffing Limitations*—The more samples that are taken, the more staff-hours will be required. Care must be taken to ensure that the available personnel can carry out the work required.

11.3.4.6 *Statistical Considerations* (**9, 10**)—One sample for any operation is rarely adequate, because the uncertainty of a single sample value is large. For long duration operations, 2 to 4 samples may be sufficient. For short duration samples, from a single grab sample up 4 to 7 samples of the same operation or phase, are the minimum required. Other considerations being equal, shorter-duration samples are often better than fewer long-duration samples covering the same total sampling period, because they can provide more task-specific information. For example, the full shift exposure can be estimated from a number of back-to-back short duration samples taken over the entire shift, and the fluctuations in exposure levels during the day can be seen. A single full-shift sample would also

estimate the full-shift exposure, but would not provide information on exposure fluctuations. For repetitive operations, conducted over a prolonged period of time, the question is not how many total samples to take, but how many samples to take each day, week, month, or year. In general, initial sampling should be done as though the work being carried out was not repetitive. After initial sampling, the number of samples taken should be based on the observed variations and on the purpose of sampling. Typically, a minimum of 10 samples is required to observe a periodicity or trend. Hence, if daily variations are important, at least 10 samples per day may be needed. If seasonal variations are important, a minimum of 10 samples per calendar quarter may be required.

11.3.5 *Termination of Sampling*—Sampling should be terminated at the end of a shift, or when there is no longer a risk of significant exposures or emissions from the contaminant(s) being evaluated. Most operations should be sampled at least annually. The frequency should be increased if the degree of hazard, lack of availability or reliability of alarm samplers, or experience with the operation indicates that the contaminant levels have changed or are likely to change.

12. Long Term Sampling (Measurement of Average Concentrations)

12.1 Long term sampling refers to the measurement of an average concentration of air contaminant over a specified duration. OELs are usually specified as time weighted average (TWA) concentrations over 8 h. The weighted mean is a basic statistical calculation (**9**, **10**).

12.1.1 In statistics, sampling refers to measurement of a small portion of a population, in order to estimate a population parameter. Generally speaking, sampling is a process consisting of the withdrawal or isolation of a fractional part of the whole (Terminology D1356).

12.1.2 In air monitoring, sampling refers to measurements of mean contaminant concentration over a stated duration. The TWA calculation averages these mean concentrations over some stated interval. The general formula for a TWA is:

$$C = \frac{\left(C_1T_1 + C_2T_2 + \ldots + C_nT_n\right)}{\left(T_1 + T_2 + \ldots + T_n\right)} \quad (1)$$

where:

C = TWA in mass per volume (typically mg/m^3), and
C_n = average air concentration for the duration T_n.

12.2 Two considerations must be borne in mind during any sampling strategy discussion: (*1*) a TWA standard is designed to protect the worker only from exposures incurred during employment, for example, while on the company premises or adjacent areas, and (*2*) the concentration of contaminant, both in the worker's breathing zone and in the general workplace air, continually varies throughout the day (due to drafts, ventilation changes, employee movements, and changes in contaminant generation). Consequently, samples taken during the day will show variation. There is also some variation due to inaccuracies in the sampling equipment and analytical method, which will not be considered here, but which must be considered when evaluating any results (**9**, **10**).

12.3 Exposure, for the purpose of developing sampling strategy, is defined as the presence of *some* airborne concentration of contaminant in the work environment.

12.3.1 Workers may be exposed to a contaminant only when they are actively working, based upon the assumption that the outer boundaries of contaminant dispersion surround an arbitrary zone in which contaminant is generated and dispersed and the worker is stationed or roams. This assumption has merit in certain situations (such as when a worst case exposure estimate is desired) but can result in errors when the purpose of sampling is to obtain an average work-shift concentration. For example, there may be some continual small contaminant concentration in the entire facility so that a worker is actually exposed from the moment of arrival on the facility premises until the worker's departure. When a contaminant generating process or procedure is shut down, exposure continues, since contaminant air concentrations will not immediately fall to zero or near zero.

12.3.2 Exposure may also occur when workers walk through areas that are not a part of their normal work stations, or when air contaminants are transported throughout the plant to areas which might not be considered part of the employee's work station (for example, change rooms, cafeterias and lavatories).

12.3.3 The least error in assessing the average work-shift concentration will generally be realized by assuming contaminant is present, in small concentrations, throughout the facility. It is important to recognize that the TWA concentration over the exposure duration is the result of continually changing momentary concentrations, including any periods where concentrations fall to zero or non-detectable levels.

12.3.4 There are two schools of thought on how samples should be taken to arrive at an average exposure concentration. Neither approach is generally preferred, but either may be more advantageous in certain situations.

12.3.4.1 *Tracking Method*—The person taking the sample must decide, from observing the worker, when to take each sample. Samples are typically taken over the entire exposure duration. This method assumes that each task, or area where a worker performs a task, exposes that worker to a unique average concentration of air contaminant. For instance, an employee may perform a number of distinct tasks, possibly in different areas of the worksite. During each task, a sample is taken to measure the average air concentration for that task. The TWA concentration of all such samples is used to estimate the work-shift exposure for comparison with an appropriate standard. *An advantage* of separately sampling the worker during each task is the ability to pinpoint those tasks which have a potential to create the greatest exposures. Once this is done, steps can be taken to reduce high exposures. *A disadvantage* is that decisions as to what tasks to sample separately are arbitrary. In addition, for most sample collection methods, there are minimum and maximum collection durations, so there is a chance that too little or too much material will be collected for analysis. Finally, having to change sampling heads or collection devices at frequent intervals may interfere with the worker's job performance, and can result in lost sampling time between samples.

12.3.4.2 *Consecutive Sample Method*—Sampling heads or collection devices are changed irrespective of the employee's tasks. For example, if a charcoal tube method specifies 60 to 240 min per tube, from 2 to 8 samples could be taken to cover an 8-h shift. Sample durations for each tube could be identical or variable, depending on the monitoring scheme. In principle the TWA result would be the same in each case. Theoretically, the consecutive sampling method is as accurate as the Tracking Method, and eliminates some of the associated problems of long-term sampling, such as sample overloading. If peak concentrations must be determined, long-term sampling can be supplemented by short-term sampling conducted during peak exposure tasks.

12.3.5 Traditionally, most discussions on approaches to sampling a work shift have considered ideal situations, where a worker works for exactly 8 h for comparison to an 8-h standard. In reality, the work shift duration may be longer or shorter than the exposure. These discussions fail to show how un-sampled time periods should be taken into account to arrive at accurate exposure estimates. It is unrealistic to assume that a worker's entire exposure can always be sampled. It is usually impossible to begin sampling the moment of a worker's arrival at the worksite. More than one person may be sampled on the same day, requiring setup and calibration for the equipment used on or around each worker. Often, some of these workers have begun their jobs, and are already being exposed to contaminants. It may be difficult to continue sampling during lunch and rest breaks, or trips to the lavatory. Equipment must usually be removed prior to the end of the shift. It is necessary to account for each of these situations.

12.4 A simplified method of visualizing air contaminant exposure is shown in Fig. 1.

12.4.1 The dotted lines (Fig. 1) illustrate actual air contaminant concentrations in a worker's breathing zone as a function of time over the duration of a work shift.

12.4.2 The horizontal lines above (Fig. 1) demonstrate possible sampling durations, timing and sampling excursions, where each number on the right side of the plot refers to a particular sampling strategy. Theoretically, strategies 1, 2, and 3 would give the most accurate measurements of total exposure over the work shift, since the worker's entire exposure is sampled. However, it may be difficult to perform sampling using these strategies. Therefore, a strategy such as 4 might be used, where nearly the entire exposure is sampled, with the exception of the beginning and end of the exposure. Likewise, in strategy 5, the only other duration not sampled is during lunch. However, any unsampled duration must be accounted for in the final TWA. In strategies 6 and 7, breaks are not sampled. Strategies 8, 9, and 10 show two samples taken at different times of the day, but significant portions of the exposure have not been sampled. These strategies may be appropriate for risk evaluation purposes, where a rough estimate of exposure is desired. Strategy 11, used for very short term sampling, may also be an appropriate means of risk evaluation. In such cases, where the average exposure concentration is desired, a significant number of short term samples (15 min or less) may be taken at random times during the exposure in the worker's breathing zone. The average of these samples will estimate the mean concentration over the exposure duration. Short term sampling strategies are mainly reserved for direct reading devices, detector tubes, and bag samples. Some fixed sampling devices for continuously recording air concentrations at different points in a room may operate using this strategy, or by sampling at frequent fixed intervals.

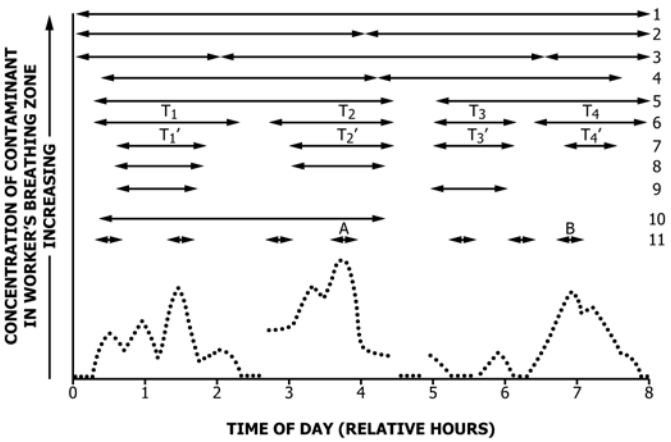

FIG. 1 Air Contaminant Exposure and Sampling Strategies

12.5 Regulatory compliance sampling strategies may be specified. For instance, a regulation may specify that full shift sampling must be conducted for at least 7 h, with any duration not sampled being considered as zero exposure, unless the compliance officer can document otherwise. The compliance officer may be required to document any measurements that purport to show concentrations exceeding the OEL.

12.6 Most long term sampling results are expressed as TWA concentrations. When a single full workshift sample cannot be taken, there are two approaches that may be used to estimate the TWA concentration from a number of shorter duration samples.

12.6.1 In the *Theoretical Duration Approach*, the TWA formula components C_n *and* T_n are estimated as follows:

$$C_n = M/AV \tag{2}$$

$$T_n = \Sigma A_n$$

where:

M = mass of sample (from analysis),
A = actual sampling duration,
V = sampling flowrate,
T_n = theoretical sampling duration summed over An sampling excursions, and
C_n = time-weighted average.

Any periods of expected zero exposure, such as break periods, lunch periods, or any long duration not sampled, where one can assume no exposure occurred, should be included in the TWA calculation. The sum of all T values should total 8 h, when the exposure duration is ≤8 h. For example, suppose the exposure shown in Fig. 1 should ideally be sampled using strategy 6, but the best that can actually be done is represented by strategy 7, then:

Strategy 7	Strategy 6	C
1.2 h	2.0 h	C_1
1.3 h	1.7 h	C_2
1.1 h	1.1 h	C_3
0.7 h	1.6 h	C_4
Sums: 4.3 h	6.4 h	

Including the theoretical zero exposure duration of (8 – 6.4) = 1.6 hours, and applying Eq 1, the TWA estimate C_D using strategy 6 is:

$$C_D = \frac{\left[(C_1 \times 2) + (C_2 \times 1.7) + (C_3 \times 1.1) + (C_4 \times 1.6) + (0 \times 1.6)\right]}{8} \quad (3)$$

There are two advantages to this approach: (*1*) a good estimate of the TWA can be obtained, even though the entire exposure duration cannot be sampled, and (*2*) high exposure periods or operations can be easily detected. The disadvantages are that the average concentration over any exposure duration must be assumed to be constant over the theoretical duration, and the theoretical duration is an estimate.

12.6.2 In the *Calculated Duration Approach*, the TWA formula components are estimated in two steps. (*1*) the average concentration C_A for the sum of the actual sample durations is calculated, using strategy 7 in the example above, as follows:

$$C_A = \frac{\left(C_1 A_1 + C_2 A_2 + \ldots + C_n A_n\right)}{\left(A_1 + A_2 + \ldots + A_n\right)} \quad (4)$$

For strategy 7 in the example above, Eq 4 becomes:

$$C_A = \frac{\left[(C_1 \times 1.2) + (C_2 \times 1.3) + (C_3 \times 1.1) + (C_4 \times 0.7)\right]}{4.3}$$

(*2*) C_A is assumed to be the average concentration for all of the non-zero exposure periods, and the TWA is estimated, using theoretical sample durations, as follows:

$$C = \left[(C_A \times 6.4) + (0 \times 1.6)\right]/8 \quad (5)$$

This approach provides a more accurate estimate of the true TWA as the sum of the sample durations approaches the actual exposure duration. An advantage of this approach is that C_A is based solely upon measured values, and the TWA estimate obtained is easily adjusted for changes in exposure period. Disadvantages are that it takes two steps, and still requires an estimate for the zero and non-zero exposure periods.

12.7 Several methods have been utilized to adjust disagreements in sample results and exposure standards *when the exposure duration is greater than 8 h.* These methods are subject to large errors in some cases.

12.7.1 *Equivalency Method*—Sampling is conducted over the exposure duration, and the concentration obtained is weighted by the exposure duration. For example, the TWA for a 10-h shift would be calculated by multiplying the TWA of the samples by the exposure duration, divided by the standard duration, or 10/8. This produces a TWA which would provide the same total exposure dose over 8 h. This method is simple, and produces a result directly comparable to an 8-h TWA standard. It is not, however, a real average over the exposure duration. The rationale for the method results from the tendency to divide all TWA calculations by 8 h, since most literature sources give examples based on 8-h samples.

12.7.2 *Adjusted Standard Method*—The TWA standard is adjusted downward, by dividing the dose in concentration-hours for the 8-h standard by the actual exposure duration. For example, a TWA standard of 100 ppm over 8 h gives a dose of 800 ppm-h. For an exposure duration of 10 h, this standard would be adjusted by dividing by ten, as follows:

$$\frac{(800\ \text{ppm} - \text{h})}{10\ \text{h}} = 80\ \text{ppm}$$

This method cannot be indiscriminately used, however. Toxicological properties of the material, particularly biological equilibrium and excretion, must be known in order to adequately judge whether the Adjusted Standard may be used. Certain 8-h standards should never be adjusted in this way, including those that were established on the basis of measurement feasibility or irritation, or any ceiling value standard. Some regulatory organizations, such as the U.S. Occupational Safety and Health Administration, have adopted the Adjusted Standard Method, where it is applicable, for compliance purposes, and many work sites have found it useful. Additional extended work-shift exposure research is needed to establish excretion and equilibrium rates for many contaminants. A consensus is needed on proper methods of approaching the extended work shift problem, particularly where the practice continues for long periods.

12.7.3 *Modified Occupational Limit (MOL)*— makes adjustments to a TWA Standard for two factors (**11**): (*1*) the increase in dose that occurs in an extended workshift or work week, and (*2*) the absence of dose during recovery time between exposures. To calculate the MOL, a Reduction Factor (RF) is determined as follows:

$$\text{RF} = \frac{8}{h} \times \frac{(24 - h)}{16} \quad (6)$$

where:

h = hours worked per day.

In the special case of a seven day work week:

$$\text{RF} = \frac{40}{w} \times \frac{(168 - w)}{128} \quad (7)$$

where:

w = hours worked per week.

The MOL is then calculated by:

$$\text{MOL} = \text{RF} \times \text{OEL} \quad (8)$$

where:

OEL = an 8-h TWA limit value, or a ceiling limit value (except where solely based on irritation).

Related models describing the adjustment of OELs for unusual work schedules have also been proposed and can be considered in addition to the strategy described here (**12-15**).

12.8 For some materials which have TWA standards, short term exposure limit (STEL) or ceiling concentration limits have been established in many countries. These limits have been set because the materials can cause acute toxicologic responses when present in sufficient concentrations for short periods of time.

12.8.1 The generally accepted sampling duration for STELs and ceiling concentrations is 15 min, although shorter and longer durations are specified for some materials. Each analytical method requires a minimum amount of material to enable detection, and all measurements must be made over a finite duration. The sample value determined is an average concentration over this finite duration. This is not of concern in the case of fast response, direct-reading instruments. With faster response instrumentation, the ability to detect peak concentrations is improved.

12.8.2 Since short-term sampling methods are used to define peak levels of contaminant within the worker's breathing zone, the samples should always be taken during those tasks which generate the greatest worker exposure. The duration of each sample should be that specified by the standard, wherever possible.

12.8.3 More than a single short-term sample is desirable, in order to verify exposures and arrive at comparable values to substantiate those exposures. Strategy 11 presents an example of a short-term sampling strategy (12.4.2).

12.8.4 If there is little variation in air contaminant concentration over an exposure duration, it is difficult to judge when there may be a peak exposure. In this situation, a random sampling plan can be used by dividing the exposure duration into consecutive 15 min intervals and sampling a significant number of these intervals chosen at random.

12.8.5 Other methods have been developed, as mathematical models, based upon plotting the logarithm of sample duration versus the logarithm of the maximum expected concentration for samples taken over various durations, such as minutes to weeks. Such predictive tools can be used to estimate the potential maximum concentration, even though no sampling has been conducted, for very short durations.

12.8.6 Techniques in short-term sampling must be flexible. Personal sampling equipment can be affixed to the worker. However, it may be desirable to conduct long- and short-term sampling on the same individual on the same day. Attachment of the second sampling pump during a suspected peak exposure period may prove cumbersome, but it is still the best option.

12.9 Ceiling value standards have been assigned to those materials which have a significant toxic effect, in most workers, whenever they reach specific concentrations.

12.9.1 A ceiling value standard is a concentration which should not be exceeded. Any variation in air concentration should occur below this value.

12.9.2 Since ceiling value standards are defined as maximum acceptable concentrations, the same as STEL's, the theory and practice of sampling for them is essentially the same as for short term sampling. For example, it would be appropriate to compare samples A and B in Strategy 11 to a ceiling standard (12.4.2).

13. Sample Quality

13.1 Part of the strategy of sampling is to plan, in advance, how the quality of the sample will be insured and maintained after collection.

13.2 *Chain of Accountability*—The only way a person responsible for sampling can know what has been sampled is by maintaining a chain of accountability or chain of custody. The person performing the sampling must:

13.2.1 Clean and calibrate the sampling equipment used, or observe its cleaning and calibration to assure proper operation and collection.

13.2.2 Observe the equipment during the sampling period to assure that no unexpected incidents or deliberate sabotage occurs.

13.2.3 Take measures to properly preserve the samples during the period between sampling and analysis including during transport from the work site to the laboratory. This may include refrigeration, packing in shock resistant materials, or addition of a fixative or preservative to the sample.

13.2.4 Maintain security and custody of the sample at all times, in accordance with Guide D4840. This includes documentation of the chain of custody, including custody sign-off sheets, or provision a secure locked receptacle for a sample awaiting analysis while it is not in the documented custody of a responsible person.

13.3 *Cross Contamination*—Multiple samples should be carefully handled to prevent cross contamination. That is, the material collected in one sample should not be allowed to spill or contaminate another. This is of particularly great concern during transfer or shipment of samples where the opportunities for cross contamination are greatest.

14. Records

14.1 *Log Forms and Notebooks*—Field data related to sample collection shall be documented in a sample log or field notebook. If sample logs are used, then they shall be bound with pre-numbered pages. All entries on sample data forms and field notebook pages shall be made using ink with the signature and date of entry (at least per page). Any entry errors shall be corrected by using only a single line through the incorrect entry (no scratch outs or use of correction fluids), accompanied by the initials of the person making the correction, and the date of the correction. The correct entry shall be annotated next to the error.

14.2 *Electronic Laboratory Notebooks*—If electronic laboratory notebooks are used in lieu of a field notebook or sample log, procedures shall be implemented to assure the integrity of the data recorded, including prevention of falsification or other unauthorized changes, and regular backup of data.

14.3 *Sampling Information*—The following information shall be recorded by the person(s) carrying out the sampling, and shall be passed to the person(s) responsible for completing the test report:

14.3.1 A statement to indicate the confidentiality of the information supplied, if appropriate.

14.3.2 Project and client name(s), and client postal address.

14.3.3 General sampling site description and address (if applicable).

14.3.4 Information as to the specific type, brand, or both, of sampling instrument used, including manufacturer and lot number.

14.3.5 Information as to the specific type, brand, or both, of sampling media used, including manufacturer and lot number.

14.3.6 Information on quality control (QC) samples, if any, such as which samples are associated with what group of field blanks.

14.3.7 For each sample collected, including field blanks: an individual and unique sample identifier and date of collection. The individual and unique sample identifier, at a minimum, shall be recorded on the sample container in addition to the field documentation.

14.3.8 For field samples (not including field blanks), record in field documentation (field notebook or sample log form) the duration in time that the sample was collected.

14.3.9 For each sample collected: name of person collecting the sample, and specific sampling location information.

14.4 *Information Pertinent to Sample Preparation and Analysis*—At a minimum, the following information shall be supplied to the laboratory analyzing the sample(s):

14.4.1 Unique identification for each sample.

14.4.2 Specific type, brand, or both, of sampling medium used.

14.4.3 A listing of the analyte(s) to be determined.

14.4.4 Analytical results for the contaminant(s) analyzed (for instance, in mass of analyte(s) per sample, number of contaminant fibers or spores per sample, etc.).

14.4.5 Contact information for the person to whom the analysis results shall be returned.

14.4.6 Any special requirements, such as sample preparation method requested.

14.5 *Laboratory Records*—Laboratory records, including electronic records, shall be prepared, controlled, and protected in accordance with the requirements of ISO/IEC 17025.

15. Summary

15.1 It is important that air sampling be conducted for a well-defined, stated purpose. Once the purpose has been stated, an effective sampling strategy can be developed. Supervisors, investigators, compliance officers, and other personnel with experience in taking samples, have developed different sampling approaches to suit different purposes for sampling. An understanding of the logic behind these sampling approaches is necessary to evaluate the results obtained.

15.2 There remains a need to develop a consensus on an extended shift sampling method. The Adjusted Standard Method needs scientific verification or revision before it can be applied reliably and routinely. Manufacturers of sampling equipment need to recognize the technical limitations equipment imposes on the sampling operation, in order to develop equipment that can more adequately accommodate user requirements.

16. Keywords

16.1 air sampling; air sampling strategies; atmosphere; occupational health; occupational safety; worker protection; workplace protection

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