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Standard Guide for Selecting Instruments and Methods for Measuring Air Quality in Aircraft Cabins[1]

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1. Scope

1.1 This guide covers information and guidance for the selection of instrumentation and test methods for measuring air quality in aircraft passenger cabins as well as in areas limited to flightcrew access.

1.2 This guide assumes that a list of pollutants to be measured, or analytes of interest, which are present, or may be present, in aircraft cabins is available.

1.3 This guide provides information and guidance to identify levels of concern pertaining to public and occupational exposures to relevant air pollutants. This guide does not address levels of concern, if any, related to degradation of materials or aircraft components because of the presence of air pollutants.

1.4 Based on levels of concern for public and occupational exposures for each pollutant of interest, this guide provides recommendations for developing three aspects of data quality objectives (*a*) detection limit; (*b*) precision; and (*c*) bias.

1.5 This guide summarizes information on technologies for measurement of different groups or classes of air pollutants to provide a basis for selection of instruments and methods. The guide also identifies information resources on types of available measurement systems.

1.6 This guide provides general recommendations for selection of instruments and methods. These recommendations are based on concepts associated with data quality objectives discussed in this guide and the information on available instruments and methods summarized in this guide.

1.7 This guide is specific to chemical contaminants and does not address bioaerosols, which may be present in the cabin environment.

1.8 This guide does not provide details on use or operation of instruments or methods for the measurement of cabin air quality.

1.9 This guide does not provide information on the design of a monitoring strategy, including issues such as frequency of measurement or placement of samplers.

1.10 Users of this guide should be familiar with, or have access to, individuals who have a background in (*a*) use of instruments and methods for measurement of air pollutants and (*b*) principles of toxicology and health-effects of environmental exposure to air pollutants.

1.11 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.12 *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

D1914 Practice for Conversion Units and Factors Relating to Sampling and Analysis of Atmospheres

D3162 Test Method for Carbon Monoxide in the Atmosphere (Continuous Measurement by Nondispersive Infrared Spectrometry)

D3631 Test Methods for Measuring Surface Atmospheric Pressure

D4023 Terminology Relating to Humidity Measurements (Withdrawn 2002)[3]

D4490 Practice for Measuring the Concentration of Toxic Gases or Vapors Using Detector Tubes

D4861 Practice for Sampling and Selection of Analytical Techniques for Pesticides and Polychlorinated Biphenyls in Air

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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] The last approved version of this historical standard is referenced on www.astm.org.

D5149 Test Method for Ozone in the Atmosphere: Continuous Measurement by Ethylene Chemiluminescence
D5156 Test Methods for Continuous Measurement of Ozone in Ambient, Workplace, and Indoor Atmospheres (Ultra-violet Absorption)
D5197 Test Method for Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology)
D5466 Test Method for Determination of Volatile Organic Chemicals in Atmospheres (Canister Sampling Methodology)
D6196 Practice for Selection of Sorbents, Sampling, and Thermal Desorption Analysis Procedures for Volatile Organic Compounds in Air
D6245 Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation

2.2 *Other Standards:*
14 CFR 25 Airworthiness Standards
29 CFR 1910.1450 Occupational Exposure to Hazardous Chemicals in Laboratories
40 CFR 50 National Ambient Air Quality Standards
40 CFR 53 Ambient Air Monitoring Reference and Equivalent Methods
40 CFR 60 Standards of Performance for New Stationary Sources—Appendix A: Test Methods
RTCA/DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

3. Terminology

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *analyte, n*—designated chemical species to be measured by a monitor or to be identified and quantitated by an analyzer.

3.2.2 *bioaerosol, n*—airborne material of biological origin, including viable microorganisms, pollens, spores, bacteria, viruses, allergens, and biological debris.

3.2.3 *ceiling limit, n*—a maximum allowable air concentration, established by the Occupational Safety and Health Administration (OSHA), that must not be exceeded during any part of the workday.

3.2.4 *concentration range, n*—a semiquantitative term referring to the extreme uppermost portion of the distribution of anticipated measurements. This term (and the dose or risk analogues) traditionally refers to the portion of the distribution that conceptually falls above about the 98th percentile of the distribution, but is not higher than the highest individual measurement.

3.2.5 *data quality objectives (DQOs), n*—qualitative and quantitative statements of the overall level of uncertainty that a decision-maker is willing to accept in results or decisions derived from environmental data. Minimum DQOs include method detection limit, precision, and bias.

3.2.6 *level of concern, n*—an exposure level or concentration that is not to be exceeded by regulation or, for unregulated pollutants, an exposure level or concentration that is believed to be associated with odor, sensory irritation, and other adverse health or toxic effects.

3.2.7 *lowest-observed-adverse-effect level (LOAEL), n*—the lowest exposure at which there is a significant increase in an observable effect.

3.2.8 *no-observed-adverse-effect level (NOAEL), n*—the highest exposure among all the available experimental studies at which no adverse health or toxic effect is observed.

3.2.9 *overall uncertainty (OU), n*—quantity used to characterize, as a whole, the statistical uncertainty of a measurement result compared to a true or accepted value. The overall uncertainty is expressed as a percentage that combines bias and precision. For a given statistical confidence level ($N\sigma$), the overall percent uncertainty may be calculated using the following formula:

$$OU = \left(\frac{\left| \bar{X} - X_{\mathrm{REF}} \right| + N\sigma}{X_{\mathrm{REF}}} \right) \times 100 \tag{1}$$

where:
$\bar{X}$ = mean value of results of a number (n) of repeated measurements,
X_{ref} = true or accepted reference value of measurement result,
σ = standard deviation of a number (n) of repeated measurements, and
N = number of standard deviations from the mean. N generally takes value of 1, 2 or 3 corresponding to 68 %, 95 %, and 99 % confidence intervals, respectively. Since the desired confidence interval is often 90 % or more, a value of 1.7 or higher typically is used for N.

For example, given a precision and bias of ±10 %, and a desired confidence interval of 95 %, the overall uncertainty using Eq 1 will be 30 %.

3.2.10 *permissible exposure limit (PEL), n*—the OSHA-mandated time-weighted-average (TWA) concentration of a chemical in air that must not be exceeded during any 8-h workshift or 40-h work week.

3.2.11 *safety factor, n*—a dimensionless number, greater than unity, to account for incomplete understanding of errors encountered in extrapolating exposure or health effects derived for one set of conditions or basis to another.

3.2.12 *spacecraft maximum allowable concentrations (SMACs), n*—developed by the National Aeronautics and Space Administration and the Committee on Toxicology from the National Research Council, based on exposure duration of 1 h to 180 days.

3.2.13 *short-term-exposure limit (STEL), n*—American Conference of Governmental Industrial Hygienists (ACGIH)-recommended 15-min TWA air concentration for a chemical which should not be exceeded at any time during a workday, even if the 8-h TWA concentration is within the threshold limit value (TLV).

3.2.14 *threshold limit value (TLV), n*—ACGIH-recommended TWA air concentration of a chemical for a normal 8-h workday and a 40-h workweek, to which nearly all workers may be repeatedly exposed without adverse effects.

4. Summary of Guide

4.1 This guide provides procedures and recommendations for the selection of test methods and equipment suited to measuring air quality in aircraft cabins.

4.2 Major steps in the selection process include identifying one or more levels of concern for each analyte to be monitored, selecting the most appropriate level of concern for each analyte, defining minimum data quality objectives that are compatible with the level of concern, defining desirable operating characteristics that are compatible with the aircraft cabin environment, and selecting instruments and test methods that meet these objectives.

5. Significance and Use

5.1 This guide may be used to identify instruments and methods for measuring air quality in aircraft cabins. Such measurements may be undertaken to:

5.1.1 Conduct monitoring surveys to characterize the aircraft cabin environment and to assess environmental conditions. Results of such measurements could then be compared with relevant standards or guidelines for assessment of health and comfort of passengers and flight attendants.

5.1.2 Investigate passenger and flight attendant complaints; or

5.1.3 Measure and compare the performance of new materials and systems for the aircraft cabin environment.

6. Identify and Select Levels of Concern

6.1 Identification and selection of the level of concern for each analyte of interest is the most important basis for defining data quality objectives. The level of concern for each analyte is defined from review of applicable regulations, standards, and guidelines using procedures described below in 6.2 and 6.3.

6.2 Use the following sources to compile levels of concerns for each analyte[4] identified for monitoring:

6.2.1 FAA Airworthiness Standards (14 CFR 21), which specify acceptable exposure levels for ozone, carbon dioxide, carbon monoxide, and cabin pressure that explicitly apply to the aircraft cabin environment;

6.2.2 Spacecraft Maximum Allowable Concentrations (SMACs), which have been defined for chemicals under exposure conditions ranging from 1 h to 180 days for the space program;

6.2.3 The Clean Air Act (40 CFR Part 50), which specifies acceptable limits for general population exposure to criteria pollutants (ozone, carbon monoxide, oxides of nitrogen, sulfur dioxide, particulate matter, and lead), and also regulates population exposure to emissions of nearly 200 hazardous air pollutants;

6.2.4 The Occupational Safety and Health Act of 1970 (29 CFR 1910), which establishes PELs and ceiling concentrations to protect workers against the health effects of exposure to approximately 200 hazardous substances;

6.2.5 ACGIH Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Values, which gives TLVs and STELs to define acceptable limits for workplace exposure.

6.2.6 AIHA *Odor Thresholds for Chemicals with Established Occupational Health Standards* is a peer-reviewed document that contains odor thresholds for a wide variety of chemicals.

6.2.7 For analytes not covered by items 6.2.1-6.2.6, specialized databases may be consulted to develop levels of concern. Such resources include the Agency for Toxic Substances and Disease Registry (ATSDR), the Health Effects Assessment Summary Tables (HEAST), the Integrated Risk Information System (IRIS), and the Registry of Toxic Effects of Chemical Substances (RTECS) (**1**)[5]. Interpretation of these information resources requires input from a qualified toxicologist.

6.2.8 Table 1 gives an example of compilation of levels of concern for selected contaminants.

6.3 Use the following approach to prioritize and select levels of concern for each analyte[6] identified from the above sources of data:

6.3.1 Since regulations applicable to the aircraft cabin environment are developed based on the knowledge and data specific to that environment, give the highest priority to levels of concern that are part of such regulations (for example, FAA Airworthiness Standards). Similarly, available consensus-developed guidelines for cabin air quality should be also given high priority because these are developed considering the effects of air pollutants on passengers and flight attendants in the aircraft cabin environment.

6.3.2 Guidelines developed for the spacecraft environment such as the SMACs developed for long-term exposures, such as the 180-day exposure period, should be considered at the next level of priority. The 180-day SMACs are based on health-effect considerations over such extended periods of time and are applicable to astronauts. These are considered as the next best alternative to cabin air quality standards or guidelines for passengers and flight attendants because the relative susceptibility of passengers (that is, general public) as compared to astronauts (that is, healthy worker population) is balanced against the duration of exposure (that is, 180-day continuous

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[4] Preparing a list of analytes of interest, if not available, requires considerable effort such as review of results of past studies on cabin air quality, assessment of sources of air contaminants, and consultation with toxicologists and health effects specialists (for example, physicians and epidemiologists) to assess potential causes of suspected or actual health effects or symptoms. As stated in the scope, the development of a list of analytes is not within the scope of this guide.

[5] The bold face numbers in parentheses refer to the list of references at the end of this standard.

[6] Although the approach given here is for individual analytes, as the understanding of health effects and the technology for instrumentation improve in the future, consideration may also need to be given to contaminants acting in toxicological groups.

TABLE 1 Compilation Table of Levels of Concern for Various Air Pollutants and Parameters

Parameters Measured	Level of Concern	Comment
CO_2	30 000 ppmv	ACGIH STEL[A]
	30 000 ppmv	FAA Airworthiness Standards (Title 14 CFR 25)
	13 000 ppmv	1-24 h to SMACs[B]
	7 000 ppmv	7-180 d SMACs[B]
	5 000 ppmv	ACGIH TLV[A] , OSHA PEL (Title 29 CFR 1910)
	1 000 ppmv	Guide 6245
CO	50 ppmv	OSHA PEL (Title 29 CFR 1910)
	35 ppmv	1-h NAAQS (Title 40 CFR 50)
	25 ppmv	ACGIH TWA[A]
	9 ppmv	8-h NAAQS (Title 40 CFR 50)
O_2	20.95 % at 2.4 km (8000 ft) cabin altitude equivalent to partial pressure of 16 kPa	FAA Airworthiness Standards (Title 14 CFR 25)
O_3	0.25 ppmv	FAA Airworthiness Standards (Title 14 CFR 25)
	0.1 ppmv	FAA Airworthiness Standards
	0.12 ppmv	1-h NAAQS (Title 40 CFR 50)
	0.1 ppmv	OSHA PEL (Title 29 CFR 1910)
	0.08 ppmv	8-h NAAQS (Title 40 CFR 50)
Particulate matter		
PM_{10}	150 µg m^{-3}	24-h NAAQS (Title 40 CFR 50)
	50 µg m^{-3}	Annual NAAQS (Title 40 CFR 50)
$PM_{2.5}$	65 µg m^{-3}	24-h NAAQS (Title 40 CFR 50)
	15 µg m^{-3}	Annual NAAQS (Title 40 CFR 50)
Organic compounds	Chemical-specific	
	~1-100 ppmv	OSHA PEL (Title 29 CFR 1910)
	to < 0.01 ppmv	SMACs[B]
	to < 0.01 ppmv	ATSDR[C]
	to < 0.01 ppmv	AIHA odor thresholds[D]
Cabin air pressure		FAA Airworthiness Standards (Title 14 CFR 25)
	75.1 kPa	2.4 km pressure altitude
	37.6 kPa	7.6 km pressure altitude

[A] Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 1997.

[B] Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants. Vols. 1-3, Committee on Toxicology, National Research Council, National Academy of Sciences, Washington, DC, 1994-96.

[C] Agency for Toxic Substances and Disease Registry (ATSDR), Minimal Risk Levels for Hazardous Substances, U.S. Public Health Service, Atlanta, GA. 1997.

[D] Odor Thresholds for Chemicals with Established Occupational Health Standards, American Industrial Hygiene Assoc., 1993.

exposure for astronauts versus intermittent exposure over much shorter periods of time for passengers or even flight attendants).

6.3.3 The next level of priority is for environmental standards such as ambient air quality standards that are developed considering health effects of exposures to air contaminants by the public.

6.3.4 The next level of priority is for standards or guidelines for occupational exposures. It should be pointed out that, while the aircraft cabin environment includes exposure of the general public (passengers) and occupational exposure (flight attendants) in the same airspace, the limits of exposure for the public should be used, as those are more stringent. The reason for stringency is that the public includes segments of more susceptible populations such as children, as compared to healthy workers that are included in considerations for occupational exposures.

6.3.5 If a workplace standard is the only basis for defining a level of concern associated with passenger exposure, then a safety factor should be considered to account for uncertainties. Sources of uncertainty include (*a*) extrapolating toxicological data from controlled animal testing to estimated health effects in humans, (*b*) extrapolating lowest-observed-adverse-effect levels (LOAEL) to a no-observed-adverse-effect level (NOAEL), and (*c*) variations in individual responses. Regulatory agencies usually require safety factor values of 10, 100, or 1000 in different situations. If the NOAEL has been derived from high-quality data in humans, then a factor less than 10 may be appropriate provided test conditions are similar to conditions under investigation. If the NOAEL is derived from less similar or less reliable studies, then a factor such as 100 or 1000 may be required (2). The selection and use of a safety factor should be done by a qualified toxicologist or health-effects specialist and the scientific rationale for the selected safety factor(s) must be documented.

6.4 Table 2 illustrates levels of concern selected based on the above approach.

7. Define Minimum Data Quality Objectives

7.1 For each analyte, specify minimum data quality objectives in terms of concentration range, method detection limit, precision, and bias.

7.1.1 Specify an upper limit of the concentration range that is at least twice the level of concern.

7.1.2 Specify the precision and bias necessary to achieve acceptable statistical confidence when comparing a measured value with the level of concern. The 99 % confidence level is commonly used as a basis for comparison. For example, given a level of concern of 100 ppmv and considering a measurement system having 10 % precision, the 99 % confidence interval (that is, 3 standard deviations) extends from 70 ppmv to 130 ppmv. Thus, a measured value of 69 ppmv would be interpreted with 99 % confidence as being below the level of concern. On the other hand, a value of 71 ppmv would be interpreted with 99 % confidence as being indistinguishable from the level of concern.

7.1.3 Specify the method detection limit (MDL) such that the MDL is well below the level of concern, considering the overall uncertainty:

$$MDL \leq \frac{LOC \times (1 - (OU/100))}{m} \quad (2)$$

where:

MDL = method detection limit,

LOC = level of concern,

OU = overall uncertainty (Eq 1), and

m = a variable whose value should be at least 2 to give sufficient ability to distinguish the level of concern from a non-detectable value (see example below).

Given a level of concern at 100 ppmv and an overall uncertainty of 30 %, for example, the level of concern minus the overall uncertainty would be at 70 ppmv. Using a value of 2 for m in Eq 2 will specify a MDL of 35 ppmv, which is about one-third of the level of concern. Using a more conservative value of 5 for m will result in a more stringent MDL of 14 ppmv.

7.1.4 When considering multiple levels of concern for a particular analyte (as could occur when interest is focused on odor threshold effects as well as compliance with regulatory criteria), use the smaller value to define the MDL, and use the larger value to define the upper limit of the concentration range.

TABLE 2 Levels of Concern Selected for Various Pollutants and Parameters

Parameters Measured	Level of Concern	Comment
CO_2	7 000 ppmv	upper
	1 000 ppmv	lower
CO	35 ppmv	upper
	9 ppmv	lower
O_2	20.9 % at 7.6 km altitude or 8 kPa partial pressure	upper
	20.9 % at 2.4 km altitude or 6 kPa partial pressure	lower
O_3	0.25 ppmv	upper
	0.08 ppmv	lower
PM_{10}	150 µg m^{-3}	upper
	50 µg m^{-3}	lower
$PM_{2.5}$	65 µg m^{-3}	upper
	15 µg m^{-3}	lower
Organic compounds	Chemical-specific	
	~100 ppmv	upper
	< 0.01 ppmv	lower
Cabin air pressure	101.3 kPa	upper
	37.6 kPa	lower

8. Define Desirable Operating Characteristics

8.1 Define desirable operating characteristics for equipment based on practical details of the monitoring objectives as well as the level of experience, resources, and facilities available to the performing organization. Consider the following factors in making final decisions regarding selection of instrumentation and methods:

8.1.1 Mode–active (requiring a pump or aspirator to convey sample) or passive (relying on diffusion),

8.1.2 Output–continuous, point-in-time, or time-weighted average,

8.1.3 Record–electronic signal, field observation, or laboratory report,

8.1.4 Mobility–handheld (< 1kg), portable (< 5kg), or stationary (>5kg),

8.1.5 Power–battery, standard alternating current, or mechanical,

8.1.6 Calibration–standard atmospheres, co-located references, laboratory procedures or factory procedures, or both, and

8.1.7 Ancillary Data–temperature, relative humidity, and air pressure may be required to adjust data to a common basis (for example, sea-level equivalent).

8.2 All electronic equipment operated in the aircraft cabin must be certified for electromagnetic compatibility with avionic systems (see, for example, RTCA/DO-160).

8.3 Instrumentation selected for aircraft cabin monitoring must be sufficiently stable to allow for acceptable operation for 8 or more h. Calibrations and zero/span checks may be conducted in a ground facility before and after a flight. Calibrations generally are not performed aboard the aircraft because the use of pressurized gases and the handling of toxic materials is prohibited in the aircraft cabin.

8.4 All electronic equipment taken aboard the aircraft must be sufficiently stable to be turned off during ascent and descent without loss of calibration.

8.5 At a minimum, cabin pressure should be monitored to permit correcting data for reduced air density at altitude. Special equipment and procedures may be required to verify correction factors for some technologies. It should be noted that simple pressure-altitude corrections are not sufficient since monitoring technologies such as non-dispersive infra red (NDIR) have a systematic error caused by pressure differences which need to be addressed.

9. Select Instruments and Test Methods

9.1 For each analyte, identify available instruments and test methods using data quality objectives and operating characteristics, as described below.

9.2 For commonly monitored pollutants, select from the technologies listed in Tables 3-11 which give examples of technologies for each pollutant or pollutant group. These tables include a wide range of technologies to give readers a feel for what is available. Several of these technologies are appropriate for use in measuring cabin air quality. Those that are clearly not appropriate are so indicated in these tables. A set of recommendations are offered in a later section.

9.3 For analytes not covered by Tables 3-11, consult ASTM standard test methods as well as compilations published by organizations such as USEPA (**3**, **4**), NIOSH (**5**), and other publications (**6**, **7**, **8**, **9**, **10**) to identify instruments and test methods.

9.4 If available equipment does not meet one or more data quality objectives, then select technologies of lesser capabilities provided that changes to the affected data quality objectives do not increase statistical uncertainty to unacceptable levels.

9.4.1 It should be recognized that relationships defined in 7.1.2 and 7.1.3 using the level of concern to determine instrument performance represents an ideal that practical instrumentation sometimes cannot meet.

9.4.2 Less-than-ideal performance can be accommodated by accepting reduced statistical confidence or by reappraising measurement objectives. Given a level of concern at 100 ppmv, for example, the 99 % confidence interval for an instrument or method characterized by ±20 % precision and bias would extend from 40 ppmv to 160 ppmv while the 90 % confidence interval would extend from 66 ppmv to 134 ppmv. Such a method or instrument would be acceptable for objectives focused on determining whether or not environmental concentrations exceed the level of concern, but results may be unacceptable if objectives seek definitive statements regarding low concentrations.

9.4.3 Collecting replicate samples and averaging results can reduce statistical uncertainty associated with time-weighted-average samples.

9.5 For each monitoring technology identified as meeting data quality objectives, evaluate operating characteristics compared to desirable characteristics listed under Section 8.

9.5.1 Portable and handheld monitoring systems featuring battery-power are generally preferred over larger and heavier stationary systems that require alternating current.

9.5.2 Monitoring systems featuring continuous output are generally preferred for monitoring objectives that involve examining the impacts of short-term and episodic sources.

9.5.3 Monitoring systems designed to collect samples for subsequent analysis in the laboratory are generally preferred for monitoring objectives that involve examining time-weighted average concentrations.

TABLE 3 Operating Characteristics of Instrumentation and Methods for Monitoring Aldehydes and Ketones

Technology	Guidance	Comments
Sorbent Tube – sample gases are collected using a cartridge with DNPH-coated sorbent that is returned to the laboratory for analysis of individual compounds by HPLC.	Test Method D5197 EPA Methods[A,B] Range: 0.01-5 ppmv Bias: ± 10 % Precision: ± 10 % MDL: 0.0005 ppmv	Field apparatus is compact. Requires external pump. Requires sophisticated laboratory. O_3 at high concentrations interferes negatively. Approximate costs: <$15 per tube plus pump (~$500) and laboratory analysis ($100 to $1000).
Liquid Impingement - sample is absorbed in DNPH solution and returned to the laboratory for analysis of individual compounds by HPLC.	EPA Methods[B] Range: 0.01-5 ppmv Bias: ± 10 % Precision: ± 10 % MDL: 0.0005 ppmv	Field apparatus is compact, but requires liquid-filled impinger. Requires external pump. Requires sophisticated laboratory. O_3 at high concentrations interferes negatively. Approximate costs: ~$50 for impinger plus pump (~$500) and laboratory analysis (~ $100). Impractical for use in aircraft passenger cabins.
Colorimetric Tube - - sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of a specific aldehyde or ketone; length of color stain is correlated with concentration.	Practice D4490 Range: 0.2-100 ppmv Bias: ± 25 % Precision: - - MDL: - -	Requires external air pump (may be hand-powered). Disposable system (single use) that relies on factory calibration. Resolution is generally lower than other technologies. Separate type of tube required for each aldehyde and ketone of interest. Approximate costs: $10 per tube plus pump (~$300). Inappropriate for quantitative measurements of cabin air quality.

[A] *Compendium of Methods for the Determination of Air Pollutants in Indoor Air*, Report No. EPA/600/4-90/010. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1990.

[B] *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1988.

TABLE 4 Operating Characteristics of Instrumentation and Methods for Monitoring Carbon Dioxide

Technology	Guidance	Comments
Non-dispersive infrared (NDIR) spectrometry – absorption of infrared radiation by CO_2 in a sample cell is compared to that of a reference (CO_2-free) absorption cell	OSHA ID-172 Woebkenberg[A] Range: 20-20,000 ppmv Bias: ± 50 ppm Precision: ± 50 ppm MDL: 200 ppmv	Very specific for CO_2; portable units are available. Some units require an external pump. Approximate costs: \$500 (handheld) \$5 000 to \$ 10 000 (portable or stationary).
Colorimetric Tube – sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of CO_2; length of color stain is correlated with concentration	Practice D4490 Range: 100-200,000 ppmv Bias: ± 25 % Precision: - - MDL: - -	Requires external air pump (may be hand-powered). Disposable system (single use) that relies on factory calibration. Resolution is generally lower than other technologies. Approximate costs: \$10 per tube plus pump (~\$300). Inappropriate for quantitative measurements of cabin air quality.

[A] Woebkenberg, M.L., and McCammon, C.S., "Direct-Reading Gas and Vapor Instruments." *Air Sampling Instruments,* B.S. Cohen and S.V. Hering, eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 1995, pp. 439-510.

TABLE 5 Operating Characteristics of Instrumentation and Methods for Monitoring Carbon Monoxide

Technology	Guidance	Comments
Electrochemical – sample air is passed through a cell wherein oxidation of CO produces a signal that is proportional to concentration.	Nagda et al.1989[A] Woebkenberg[B] Range: 1-100 ppmv Bias: ± 5 % Precision: ± 5 % MDL: < 1 ppmv	Can be very specific for CO; portable units are available. Specificity is achieved by inlet scrubber of uncertain efficiency for some chemicals. Approximate costs: \$500 (handheld) \$5 000 to \$10 000 (portable or stationary)
Non-dispersive infrared (NDIR) spectrometry – absorption of infrared radiation by CO in a sample cell is compared to that of a reference (CO-free) absorption cell.	Test Method D3162 EPA 40CFR53 Woebkenberg[B] Range: <1-100 ppmv Bias: ± 10 % Precision: ± 10 % MDL: 0.5 ppmv	Very specific for CO, EPA reference-grade measurement. Approximate costs: \$5 000 to \$10 000 (portable or stationary).
Colorimetric tube – sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of CO; length of color stain is correlated with concentration.	Practice D4490 Range: 5-100 000 ppmv Bias: ± 25 % Precision: - - MDL: - -	Requires external air pump (may be hand-powered). Disposable system (single use) that relies on factory calibration. Resolution is generally lower than other technologies. Approximate costs: \$10 per tube plus pump (~\$300). Inappropriate for quantitative measurements of cabin air quality.

[A] Nagda, N.L., Fortmann, R.C., Koontz, M.D., Baker, S.R., and Ginevan M.E. Airliner Cabin Environment: Contaminant Measurements, Health Risks, and Mitigation Options. Report No. DOT-P-15-89-5. U.S. Department of Transportation, Washington, DC, 1989.

[B] Woebkenberg, M.L., and McCammon, C.S., "Direct-Reading Gas and Vapor Instruments." *Air Sampling Instruments,* B.S. Cohen and S.V. Hering, eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 1995, pp. 439-510.

9.5.4 Not withstanding the considerations given in 9.5.1-9.5.3 related to operating characteristics, the first and foremost consideration should be toward meeting the primary requirements of detection limit, precision and accuracy. Thus, a heavier or nonportable equipment that meets these requirements would be preferred to a portable, battery powered instrument that does not satisfy the primary requirements.

9.6 Evaluate appropriateness of the measurement instruments and methods for suitability of their use in commercial aircraft cabins. For example, instruments requiring continuous gas supply are not appropriate as pressurized gas cylinders are not permitted on aircraft. For conducting measurements on passenger flights, the equipment should be safe for operating in the cabin environment, non-intrusive, and self sufficient in terms of power requirements. For ground testing or testing on non-revenue test flights, stationary or bench-top instruments may be appropriate, as 110–v power supply can be available.

9.7 *Document Final Decisions*—At a minimum, the measurement systems selection report should address the following topics:

9.7.1 *Monitoring Objectives*—Describe the purpose of the measurements and describe the analytes selected for measurement.

9.7.2 *Levels of Concern*—Summarize the basis for selecting levels of concern for each analyte.

9.7.3 *Data Quality Objectives*—For each analyte, summarize the basis for specifying concentration range, detection limit, precision, and bias.

9.7.4 *Selections*—Summarize the basis for selecting each test method and equipment item.

TABLE 6 Operating Characteristics of Instrumentation and Methods for Monitoring Oxygen Partial Pressure

Technology	Guidance	Comments
Paramagnetism – magnetic resistance of the air path within a closed magnetic circuit varies in proportion to the O_2 concentration	Range: 0-100 % O_2 Bias: ± 0.02 % O_2 Precision: ± 0.03 % O_2 MDL: - -	No standard methods exist. Technology is very specific for oxygen; requires correction for air pressure; suited for ″long-life″ applications because no chemical reactions are involved. Calibration can only be verified against ambient air under field conditions. Approximate costs: \$5 000 to \$10 000 (portable or stationary).
Electrochemical – sample air is passed through a cell wherein reduction procedures a signal that is proportional to O_2 concentration.	Woebkenberg[A] Range: 0-25 % O_2 Bias: ± 2 % FS Precision: - - MDL: - -	No standard methods exist. Externally applied voltage and inert electrodes permits nondegradeable operation. Calibration can only be verified against ambient air under field conditions. Approximate costs: \$500 (handheld) \$5 000 to \$10 000 (portable or stationary).
Colorimetric Tube – sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of O_2; length of color stain is correlated with concentration.	Practice D4490 Range: 5-23 % Bias: ± 25 % Precision: - - MDL: - -	No standard methods exist. Requires external air pump. Disposable system (single use) that relies on factory calibration. Resolution is generally lower than other technologies. Approximate costs: \$10 per tube plus pump (~\$300). Inappropriate for quantitative measurements of cabin air quality.

[A] Woebkenberg, M.L. and McCammon, C.S., "Direct-Reading Gas and Vapor Instruments, *Air Sampling Instruments*, B.S. Cohen and S.V. Hering, eds, American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH,1995, pp 439-510.

TABLE 7 Test Methods Operating Characteristics of Instrumentation and Methods for Monitoring Ozone

Technology	Guidance	Comments
UV absorption photometry – absorption of ultraviolet radiation by O_3 is compared to absorption in an ozone-free (reference) cell.	Test Methods D5156 EPA 40CFR53 Woebkenberg[A] Range: 1-1 000 ppbv Bias: ± 10 % Precision: ± 10 % MDL: 1 ppbv	Very specific for O_3. Commercially available units are generally too expensive and bulky for portable operation. One prototype system has been developed and tested for radiosonde operation[B] . Approximate costs: \$5 000 to \$10 000.
Chemiluminescence – light produced by gas phase reaction between O_3 and ethylene is measured.	Test Method D5149 EPA 40CFR53 Woebkenberg[A] Range: 1-1,000 ppbv Bias: ± 10 % Precision: ± 10 % MDL: 1 ppbv	Very specific for O_3. Commercially available units are generally too expensive and bulky for portable operation. Requires supply of ethylene for photochemical reaction. Ethylene is highly flammable and, thus, is unsuitable for use. Approximate costs: \$5 000 to \$10 000.
Electrochemical – sample air is passed through a cell wherein ozone-specific reactions produce a signal that is proportional to concentration.	Woebkenberg[A] Range: 30- 1000 ppbv Bias: ± 10 % Precision: ± 10 % MDL: 30 ppbv	Portable units available. Electrochemical cells may exhibit sensitivity to changes in pressure and humidity. May be inadequate at lower concentrations. Approximate costs: \$500 (handheld) \$5 000 to \$10 000 (portable or stationary).
Dry Colorimetry – sample air passes through a paper tape impregnated with analyte-specific dry reagent system; photometrically measured color change is in direct proportion to concentration.	Woebkenberg[A] Range: 31-300 ppbv Bias: ± Precision: ± 5 % MDL: 31 ppbv	Portable units available. System can be reconfigured for up to 50 different gases by changing to other reagent-impregnated tapes. May be inadequate at lower concentrations. Approximate costs: \$5 000 to \$10 000 (portable or stationary).
Colorimetric Tube – sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of O_3; length of color stain is correlated with concentration.	Practice D4490 Range: 50-300 000 ppbv Bias: ± 25 % Precision: - - MDL: - -	Requires external air pump (may be hand-powered). Disposable system (single use) that relies on factory calibration. Resolution is generally lower than other technologies. Approximate costs: \$10 per tube plus pump (~\$300). Inappropriate for quantitative measurements of cabin air quality.

[A] Woebkenberg, M.L., and McCammon, C.S., "Direct-Reading Gas and Vapor Instruments", *Air Sampling Instruments*, B.S. Cohen and S.V. Hering, eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 1995, pp. 439-510.

[B] Bognar, J.A. and Birks, J.W., *Analytical Chemistry*, Vol 68, 1996, pp. 3059-3062.

TABLE 8 Operating Characteristics of Instrumentation and Methods for Monitoring Particulate Matter

Technology	Guidance	Comments
Optical Backscattering – aerosol mass is measured based on backscatter from a calibrated light source probing a characteristic sample volume.	Nagda et al.[A] Pui and Swift[B] Range: to mg m^{-3} Bias: ± 10 % Precision: ± 10 % MDL: 10 μg m^{-3}	Requires aerosol-specific calibration; size selective monitoring requires external air pump and aerodynamic inlet. Approximate costs: $1 000 to $5 000 (handheld).
Gravimetric – sample air is accelerated through one or more stages of an inertial impactor to separately deposit size fractions. Aerosol mass is determined by weighing tared substrate in the laboratory.	EPA 40CFR53 Hering[C] Range: to mg m^{-3} Bias: ± 10 % Precision: ± 10 % MDL: 10 μg m^{-3}	Can be configured for inhalable (10 μm) and respirable (2.5 μm) size ranges. Requires external air pump. Requires laboratory support for mass determination. Approximate costs: $100 for inlet for plus pump (~$500) and laboratory analysis (< $ 100).
Beta Attenuation – sample air is accelerated through a size selective inlet to deposit aerosols onto a glass fiber filter tape. Aerosol mass is determined from attenuation of low level β rays.	EPA 40FCFR53 Pui and Swift[B] Range: to mg m^{-3} Bias: ± 10 % Precision: ± 10 % MDL: 10 μg m^{-3}	Can be configured for inhalable (10 μm) and respirable (2.5 μm) size ranges. Radiation license and laboratory safety plan may be required. Approximate costs: $5 000 to $10 000 (portable or stationary).

[A] Nagda, N.L., Fortmann, R.C., Koontz, M.D., Baker, S.R., and Ginevan M.E., Airliner Cabin Environment: Contaminant Measurements, Health Risks, and Mitigation Options. Report No. DOT-P-15-89-5, U.S. Department of Transportation, Washington, DC, 1989.

[B] Pui, D.Y.H. and Swift, P.L. "Direct-Reading Instruments for Airborne Particles", *Air Sampling Instruments*, B.S. Cohen and S.V. Hering, eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 1995, pp. 337-368.

[C] Hering, S.V. Impactors, Cyclones, and Other Inertial and Gravitational Collectors, *Air Sampling Instruments*, B.S. Cohen and S.V. Hering, eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 1995, pp. 279-321.

10. General Recommendations for Selecting Instruments

10.1 Specify the upper limit of the concentration range to reach values at least twice the level of concern.

10.2 Specify the precision and bias to achieve an acceptable statistical uncertainty interval when comparing a measured value with the level of concern.

10.3 Specify the method detection limit such that when considered with the precision and bias, the lower bound of the 99 % statistical confidence interval for a measured value in the vicinity of the level of concern is at least a factor of ten greater than the method detection limit.

10.4 Table 12 gives technologies that may be appropriate for further consideration in selecting instruments and test methods for measuring air quality aboard aircraft cabins.

10.5 Document final decisions. At a minimum, the measurement systems selection report should address test objectives, levels of concern, data quality objectives, and the underlying rationale for selecting individual equipment items.

11. Keywords

11.1 active sampling; aircraft; bias; air quality; cabin; concentration range; data quality objectives; instrumentation; level of concern; method detection limit; occupational exposure; operating characteristics; passive sampling; precision; public exposure; test methods

TABLE 9 Operating Characteristics of Instrumentation and Methods for Monitoring Volatile Organic Compounds

Technology	Guidance	Comments
Canister Collection – sample gases are collected into a passivated stainless steel container that has been previously evacuated and then returned to laboratory for analysis of individual compounds by GC/MS.	Test Method D5466 EPA Methods[A] Range: to high ppmv Bias: ± 25 % Precision: ± 25 % MDL: <0.001 ppmv	Evacuated canister may be filled passively or using a pump. Requires sophisticated laboratory and careful attention to cleaning canister prior to reuse. Extremely low humidity may affect recovery of some VOCs.[B] Canister volume (up to 6L) affects field logistics. Approximate costs: $500 for canister plus laboratory analysis ($100 to $500).
Sorbent Tube – sample gases are collected onto a granular sorbent and then returned to laboratory for thermal desorption and analysis by GC/MS.	Practice D6196 EPA Methods[A,C] Range: to high ppmv Bias: ± 25 % Precision: ± 25 % MDL: <0.001 ppmv	Sample collection requires different types of sorbents for polar, nonpolar compounds. Commercially available sorbent tubes may be packed with up to 3 different sorbents. Sorbent tubes can be reused after reconditioning in thermal desorber with attention to quality control. Sample collection requires external pump. Technology requires sophisticated laboratory. Approximate costs: up to $50 for sorbent tube plus pump (~500) and laboratory analysis ($100 to $500).
Bag Collection – sample gases are collected into a polymeric bag and then returned to laboratory for analysis of individual compounds by GC/MS.	EPA Methods[C] Range: to high ppmv Bias: ± 25 % Precision: ± 25 % MDL: <0.001 ppmv	Bag volume (up to 100 L) affects field logistics. Sample losses due to permeation and formation of artifacts are commonly observed. Bags should not be reused for sampling low concentration environments. Approximate costs: up to $50 for bag plus pump (~500) and laboratory analysis ($100 to $500). Due to changes in pressures experienced in a cabin environment, the possibility of sample losses is magnified and thus this method is inappropriate for cabin air quality sampling.
Portable GC – Sample gases are delivered to a chromatographic column for separation and detection of individual VOCs.	Woebkenberg[D] Range: to high ppmv Bias: ± 25 % Precision: ± 25 % MDL: <0.001 ppmv	Technology may not be easily optimized for some compounds of interest. Most commercially available units require a pressurized source of carrier gas. Hydrogen carrier gas is unsuitable for use in aircraft cabins. Operator training required. Approximate costs: $10 000 to $50 000.
Fourier Transform Infrared Spectroscopy – sample gases are introduced into a chamber wherein absorption in specific IR wavelengths is measured acoustically.	Woebkenberg[D] Range: to high ppmv Bias: - - Precision: ±1 % (FS) MDL: <0.001 ppmv	May be configured for any IR-absorbing gas. Sensitivity and selectivity for some gases is limited. Operator training required. Approximate costs: $10 000 to $50 000.
Infrared Absorption Spectroscopy – sample gases are introduced into a chamber wherein absorption in specific IR wavelengths is measured.	Woebkenberg[D] Range: to high ppmv Bias: - - Precision: ±1 % (FS) MDL: <0.001 ppmv	May be configured for any IR-absorbing gas. Sensitivity and selectivity for some gases is limited. Operator training required. Approximate costs: $10 000.
Colorimetric Tube – sample gases are drawn through a chemically treated sorbent bed that changes color in the presence of the target VOC; length of color stain is correlated with concentration.	Practice D4490 Range: Varies by Chemical Bias: ± 25 % Precision: - - MDL: - -	Requires external air pump (may be hand-powered). Disposable system (single use) that relies on factory calibration. Resolution is generally lower than other technologies. Separate type of tube required for each VOC of interest. Approximate costs: $10 per tube plus pump (~$300). Inappropriate for quantitative measurements of cabin air quality.

[A] *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*, Report No. EPA/600/R-96/010b, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1996.

[B] *NIOSH Manual of Analytical Methods*, Publication 94-113, 4th ed., Department of Health and Human Services, National Institute of Occupational Safety and Health, Washington, DC, 1994.

[C] *Compendium of Methods for the Determination of Air Pollutants in Indoor Air*. Report No. EPA/600/4-90/010. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1990.

[D] Woebkenberg, M.L., and McCammon, C.S., "Direct-Reading Gas and Vapor Instruments," *Air Sampling Instruments,* B.S. Cohen and S.V. Hering, eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 1995, pp. 439-510.

TABLE 10 Operating Characteristics of Instrumentation and Methods for Monitoring Semi Volatile Organic Compounds

Technology	Guidance	Comments
Sorbent Tube – sample collected on polyurethane foam (PUF) cartridge that is returned to laboratory for analysis of individual compounds by GC/FID, GC/MS, or HPLC.	Practice D4861 EPA Methods[A,B] Range: to high ppmv Bias: ± 25 % Precision: ± 25 % MDL: <0.001 ppmv	Collects particle-bound and gas phase; field apparatus is compact. Requires external pump. Requires sophisticated laboratory. Approximate costs: $70 for PUF tube plus pump (~500) and laboratory analysis ($100 to $500).

[A] *Compendium of Methods for the Determination of Air Pollutants in Indoor Air*, Report No. EPA/600/4-90/010, U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 1990.

[B] *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1988.

TABLE 11 Operating Characteristics of Instrumentation and Methods for Monitoring Cabin Air Pressure

Technology	Guidance	Comments
Electronic Altimeter – deflection of a diaphragm sealed against a constant pressure is sensed electronically; signal is proportuional to barometric pressure.	Test Method D3631 Range: 60 - 110 kPa Bias: ± 50 Pa Precision: ± 50 Pa MDL:	Temperature compensation is required, and may be integrated into electronics. Approximate costs: $500 to $1 000.
Aneroid Altimeter – deflection of an evacuated elastic capsule is mechanically amplified for registry on a dial as barometric pressure.	Test Method D3631 Range: 60 - 110 kPa Bias: ± 50 Pa Precision: ± 50 Pa MDL:	Temperature compensation is necessary. Approximate costs: $500 to $1 000.

TABLE 12 Examples of Recommendations for Selection of Technologies for Measuring Air Quality in Aircraft Cabins

Pollutant	Measurement Technology	Comment
Aldehydes and ketones	sampling on DNPH-coated sorbent tube followed by HPLC analysis	Meets DQOs and is portable and practical; liquid impingement followed by HPLC analysis also meets DQOs but is less practical.
CO_2	non-dispersive infrared (NDIR) spectrometry	Meets DQOs, is portable and practical.
CO	electrochemical	Meets DQOs; portable NDIR units more desirable but not available.
O_2 Partial pressure	paramagnetism or electrochemical	Paramagnetism preferred on technical grounds but is more expensive and requires pressure correction.
O_3	UV absorption photometry	Meets DQOs; there is no commercially available portable instrument; chemiluminescence technology also meets DQOs but is not practical since it requires a supply of ethylene
PM_{10} and $PM_{2.5}$	optical backscattering	Meets DQOs, is portable and practical; gravimetric method would not meet DQOs because sufficient mass may not be collected during a typical flight.
Volatile organic compounds	canister collection or sorbent tubes followed by GC/MS analysis	Both meet DQOs; sorbent tubes are applicable to sampling and analysis of a wider range of VOCs than canisters, but require a pump. Canisters are applicable to collection of very volatile compounds, many non-polar VOCs, and selected polar VOCs. The performance of VOC sampling methods should be evaluated for the expected range of VOCs before use.
Semi-volatile organic compounds	polyurethane foam cartridge followed by GC/MS analysis	Meets DQOs, is portable and practical.
Cabin air pressure	electronic or aneroid	Meets DQOs, is portable and practical.

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