TECHNICAL REPORT

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Cleanrooms and associated controlled environments —

Part 21: **Airborne particle sampling techniques**

Salles propres et environnements maîtrisés apparentés —

Partie 21: Techniques de prélèvement des particules en suspension dans l'air

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by ISO/TC 209, *Cleanrooms and associated controlled environments*.

A list of all parts in the ISO 14644 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides clarification on the application of sound airborne particle sampling techniques in support of ISO 14644-1:2015 for classification of cleanrooms and clean zones, and ISO 14644-2:2015 for airborne particle monitoring, to provide evidence of cleanroom performance related to air cleanliness by particle concentration. It provides information on how to gather appropriate, accurate and repeatable data, and how to interpret this information for the purpose of improving process protection. This also includes information on the choice of measurement methods and apparatus configuration, calibration, repeatability/reproducibility and the uncertainty associated with measurement. In short, what can be reasonably attained with the current technology.

This document addresses potential misinterpretation of the use of ISO 14644-1:2015, C.4.1.2 in informative Annex C, which suggests the use of limited tubing length for sampling macroparticles. The phrase in question has been applied beyond the context intended in ISO 14644-1, to other applications. This document also provides extra clarity on the use of the M Descriptor in ISO 14644-1:2015, Annex C, specifically in relation to consideration of ≥5,0 µm alongside ISO Class 5 (EU-PIC/S GMP Grade A and B at rest).

It provides information on the uncertainty associated with sampling particles ≥5,0 µm and macro-particles, and measures that can be taken to reduce that uncertainty.

It addresses the importance of understanding that:

— for classification, the quality of the sample is the most important factor;

— for monitoring, the quality of the data is the most important factor;

— direct sampling without tubing is preferred. However, sample tubing is sometimes necessary to get a representative sample at a significant or critical location;

— to reduce sampling loss in tubing, this tubing is as short and straight as possible;

— a sampling system is evaluated to assess the impact of any compromises in its set up.

An evaluation of existing sampling systems can deem them suitable for continued use even if the system is assessed as less than optimal.

The scientific basis for airborne particle counting, and the performance characteristics of airborne particle counters, particularly LSAPC, is amply documented in established technical publications (see Bibliography).

Cleanrooms and associated controlled environments —

Part 21: Airborne particle sampling techniques

1 Scope

This document discusses the physical limitations of probe and particle counter placement, and any tubing that connects the two, particularly in providing representative samples where particles 5 micrometres and greater are of interest.

The document further identifies the key factors of sampling performance when classifying and monitoring, and good practice to determine and maintain an acceptable compromise between attainable accuracy in counting and feasibility of counting in real-life situations.

This document includes a decision tree, used to identify key considerations when sampling airborne particles, and whether the system requires further assessment. There are also examples provided to illustrate typical application challenges and show how the decision tree can be used.

It is assumed that this document is read in conjunction with ISO 14644-1 and ISO 14644-2. This document is not a manual, but an explanatory document. It does not describe measurement methods, which is handled in ISO 14644-1 and ISO 14644-2, but provides information to help make effective choices of sampling configuration, when evaluating a new or existing system.

2 Normative documents

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org

3.1
classification
method of assessing level of cleanliness against a specification for a cleanroom or clean zone

Note 1 to entry: Levels should be expressed in terms of an ISO Class, which represents maximum allowable concentrations of particles in a unit volume of air.

[SOURCE: ISO 14644-1:2015, 3.1.4]

3.2
monitoring
observations made by measurement in accordance with a defined method and plan to provide evidence of the performance of an installation

Note 1 to entry: Monitoring may be continuous, sequential or periodic; and if periodic, the frequency shall be specified.

Note 2 to entry: This information may be used to detect trends in operational state and to provide process support.

[SOURCE: ISO 14644-2:2015, 3.2]

3.3
particle size
diameter of a sphere that produces a response, by a given particle-sizing instrument, that is equivalent to the response produced by the particle being measured

Note 1 to entry: For discrete-particle light-scattering instruments, the equivalent optical diameter is used.

[SOURCE: ISO 14644-1:2015, 3.2.2]

3.4
macroparticle
particle with an equivalent diameter greater than 5 µm

[SOURCE: ISO 14644-1:2015, 3.2.5]

3.5
M descriptor
designation for measured or specified concentration of macroparticles per cubic metre of air, expressed in terms of the equivalent diameter that is characteristic of the measurement method used

Note 1 to entry: The M descriptor can be regarded as an upper limit for the averages at sampling locations. M descriptors cannot be used to define air cleanliness classes by particle concentration, but they may be quoted independently or in conjunction with air cleanliness classes by particle concentration.

[SOURCE: ISO 14644-1:2015, 3.2.6]

4 Determination of airborne particle concentration

4.1 General

Airborne particle concentration is the primary attribute and essential parameter that determines and denotes the cleanliness level of a cleanroom or clean zone.

In classification, ISO 14644-1 states that "The use of light scattering (discrete) airborne particle counters (LSAPC) is the basis for determination of the concentration of airborne particles, equal to and greater than the specified sizes, at designated sampling locations".

ISO 14644-1 does not provide for classification of particle populations that are outside the specified lower threshold particle-size range, 0,1 µm to 5 µm. According to ISO 14644-1, an M descriptor (see ISO 14644-1, Annex C) may be used to quantify populations of macroparticles (particles larger than 5 µm).

In monitoring, an LSAPC is also used for airborne particle counting, often supported by other methods, as indicated in ISO 14644-2.

For both classification and monitoring, the choice of the counter takes account of the effective particle size range and sampling flowrate with regard to sample size.

For monitoring, the effectiveness of the sampling system is determined by the appropriate choice of sampling location and the ability of the system to capture particles and deliver them to the counting mechanism.

A key driver in quality management is continuous improvement. When we apply the dynamic cycle tool Plan-Do-Check-Act (PDCA) to cleanroom contamination control, key information is used from classification and monitoring activities to establish and demonstrate that control. Changes and improvements will lead to re-evaluation and a repeat of this cycle. Figure 1 below illustrates the importance of classification and monitoring and how these influence the process of continual improvement.

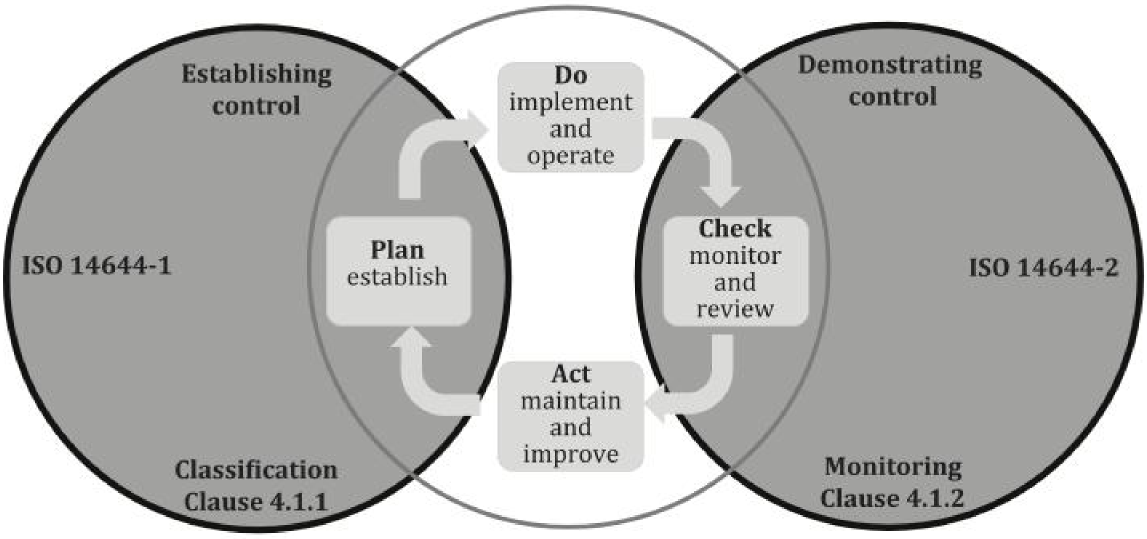


Figure 1 — Strategy for contamination control

All particle counting systems have the potential to delay or prevent a particle from reaching the counting mechanism of the LSAPC. The likelihood of this increases with the particle's size and the length and complexity of its pathway through the system. Good practice is applied to minimise particle loss and potential gain through shedding and false counts. The following sections explain the relevant aspects of the determination of airborne particle concentration that is performed in classification and monitoring. Guidance will be given in Clause 5 on the application of particle counting technologies and associated sampling methods.

4.2 Classification

In classification, the cleanliness of the cleanroom is specified for a state of occupancy and considered particle size(s). The sizes available for classification are defined in ISO 14644-1:2015, Table 1, and all sizes considered are measured simultaneously, with the same LSAPC instrument. Sampling locations and minimum sample volumes are selected using the procedure described in ISO 14644-1. Satisfactory airborne particle concentration results obtained by sampling at these locations provide confidence that the volume measured will comply with the specified class.

The reference method for classification supposes a degree of reproducibility to establish control for a specified state of occupation, both initially and when classification is reconfirmed. As such, the quality of the sample taken and precision of the values recorded is paramount.

The measurement of airborne nanoscale particles, <0,1 µm, uses another type of instrument, not included in this document. Values obtained at the nanoscale are not appropriate for classification. This application is considered in ISO 14644-12.

ISO 14644-1:2015, Table 1 provides the range of particle sizes and particle concentrations deemed statistically appropriate for classification.

NOTE ISO 14644-1, Table E.1 shows application of the same threshold particle sizes for decimal classes, and ISO 14644-1, Formula E.1 enables calculation of the maximum particle concentration for intermediate particle sizes within the normative range.

Note f) to ISO 14644-1:2015, Table 1, indicates a special case for recording larger particles when classifying at ISO 5. It provides an example where particles ≥5 µm are sampled with a specified limit of 29 particles/m^3 as a complement to classification at ISO 5 measured on sizes that are included in ISO 14644-1:2015, Table 1 as appropriate for that class. This complement is expressed via the M

Descriptor, in this case as “ISO M (29; ≥5 μm); LSAPC” for ISO 5 and refers on to ISO 14644-1:2015, C.7. For some applications, it can be necessary to also sample other sizes outside those for which ISO 14644-1:2015, Table 1 defines concentrations. ISO 14644-1:2015, C.7 in informative Annex C provides an example of adaptation of the M descriptor to accommodate consideration of ≥ 5 μm particle size for ISO Class 5 at this particle size threshold, where ISO 14644-1:2015, Table 1 does not specify a concentration limit.

ISO 14644-1:2015, Annex C is concerned with the broader techniques of measurement of macroparticles (particle size thresholds not in ISO 14644-1:2015, Table 1), by a variety of appropriate methods and instrumentation, including the LSAPC, and expression of the result. This subject is not considered within the scope of this document. When measuring and recording particles > 5,0 μm (macroparticles) alongside those measured within the ISO 14644-1:2015, Table 1 range, their value is expressed as an M descriptor, in support of classification.

4.3 Monitoring

Monitoring is explained and illustrated in ISO 14644-2:2015. The activity involves recording and analysing data on a variety of parameters to support demonstration of control.

The trending of data obtained from monitoring with LSAPC is used to understand the variation in the number of particles over time and its relationship with the specified and maintained cleanliness of the cleanroom or clean zone. Data obtained and analysed is used to evaluate whether air quality is maintained at a satisfactory level at locations considered significant or critical for the process, at the appropriate occasions. This data can be analysed along with other monitoring parameters to provide a holistic approach to demonstrating control.

Monitoring is applied to demonstrate that the air cleanliness at a defined location complies with the required level at a defined point in time, during operation, and often during periods at rest. Particle sizes used for monitoring can be different from those required for classification. This is clearly shown in EU & PIC/S GMP Annex 1 (2022) where monitoring is subject to limits for particle sizes (>5,0 μm) not identified as reliable for the purpose of classification at ISO5. Results are often expressed per unit of time, rather than accumulated to a unit volume. Other indirect indicators may also inform on the satisfactory operation of the installation or equipment.

In ISO 14644-2, guidance is provided on where, when and how to monitor the airborne particle concentration, and how to complement this with other indicators of cleanroom or process zone performance.

In monitoring, the reproducibility of sampling efficiency, and the ability to detect variations over time, are more important than absolute precision in the data obtained at a particular point in time.

Analysis of variations over time can help to understand the process, and provide trending data to assist the management of critical parameters in order to maintain control as required.

Monitoring performed using a mobile or fixed LSAPC can be periodic or continuous. In monitoring, minor particle loss in the sampling system is typically accepted since this will not affect the trending of the local air cleanliness unless the alert or action level is very low.

NOTE It is important that the system is verified as able to record the considered particle sizes in a satisfactory manner.

4.4 Other LSAPC applications

LSAPCs are also used for measuring high airborne particle concentration at defined sample locations during the Recovery Test (ISO 14644-3:2019, B.4), the installed filter system leakage test (ISO 14644-3:2019 B.7) the containment leak test (ISO 14644-3:2019, B.8) and the Segregation Test (ISO 14644-3:2019, B.11). This document does not examine the detail of these and other applications.

In addition, the LSAPC can be used for investigation of particle concentrations at specific locations for the purposes of characterisation, without any attempt to predict compliance of a whole surface or room to a specified class. This activity is not expressly considered in ISO 14644-1 and ISO 14644-2, except in ISO 14644-1:2015, Annex C but can be a valuable part of establishing and demonstrating control.

5 Sampling airborne particles – things to consider

5.1 General

The sampling of airborne particle concentration at a specific location, to determine air cleanliness, cannot always be performed by placing the LSAPC directly at the location, due to limitations on access, instrument size and the need to avoid disturbance of a critical volume by the counter exhaust and heat gain. Consequently, a sample will often need to be drawn from the test location to the instrument for measurement.

The approach taken ensures that:

— the sample is representative;

— a suitable volume is taken, relative to the particle size;

— collecting the sample does not affect the operation of the process;

— the particles sampled do reach the device;

— the location of the LSAPC is not influenced by other factors.

Consideration of influencing factors is discussed further in this clause.

5.2 Instrument selection

5.2.1 General

There are several types of LSAPC that can be used to determine classification, and in routine monitoring. The choice of instrument type, for classification or monitoring, is typically a balance between:

— Sample volume required for statistical significance:

  — a minimum number of particles is required to determine a classification state;

  — low concentrations of particles require large sample volumes, and/or sequential sampling.

— Total test time:

  — particle counter sample at a fixed volumetric flow rate;

  — minimum sample volumes determine the time required to sample at each location;

  — higher flowrates will reduce test duration;

— sample tubing requirements.

Manufacturers will provide recommended dimensions for tubing.

Table 1 describes different types of instrument and their typical applications.

Table 1 — Comparison of particle counter types

Function	Portable particle counter	Handheld particle counter	Remote particle sensor
Number of size channels	Typically 4-6	Typically 2-6	Typically 2-6
Smallest channel (sensitivity)	Application dependant, typically 0,1 µm, 0,3 µm or 0,5 µm	Application dependant, typically 0,2 µm, 0,3 µm or 0,5 µm	Application dependant, typically 0,1 µm, 0,2 µm, 0,3 µm or 0,5 µm
Sample flow rate	28,3 l/min (1 cfm) or greater (50 l/min, 75, l/min, 100 l/min)	Low flowrate of 2,83 l/min (0,1 cfm)	Flowrates of 28,3 l/min or 2,83 l/min
Power	Mains or battery	Mains or Battery	Mains, or power over Ethernet
Mobility	Carried by hand, placed on mobile cart, probe on tripod/stand or fixed to the top of the LSAPC	Lightweight carried in hand or placed on tripod/stand	Fixed location mounted to equipment or infrastructure
Display	Local interactive display with many operator features	Local display with fewer operator features	None – connected to central system for data display
Printer	Onboard	External accessory	None – connected to central system
Typical applications	Cleanroom classification, portable and in-situ monitoring. HEPA filter leak testing, recovery tests,	Cleanroom classification, and portable monitoring, recovery tests	Continuous monitoring of individual locations[a]

[a] Fixed monitoring devices in cleanrooms and clean zones are sometimes used to support classification, on condition that the sample volume considered is consistent with the requirements of ISO 14644-1, and the timing and duration of the sample are designated for classification activity. Appropriate sensitivity for capture of the specified particle sizes, positioning of the sampling head and absence of disturbance of the critical location are determined for each case, to assess the suitability of this use of the remote sensor.

5.2.2 Considered particle size selection

The range of particle sizes considered in the ISO 14644-1, Table 1 classification is ≥0,1 µm, ≥0,2 µm, ≥0,3 µm, ≥0,5 µm, ≥1,0 µm and ≥5,0 µm. Selected particle sizes will include all particles equal to or greater than the selected size.

For classification and for monitoring, the chosen size(s) can be driven by the significance, for product or process cleanliness, of specific particle sizes and concentrations, but are also often determined by applicable regulation or industry guidance. It is also possible to select specific sizes not featured in ISO 14644-1:2015, Table 1. Concentrations for intermediate sizes within the table can be calculated.

The measurement of airborne nanoscale particles, <0,1 µm, uses another type of instrument, not included in this document. This application is considered in ISO 14644-12.

In some scenarios, alternative levels of air cleanliness are selected, at specific particle sizes larger than 5 µm which are not within the size range applicable to classification. These are defined as macroparticles and ISO 14644-1:2015, Annex C provides guidance for sampling only these larger particles. Their measured concentration can be described by use of the M Descriptor, with mention of the measurement method used.

This specific mention does not mean that the whole of ISO 14644-1:2015, Annex C applies to classification. The rest of the guidance expressed in this informative Annex is solely concerned with the measurement of macroparticles per se.

In particular, the guidance given in ISO 14644-1:2015, Clauses C.3, C.4, C.5 is not applicable to classification of particles in the size ranges detailed in ISO 14644-1:2015, Table 1.

For monitoring applications, additional particle sizes to those used for classification can be beneficial for trending if considered relevant.

5.2.3 Required sample volume and sample flow rate

The need to perform either classification or monitoring will typically determine the type of instrument and the flow rate chosen, as high sample flowrate instruments allow for a specific sample size to be taken in a shorter amount of time. Shorter sample duration time is beneficial for routine classification and facility monitoring where individual samples are taken throughout an area and the instrument is moved between samples. Sample time is balanced against the statistical accuracy of the measurement and the potential for monitoring a sample location's change of state over time.

5.3 State of occupancy

5.3.1 General

In ISO 14644-1, three occupancy states are defined:

— as-built;

— at-rest;

— operational.

For each occupancy state an ISO class and particle size or sizes will be designated for a specific cleanroom or clean zone.

At-rest and operational states are typically used for routine classification and monitoring, classification as-built can be useful for new projects, particularly if the cleanroom is to be commissioned before equipment is installed.

Particle size distribution will vary between the at-rest and operational states. Larger particles will settle out as part of the room recovers to the at-rest state, whereas in operation there is variation through the particle size distribution due to a more diverse set of particle sources. Depending on the application considered, this can influence alarm and action limits for monitoring.

5.4 Sample locations – points to consider

5.4.1 General

The selection of an appropriate sampling location is important, to ensure a representative sample is obtained when classifying, and to reflect activity at a critical or representative location when monitoring.

5.4.2 Sampling locations for classification

For classification, ISO 14644-1:2015, Annex A, A.4.2 describes the selection of locations. It can be necessary to position the sample probe at a number of different locations, potentially at different heights.

Some particle loss always exists in airborne sampling. Therefore, a prudent approach to minimise particle loss can be to use no tubing at all, so that the sample is drawn directly from the sample probe into the LSAPC. However, in some cases it is not possible to place the counter directly at the location. In these cases, sample tubing will link the probe to the counter positioned at some distance.

ISO 14644-1:2015, A.5.1 states "Set up the particle counter (see A.2) in accordance with the manufacturer's instructions." The following clause A.5.2 concerns orientation of the sampling probe. There is no explicit restriction on tube length. Such restriction can be included in the manufacturer's recommendations. The LSAPC can be placed at convenient location(s) with the sample probe mounted on a tripod, so that height and location are easily adjustable. This is true for cleanrooms, unidirectional flow workstations, isolators, restricted access barrier systems (RABS), safety cabinets etc.

5.4.2.1 Practical challenges associated with counting without use of sample tubing

ISO 14644-1 states that sample heights can differ between areas under test and even between sample locations within a single area under test. Ensuring the LSAPC sample probe is at the correct height when fixed directly to the counter, without tubing, may require some attention. An LSAPC with 28,3 l/min or greater sample flow rate is not a lightweight instrument.

a) In cleanrooms, the LSAPC is placed either freestanding, or on a cart/trolley bench. Effective use of a trolley bench requires that this be adjustable to meet various specified sample heights. This is not a practical solution. For some locations, it is not always possible to place the LSAPC on a flat surface to ensure correct probe orientation. This situation also excludes use of a trolley.

   NOTE Only a handheld particle counter can be used to respond to this latter challenge, but sampling efficiency for large particles is limited by the low flowrate (2,83 l/m) of such a counter. For unidirectional horizontal flow workstations, it is impossible to sample correctly without recourse to a sample tube. The probe cannot be positioned in the correct direction, nor at the required height.

b) For unidirectional vertical flow workstations, class II safety cabinets, downflow isolators etc. the LSAPC can sit inside the critical environment. However, depending on the shape, size and flowrate of the LSAPC such placement can disturb the airflow characteristics of the clean zone. Also, this limits the sample probe position to one height.

5.4.2.2 Practical challenges associated with use of a short - ≤1 m - length of tubing

a) Some particle loss will inevitably occur with use of tubing. This can be minimised by maintaining a straight run of the tubing but some loss is to be expected.

b) For cleanrooms, a tripod can be used. This adds some flexibility to location positions and heights (but limited to a maximum of 1 m above the LSAPC). This short length of tubing restricts the practical movement and placement of the LSAPC, which can sit virtually under or next to the probe (which is mounted on a tripod). Process equipment and chosen sample heights can limit that possibility.

c) Sampling at significant height above practical counter placement presents specific challenges, due to the distance between the counter and the sampling location.

d) If the tripod in a cleanroom is placed too far from the counter, the tubing can restrict distance, and pull over the tripod and sample probe.

e) In horizontal unidirectional airflow workstations, where the critical working area is on or above a flat surface or bench, a small tripod with probe attached by tubing to the LSAPC can be difficult to direct horizontally. This is because the counter must be out of the airflow, and placed on the floor or trolley bench. The tube can be too short for this distance and smaller tripods are more prone to toppling over, especially with the higher flowrate LSAPC and consequent wider tubing radius (and tube rigidity). The alternative is to set up a large tripod at the exit plane and turn the sample head toward the airflow. However, this is sampling at the exit and not necessarily in the working area. It can be a workable solution if the LSAPC can be placed below the exit plane opening and near the tripod.

f) For Isolators the issues can be more complex. The tubing comes from the probe, which is likely to be on a small tripod, out of the isolator and onto the LSAPC, all within 1 m. Some manufacturers install connection ports in the front fascia/screen or on the top of the critical working area (chamber) to connect a tube from the tripod to the port and then another tube from the port to the LSAPC. This creates difficulty, in some scenarios, in keeping the total length under 1 m, especially with multiple sample locations. There are also potential issues again with tripod stability. A practical compromise can be to use a cut and taped glove finger to feed the tubing into the isolator, and close the required sampling point. This can work, unless the glove is in use (operational activity).

g) Entry/Exit transfer boxes also present challenges. Often there are no gloves or ports. Consequently, the LSAPC is placed inside the small inside space. Accordingly, there is no tubing length issue, but there are very restricted options on location, and a risk of compromising airflow. If the volume sampled is a port, then again the issues in e) above are replicated.

h) Open-fronted downflow cabinets and class II safety cabinets have similar issues to those above: small tripod, inflexible tubing, and length from tripod to counter. These tend to be less of a restriction/issue in the field.

i) Sampling hot air volumes, as for instance in depyrogenation tunnels, presents particular challenges. An LSAPC cannot take in high-temperature air. Cooling the sample often involves longer tubing. This requires special attention.

5.4.2.3 "Operational" classification with tubing presents additional practical challenges

a) The routing of tubing, especially within confined environments such as isolators, can make short tubing a real problem. The tubing run can obstruct the process.

b) The locating of the probe and/or tripod can interfere with the process, process equipment or operations.

5.4.3 Sample locations for monitoring

Sample locations within the cleanroom or clean zone are determined by a risk-based approach and often defined as 'critical locations' as part of a contamination control programme.

The critical location is a process point or small area, or perhaps represents a more general background environment.

For a continuous monitoring system, the sample inlet is more likely to be fixed, or perhaps fixed and connected with a probe and tripod, where movement within a defined localised area is required.

For a routine (periodic) monitoring programme, the sample probe can be connected to a portable counter and enable a number of different locations to be sampled, along with potentially different orientations, as for classification (i.e. pointed towards primary direction of airflow).

Some particle loss always exists in airborne sampling. Where particle loss in the sample is of concern, a prudent approach to minimise such loss can be to use no tubing at all, so that the sample is drawn directly from the sample inlet into the LSAPC.

This is possible in some scenarios, where the counter can be directly positioned at the critical location. However, for most applications, continuous or routine, some form of tubing will be required to connect the sample inlet and LSAPC.

For routine monitoring where a movable particle counter is used, the challenges and considerations detailed in 5.4.2 are also applicable.

For monitoring using a fixed particle counter, the following considerations are important.

a) The choice between a counter fitted with an integral pump or linked to a central vacuum pump is fundamental. Noise, size, and heat gains are likely to be factors that influence the location for a fixed LSAPC. Integral pump units are larger than those connected to a central vacuum system, but avoid the need for complex vacuum pipework and plantroom space for the pump.

b) In cleanrooms, the LSAPC is often mounted on a wall, a pillar, or a fixed structure. This can limit the location options, and not enable satisfactory positioning to obtain a representative sample. Depending on the room grille distribution, airflow patterns and working height, a location near the wall could be misrepresentative of the cleanroom and critical location. If tubing is required, the sample tubing length will often be quite short. However, if sample tubing is required to gain access to a critical location at working height, this can hinder the process or movement of personnel.

c) For unidirectional flow workstations (both horizontal and vertical flow variants) the isokinetic sampling probe needs to be close to the critical location without hindering the process or restricting the process equipment. An isokinetic probe and sample tubing are required, connected from within the critical work zone to an LSAPC location outside the work zones but as close as possible to the critical location. The LSAPC is lower than the sample height to avoid sampling upward through tubing.

d) In horizontal or vertical unidirectional flow workstations, isolators and RABS, it is likely the tubing run will be longer than ideal, and is also likely to require a number of bends and possibly connectors or valves. Large radius bends contribute to the overall length of a tube, and can force a sampling location to be above the working height. These factors all influence the efficiency of particle sampling. It is therefore likely that in many installations an assessment can help to understand the potential losses in the sampling system. It can also be useful to make a choice between the tubing materials and finishes available. Tubing runs can be examined and optimised before implementation. Special installation fixtures and tailor-made solutions can be considered at the early stage of separative device design for the shortest possible sampling system.

5.5 Instrument measurement issues

5.5.1 General

When reviewing the potential errors associated with particle counting, there are several associated risks, which can be collated into three main topics for discussion:

a) sampling errors (5.5.2);

b) sample measurement errors (5.5.3);

c) sample transportation errors (5.5.4).

When a sample is taken without the need for transport (tubing) between the sample location and measurement of the sample by the particle counter, the sampling error and measurement error are primary areas of concern.

Sampling errors and sample measurement errors relate to the particle counter and its sample probe and are covered below in 5.5.2 and 5.5.3. Sample transportation errors relate to sample tubing and are covered in 5.5.4.

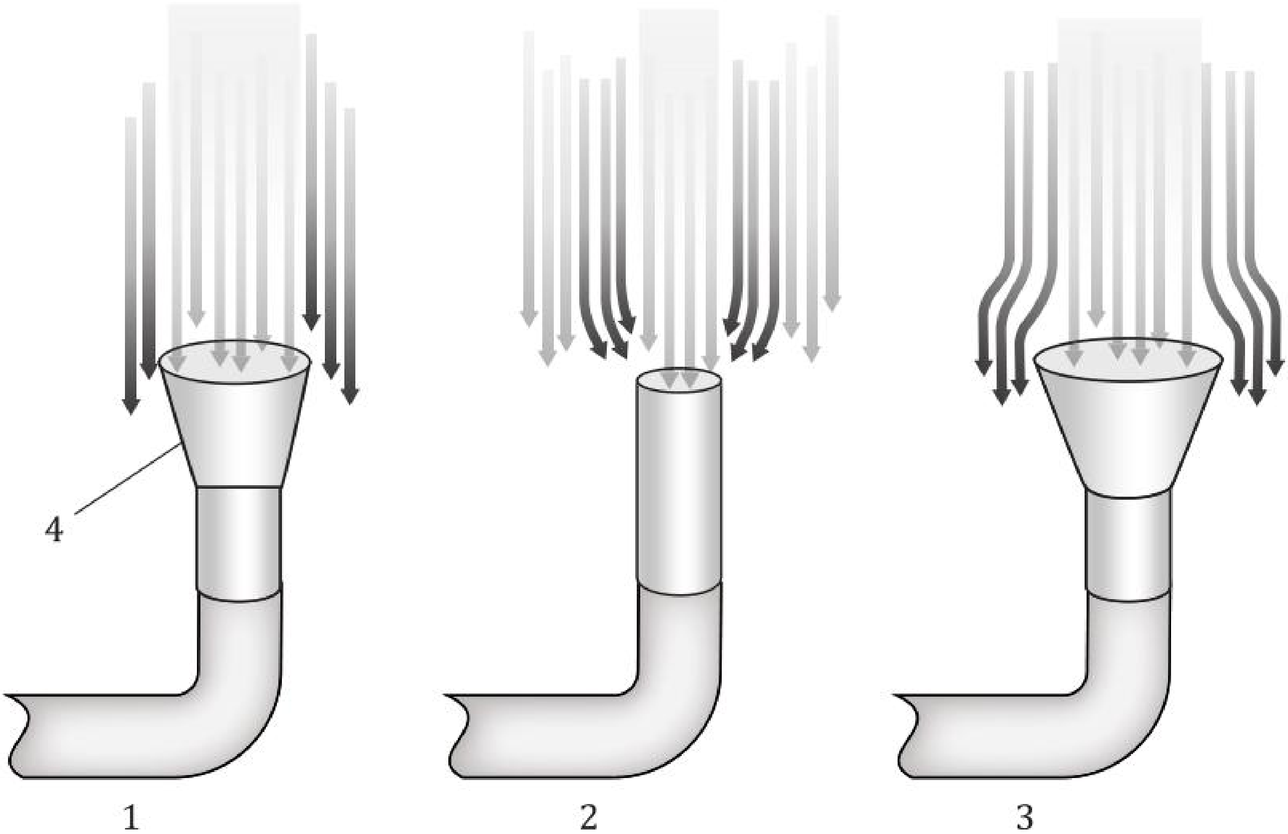
5.5.2 Sampling errors

5.5.2.1 Sample inlet design and placement

When a sampling probe is used, attention is paid to sample probe design and placement, to avoid particle loss.

5.5.2.2 Isokinetic sampling

Isokinetic sampling, where the local air flow velocity and the inlet velocity of the air entering the sampling probe are equal, is relevant when sampling in unidirectional airflow conditions. To extract the most statistically representative sample of the particles within this uniform volume of air, a suitably designed and sized isokinetic sampling probe is used. This causes minimal deviation in airflow, thereby reducing sampling errors and size distribution biasing.



Key

1 isokinetic sampling

2 super-isokinetic sampling

3 sub-isokinetic sampling

4 isokinetic sampling probe

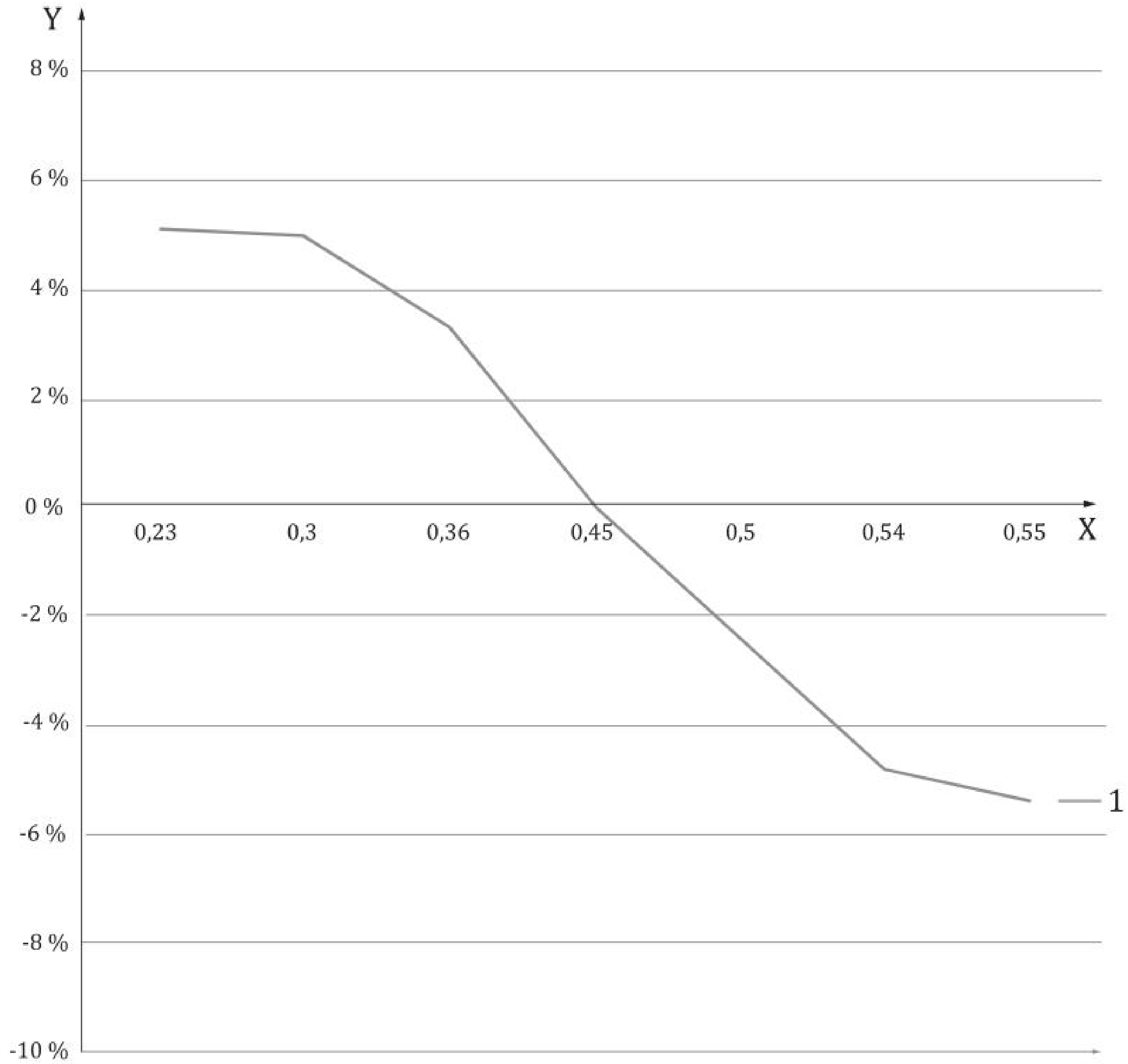
Figure 2 — Isokinetic sampling and variants

Variations to sample air flow and instrument flowrates require suitable sizing, to achieve isokinetic conditions. For example, low-flowrate instruments will have smaller-diameter probe inlets, and high-flow instruments will have larger diameter inlets for comparable sampling behaviour.

Super-isokinetic sampling will typically yield an increase of smaller particles in relation to large particles, as the smaller particles are more likely to be redirected through the airstream, and the smaller available opening restricts the sampling of large particles, that retain more momentum within the airstream and remain unsampled. Sub-isokinetic sampling offers a larger opening for oversampling large particles, but the airstream lines are now deflected due to a positive pressure at the inlet to the Isokinetic sampling probe, that causes the smaller particles to be under-sampled.

A tolerance of 5 % sampling error around truly isokinetic sampling has historically been considered acceptable (see Reference [5]). This value for tolerances is robust across a range of airflow velocities and instrument flowrates. The tolerance is a function of how particles of different sizes slip within the air-stream lines during a change in direction associated with either super-isokinetic or sub-isokinetic sampling.

For example, a 28,3 l/min counter would use an isokinetic sampling probe measuring 36,5 mm in internal diameter, for typical unidirectional airflow applications (airflow velocity = 0,45 m/s). Sampling error ranges for ±5 % for airflow velocities at probe height are illustrated in Figure 3 below. Considering the tolerances for this instrument, the airflow velocity is within specification between 0,22 m/s and 0,54 m/s. For further information, see Reference [5].



Key

X airflow velocity at probe height m/s

Y Sampling error

1 nominal airflow velocity, standard probe

Figure 3 — Sampling error variations for 5,0 µm particles for 28,3 l/min flowrate instrument

5.5.2.3 Isoaxial sampling

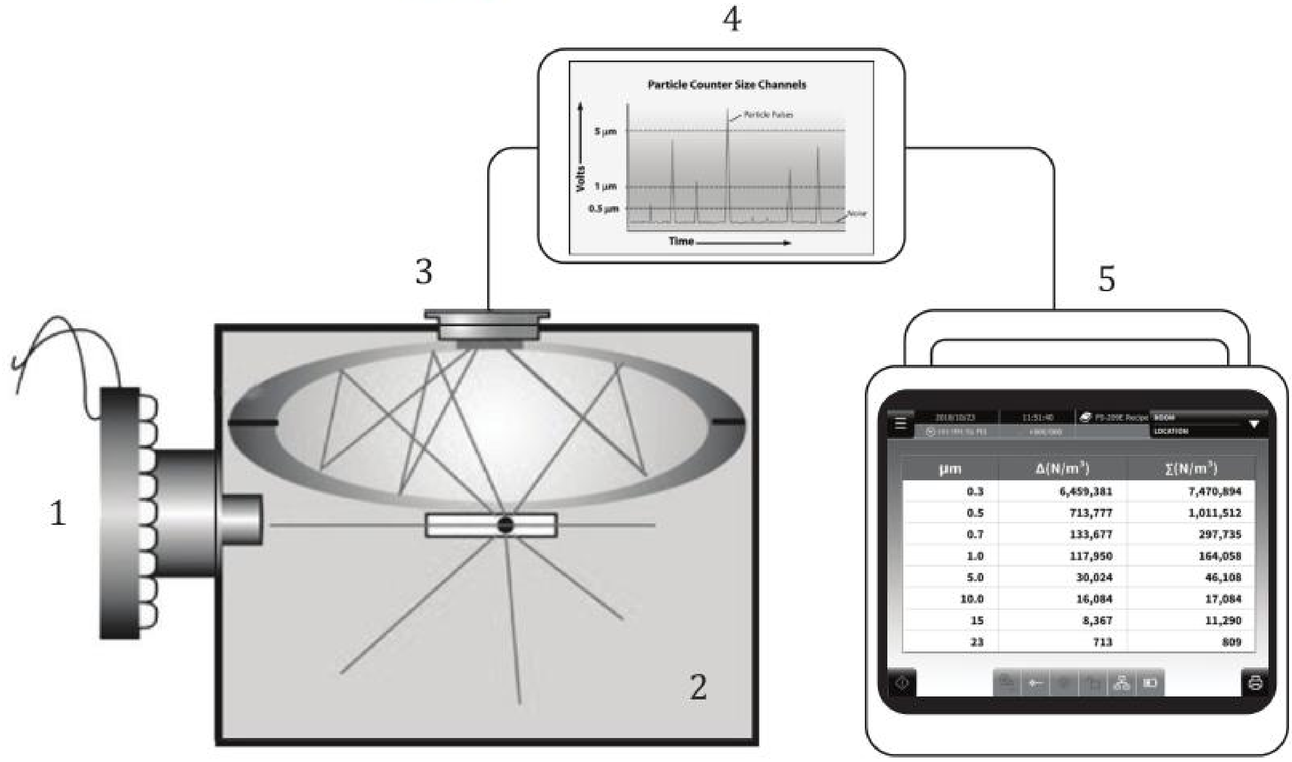
Isoaxial sampling is a sub-component of isokinetic sampling. ISO 14644-1 requires that the sample probe be directed to face toward the primary airflow direction - the angle of sampling is referred to as 0° orientation. In practice, varying the angle of inlet toward the primary air creates an elliptical-shaped probe orientation and this creates a change in how particles will 'slip' through the sampled air, effectively changing the size of opening as per isokinetic sampling. Angles beyond 20° demonstrate potential errors (see Reference [4]).

5.5.3 Sample measurement errors

5.5.3.1 General

This section lists the major components of particle counter measurement and its variability, from both design and practical application perspectives.

Aerosol particle counters function using the principles of light scattering. Laser optical particle counters employ five major systems (see Figure 4):



Key

1 lasers and optics

2 viewing volume

3 photodetector

4 pulse height analyser

5 user interface

Figure 4 — Principal systems of a laser optical particle counter

5.5.3.2 Variable parameters in measurement

The following variables, and their impact, can be considered by the operator when sampling.

— Coincidence, where it is probable that two or more particles pass through the viewing volume at the same electronic speed and are counted as a single larger particle. This effect typically only occurs at, or near, the saturation point of the particle counter. Ensuring that intended maximum concentrations are not near the saturation point of the selected particle counter will reduce the influence of this factor.

— Contamination of the optical chamber can lead to reduced light scattering detection, especially if the contamination is on the mirrors or photodetector. When significant contamination occurs, less light is scattered than that recorded during calibration and the particle will appear smaller. This will reduce the number of particles detected in a particular size range.

There are other variables that cannot be compensated for by the operator. These "uncontrollable variables" are detailed here to give an understanding of possible impact.

— The shape and orientation of the particle: particles are seldom smooth and shaped like the polystyrene latex (PSL) spheres used in calibration. Such particles can be flakes of skin or jagged fibers. When they float through the viewing volume sideways, they will scatter a different amount of light than if they travel through lengthwise.

— The albedo (reflectivity) of the particle.

— The wavelength of the laser.

— Collection optics.

— The laser intensity is not uniform.

Calibration testing tries to normalize these parameters and gives a range of acceptable tolerances based on a collective calibration review using controlled particle size standards (over which there is also some discussion and variance). See ISO 21501-4.

5.5.4 Sample tubing issues

5.5.4.1 General

When a sample is taken at a designated location, whether for classification or monitoring, and there is a requirement for sample tubing to transport the sample from source to the point of measurement (LSAPC), this section discusses the criteria that influence transport of particles and describes the best practices to assist with the design of an airborne particle counting sampling system.

As described in 5.5.3, there are inherent errors in sampling and in the tolerances of instrumentation: the factors identified during transport are accumulative to those errors, and need to be understood when determining appropriate measuring requirements for classification, where accuracy is primordial, or for monitoring. Use of any sample tubing will affect what is measured, in relation to the source sample: it is the degree to which acceptable tolerances can be achieved that is to be determined.

5.5.4.2 Sample tubing materials

There are several choices of tubing that can be used depending on the situation to be sampled.

Smooth-bored stainless steel is a preferred choice for fixed locations, as it is resistant to corrosion, withstands variable temperatures, and dissipates static build-up when grounded. Selection ensures it is free from internal contamination and seams.

Bev-a-Line tubing with a Hytrel liner offers many of the properties of stainless steel, with the added advantage of being flexible and easy to replace. Attention is given to conductivity, temperature and chemical exposure. For higher heat applications, Tygon PFA is used as it has a higher deformation temperature than other flexible tubing types. Hytrel does degrade in contact with certain chemicals. Where applications involve such chemicals, Tygon 2475 is used; it has a smooth lining and is nonreactive. Care is taken to replace with compatible tubing.

Selection of the internal diameter of tubing is often based on the Reynolds number calculation performed to ensure turbulent flow, but this will require consideration of tubing length and bends.

Consideration is given to cleaning, drying and refitting tubing at appropriate intervals, using suitable cleaning agents. A zero count is performed after refitting.

5.5.4.3 Sample tubing length

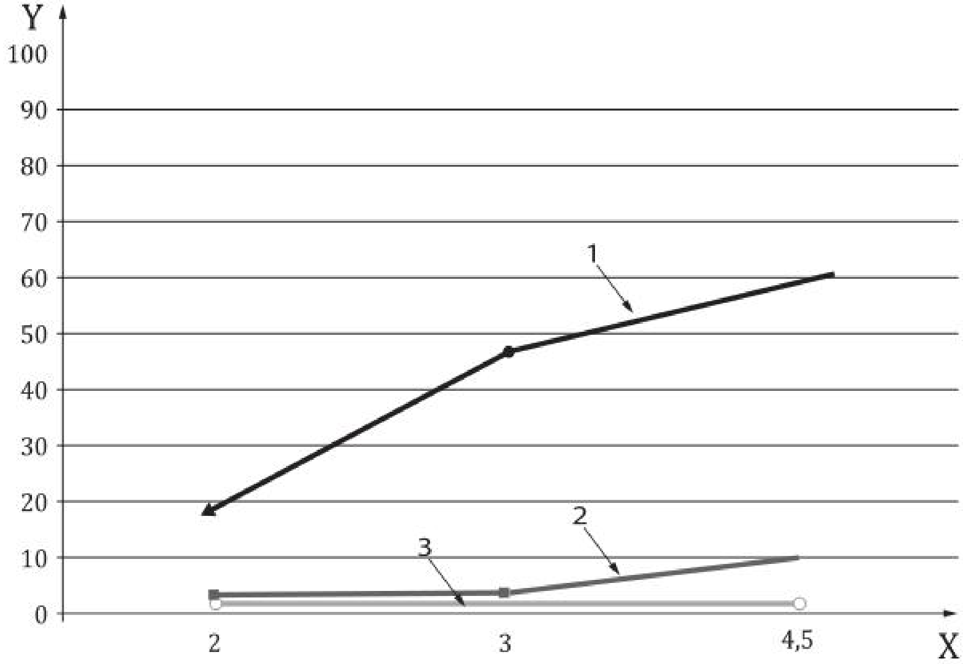
There are many mechanical dynamics that act on particles moving within tubing, to cause particle attrition or sedimentation during transportation. These mechanical dynamics are correlative to tubing length, i.e. the longer the tubing, the more effect these forces have on particles in transit, and the greater the attrition due to length.

To reduce the losses in straight linear horizontal tubing, turbulent flow within the tube ensures sedimented particles are re-entrained into the flow stream and carried to the measurement location. The Reynolds number (a dimensionless value for transport tubing that describes if the flow is demonstrating turbulent or laminar flow characteristics) is considered to influence particle transport efficiency.

The subsequent release to the LSAPC of particles sedimented in the sampling tubing can also disturb results obtained.

Particle losses in tubing principally demonstrate a combination of losses due to sedimentation for particles ≥5,0 µm, but submicron particles are also lost due to secondary forces acting on the particles, such as electrostatic attraction to tubing materials, Brownian motion, diffusion and thermophoretic forces.

In Figure 5, an experimental relation between particle transport and tube length is shown for three particle sizes.



Key

X length of tubing in metres

Y percent loss

1 5,0 µm particles

2 1,0 µm particles

3 0,5 µm particles

Figure 5 — Particle transport vs. tubing length: one example of findings from a manufacturer's particle loss experiment with 28,3 l/min flowrate and horizontal 10 mm tubing

5.5.4.4 Sample tubing bends

When tubing runs require a change of direction, the radius of each bend is assessed for particle losses. When a particle travelling in a straight line is required to change direction, the inertia of the particle relative to the streamlines of airflow can cause it to impact on the walls of the tubing in the bend and can be deposited. Depending on the particle's stopping distance, this impaction can be reduced by ensuring a smooth transition through the change of direction.

A long-radius bend is preferred for transportation of particles in tubing for several reasons: it provides a more gradual change in direction, and reflects the closest approach to straight tubing transport, also the angle of impaction on the pipe wall is relatively small, minimizing the risk of attrition.

A common recommendation (see ASTM F50[6]) is that tubing bend radius be >150 mm (for standard-issue tubing used for 28,3 l/min instruments). However, the 'ideal' radius can change with different tube section and flowrate, and the practicalities of such bend radius can make it difficult to sample at the appropriate working position.

5.5.4.5 Other sample tubing considerations

Additional elements that can be added to sample tubing to ensure an engineering solution for clean air devices include the following components.

5.5.4.5.1 Fittings and connectors

When tubing passes through a partition, enclosure panel, or a closed clean air device, a transition fitting can be required. Care is taken to ensure that there are no shoulders or obstructions that can reduce the internal diameter of the tubing, and restrict a smooth transition through the transfer connection. Any change of diameter can cause turbulence and create the potential for impaction of particles on the connector or tubing. The impact of connectors is considered as part of the overall assessment of potential transportation losses.

5.5.4.5.2 Valves

There are applications where it is necessary to isolate a particle counter. The primary use is where cleaning agents can contaminate the internal optical flow path of the particle counter and potentially degrade performance. To isolate the flow to the particle counter, either capping the inlet to prevent ingress of air in conjunction with stopping the vacuum source (external or internal pump), or using an isolation valve, or series of valves, is employed.

Adding a valve to a system creates a potential particle trap, or a restriction to flow that may cause particle build-up. These accumulated particles then have the potential to shed, at unknown intervals, in quantities, or sizes, which cause undesirable events.

Systems are selected without valves that restrict flow, as these present a greater potential for trapping particles and restricting flow to the particle counter. Great care is taken to reduce the tubing length to a minimum: a relationship exists between particle attrition and tubing length, and valves act in a similar manner.

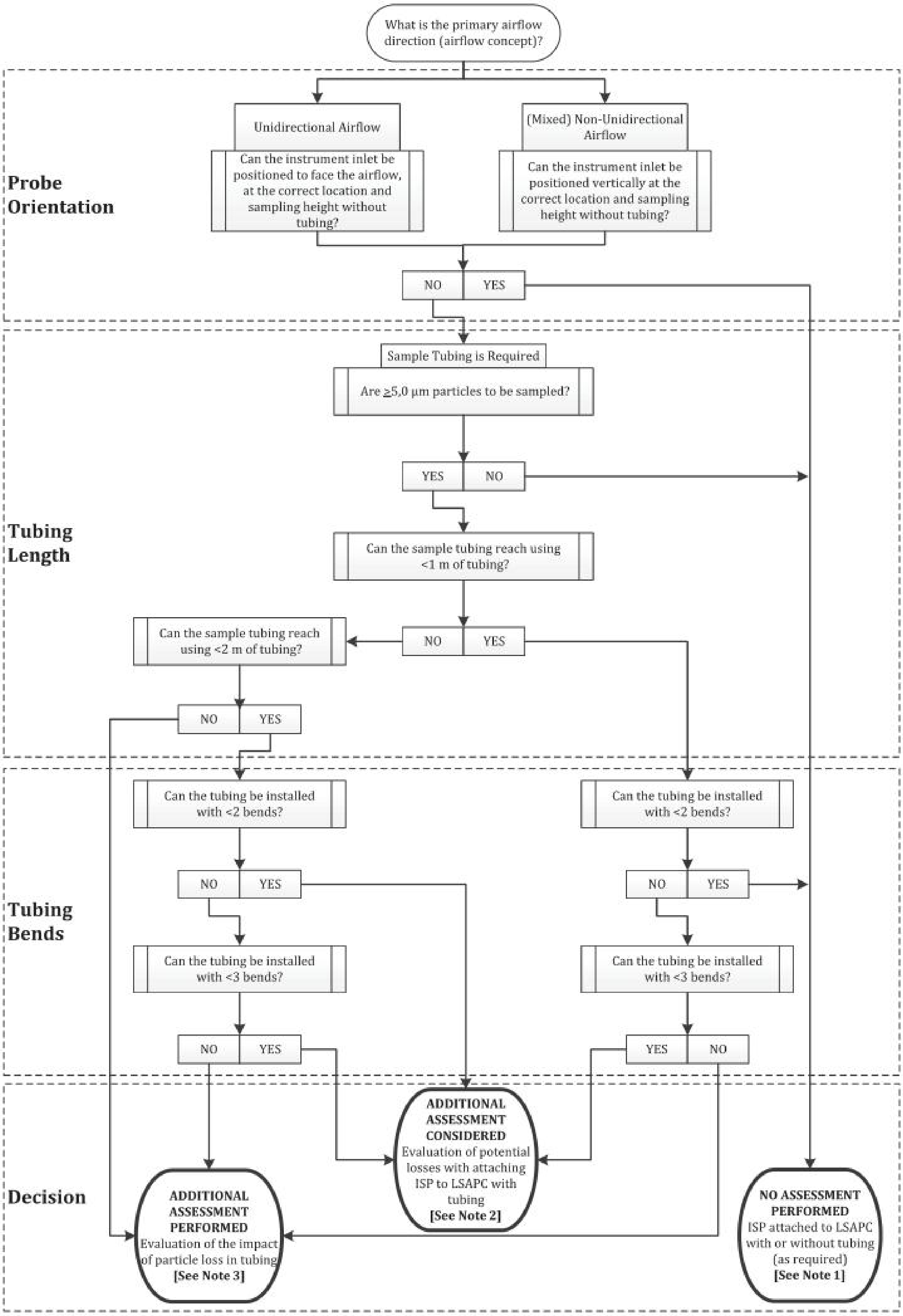
To reduce the influence of valves on particle collection, dry, unwetted setting materials are used, to reduce potential sticking of particles and not degrade over time.

Where three-way valves are used the configuration allows for the ball valve to flow the sample air stream directly to the particle counter, when in the normally-open position. The actuation to the closed position can then divert the sample to the third leg of the valve. The angle of this side flow is not part of normal particle counting and can be acute (90°).

Twinned two-way valves can emulate the same functions as the three-way valve: care is taken to avoid elongating the tubing length before the side flow valve, ensuring as short a dead leg as possible, and reducing the period required to establish homogenous flow.

5.6 Decision tree

Sample tubing issues described in 5.5.4 above create the potential for particle losses to occur when sampling airborne particles. The probability of losses increases when sampling larger particle sizes and when sample tubing is used. The process of considering particle loss and determining suitable sampling of airborne particles can be evaluated using the decision tree (see Figure 6). This decision tree requires consideration of probe orientation, sample tubing length, and sample tubing bends, before a decision on the quality of the measurement can be determined. Other factors such as connections and valves on the sample tubing line also need to be considered and evaluated when included along with tubing and tubing bends.



ISP = isokinetic sampling probe

Connectors Tubing connectors can be required for transitions through machinery for sample measurement. Efficient connectors have smooth bore and no step transitions, and do not significantly change tubing diameter.

Valves Where isolation valves are employed, the flow can be through a full flow mechanism that does not significantly reduce tubing diameter.

NOTE 1 Particle losses in these applications have a low impact on measurement quality.

NOTE 2 Particle losses in these applications can affect the quality of measurement. Additional information is sought to understand the impact of the effects.

NOTE 3 Particle losses in these applications can affect the quality of measurement. A review of the system installation is performed to fully evaluate the impact of particle losses.

Figure 6 — Decision tree

5.7 Examples of use of the decision tree

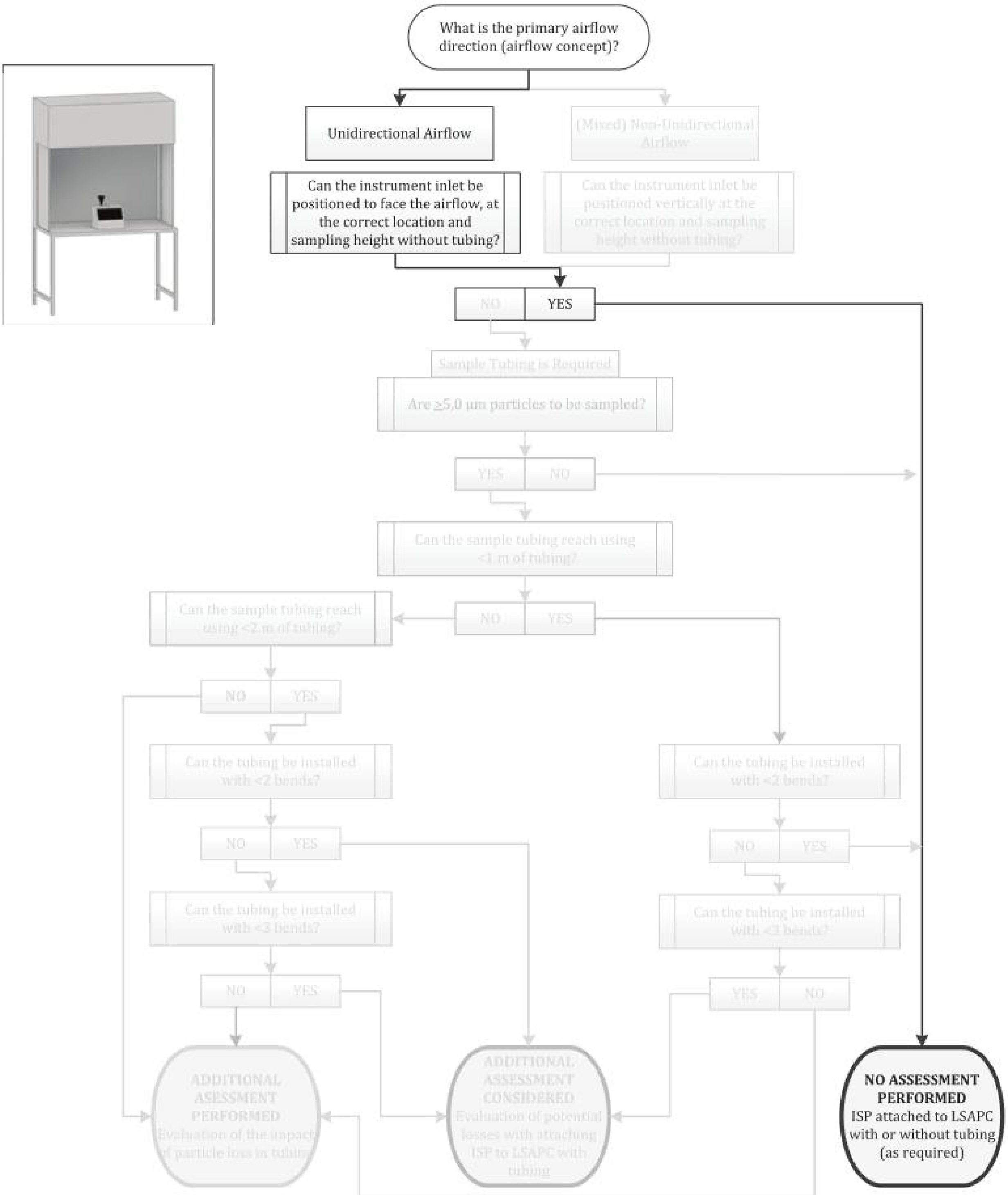
5.7.1 General

Three examples of how the decision tree is used for a clean zone with unidirectional vertical air flow are shown below.

5.7.2 Example 1

5.7.2.1 General

The instrument sample probe is connected directly to the counter, with no sample tubing. The isokinetic probe is facing the direction of airflow. Figure 7 provides a decision tree for Example 1.



ISP = isokinetic sampling probe

Figure 7 — Decision tree Example 1

5.7.2.2 Potential advanced considerations

None

5.7.2.3 Points considered to reduce the risk

— The particle counter exhaust is HEPA filtered, or this exhaust is tubed out of the clean area.

— Exhaust airflow can also cause turbulence within unidirectional area.

— Aerodynamic interference from the particle counter.

5.7.3 Example 2

5.7.3.1 General

The instrument sample probe is connected to the counter by 1,3 m of sample tubing and including 2 bends. The particle counter is mounted adjacent to the clean zone. The isokinetic probe is facing the direction of airflow. Figure 8 provides a decision tree for Example 2.

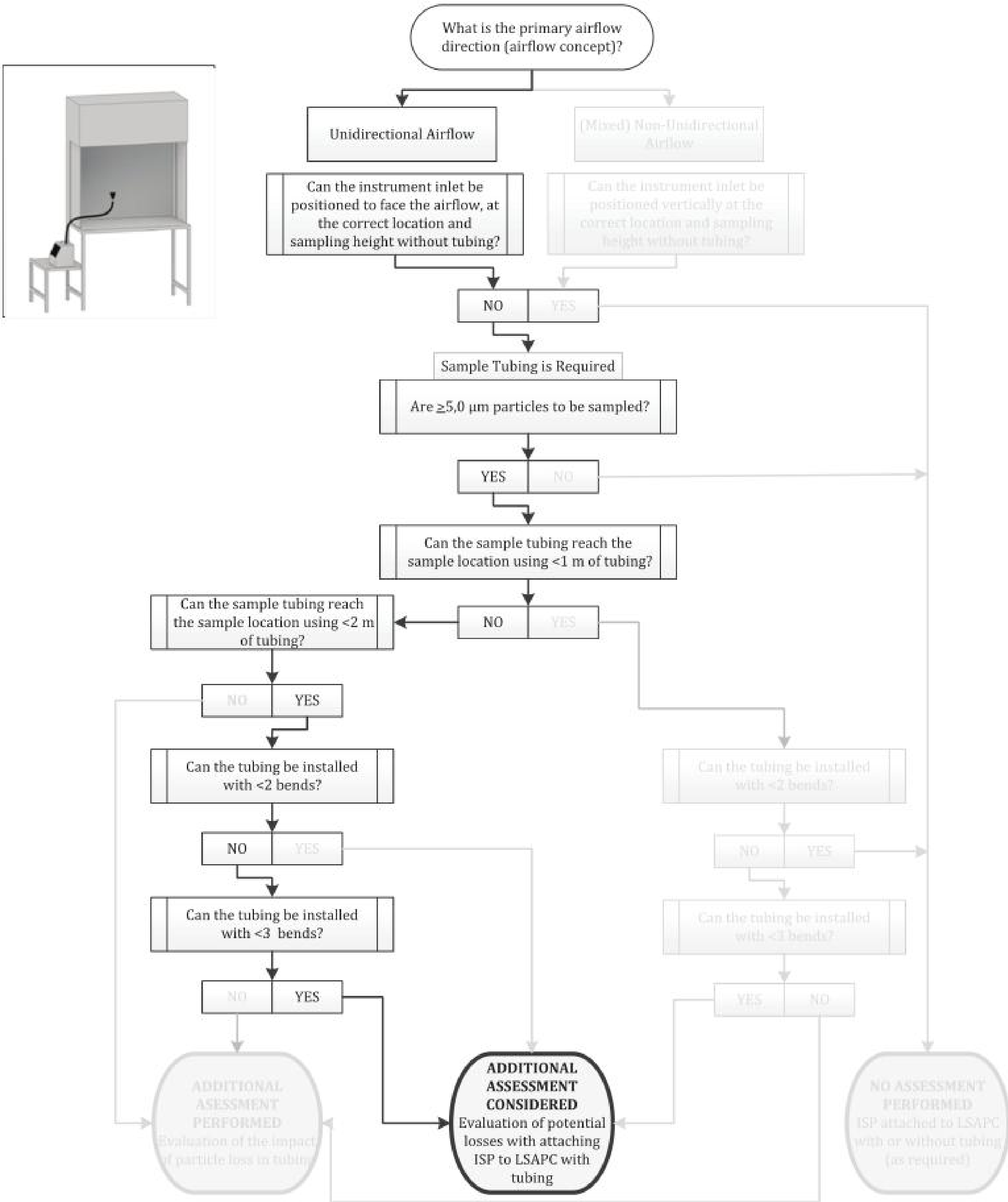


Figure 8 — Decision tree Example 2

5.7.3.2 Potential advanced considerations

— Consideration given to a less compromised installation (tubing material, length, tubing diameter, location of ISP and instrument).

— Transit losses reviewed against documented studies to determine impact.

— Alert and action thresholds reviewed for suitability.

— Historical data reviewed to ensure system condition changes are captured.

5.7.3.3 Points considered to reduce the risk

— Rigid type conduit, such as stainless-steel tubing, used to reduce the risk of certain peaks due to shaking and unwanted contact with the sample tube. Rigid type conduit can ensure that the tube bends are in the same radii and fixed position at all times.

— Installation of tools to reduce distance and number of bends such as custom-made fixtures and upgrades.

— Larger diameter tubes can reduce particle losses in bends.

— Maintaining and cleaning the tubing within a reasonable time frame ensures that the tubing is free from accumulated particle residues.

5.7.4 Example 3

5.7.4.1 General

The instrument sample probe is connected to the counter by 1,5 m of sample tubing and includes 4 bends. The particle counter is mounted below the clean zone. The isokinetic probe is facing the direction of airflow. Figure 9 provides a decision tree for Example 3.

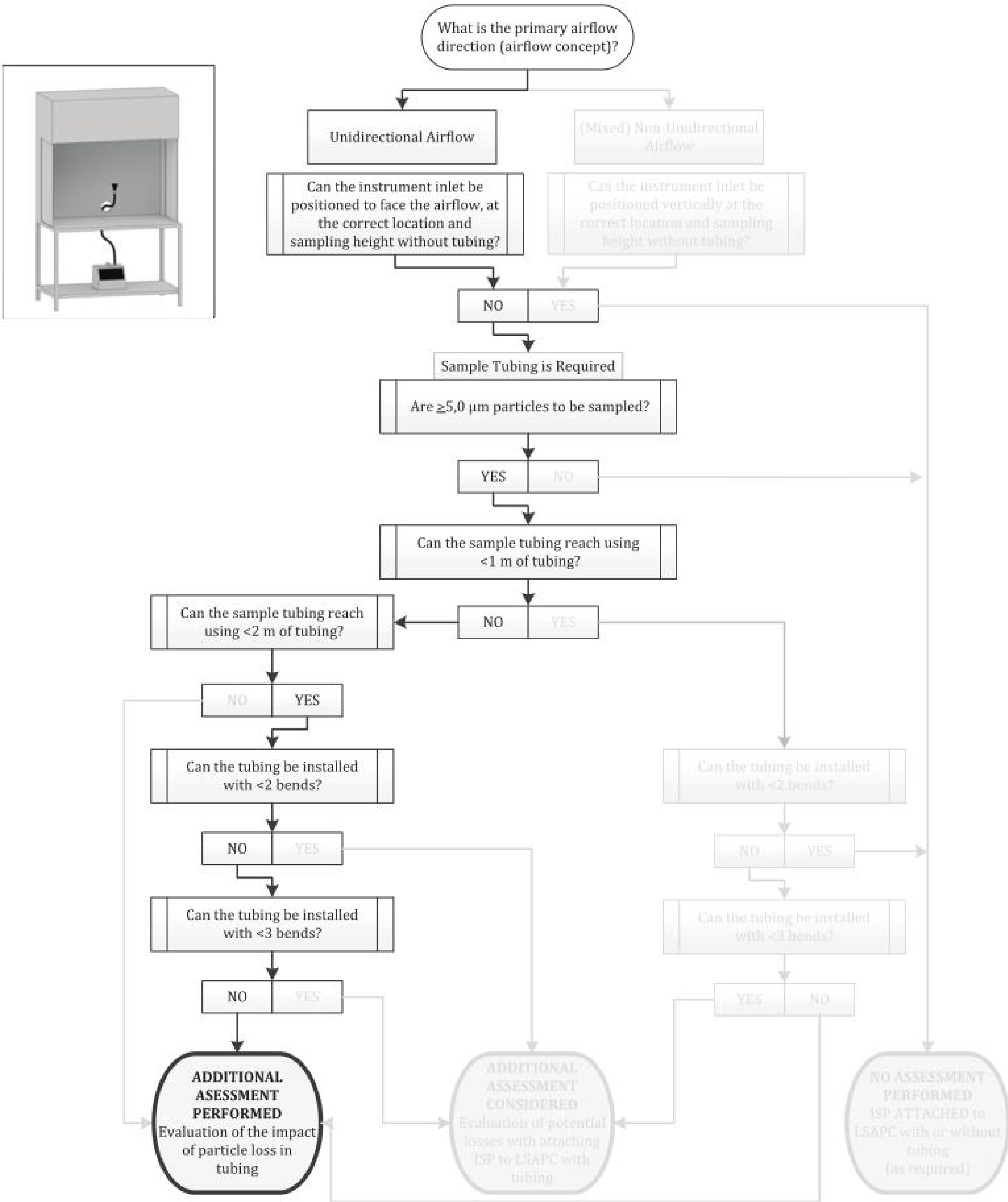


Figure 9 — Decision tree Example 3

5.7.4.2 Potential advanced considerations

— Consideration given to a less compromised installation (tubing material, length, tubing diameter, location of isokinetic sampling probe and instrument).

— Transit losses reviewed against documented studies to determine impact.

— Alert and action thresholds reviewed for suitability.

— Historical data reviewed to ensure system condition changes are captured.

— Transit loss testing or thorough assessment performed when documented review considers the macro-particle losses to be excessive.

5.7.4.3 Points considered to reduce the risk

— Rigid type conduit, such as stainless-steel tubing, used to reduce the risk of certain peaks due to shaking and unwanted contact with the sample tube. Rigid type conduit can ensure that the tube bends are in the same radii and fixed position at all times.

— Installation of tools to reduce distance and number of bends, such as custom-made fixtures and upgrades.

— Larger-diameter tubes can reduce particle losses in bends.

— Maintaining and cleaning the tubing within a reasonable time frame ensures that the tubing is free from accumulated particle residues.

— Particle loss engineering studies performed with same flowrate particle counter assist with determining potential losses and the degree of risk.

6 Verifying a system

Verifying a system in terms of sampling accuracy can be performed through an assessment of the installation and ensuring that certain activities are performed.

An example of verification of a sampling system can involve the following.

a) Verification that the particle counter has been calibrated to ISO 21501-4 and the device is within its calibration period.

b) An assessment on the tubing installation has been performed, as shown in the decision tree in 5.6.

c) For unidirectional airflow, an assessment of the isokinetic sampling error has been performed and is within ±5 %.

d) A zero count has been performed as described in ISO 14644-1:2015, A.5.1, this ensures that there are little or no residual particles in the tubing and that the installation is not experiencing interference from any adjacent objects.

e) For an existing installation, a review of previous data and other monitoring data taken in parallel can be made.

NOTE A quantitative assessment of a system in situ [points b) and e)] can provide results that are not repeatable, in comparison with simulation of the system on a test bed (see References [8] and [9]).

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