International Standard

ISO/ASTM 52933

First edition
2024-03

Additive manufacturing — Environment, health and safety — Test method for the hazardous substances emitted from material extrusion type 3D printers in the non-industrial places

Fabrication additive — Environnement, santé et sécurité — Méthode d'essai pour les substances dangereuses émises par les imprimantes 3D de type à extrusion de matière dans les lieux non industriels

Reference number
ISO/ASTM 52933:2024(en)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

ASTM International
100 Barr Harbor Drive, PO Box C700
West Conshohocken, PA 19428-2959, USA
Phone: +610 832 9634
Fax: +610 832 9635
Email: khooper@astm.org
Website: www.astm.org

Published in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had/had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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.

The committee responsible for this document is ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM Committee F42, *Additive Manufacturing Technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on Additive Manufacturing, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

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 refers to the assessment of hazardous substances emitted during operation of material extrusion type AM machines, commonly known as “3D printers” installed in schools or public places for educational and hands-on purposes, and basic countermeasures for reducing the substances.

This document provides the necessary information and test procedures to reflect the characteristics of the AM process based on the previous international standards related to indoor air quality and to assess hazardous substances in the non-industrial places.

Operator, supervisor, and manager who are working at the non-industrial places will be able to use this document to measure and diagnose air quality. This document also includes appendices to help them try to reduce the hazardous substances emitted into the non-industrial spaces.

Additive manufacturing — Environment, health and safety — Test method for the hazardous substances emitted from material extrusion type 3D printers in the non-industrial places

1 Scope

This document specifies a test method for measuring hazardous substances emitted during the operation of material extrusion type AM machines commonly used in the non-industrial places and includes non-normative suggestions for ways to reduce them.

This document specifies some of the main hazardous substances emitted from this type of machine during operation for currently commonly used materials, it describes the additional information and the associated test method for measuring hazardous substances, and includes considerations for reducing the hazardous substances and basic countermeasures.

This document specifies how to measure concentrations of hazardous substances generated in the non-industrial places (school, public place and so on) in which this type of machines are installed, and to maintain an acceptable work environment by managing field facilities, machines, filaments, and additive manufactured products for the reduction of hazardous substances.

However, this document does not cover all gas-phase chemical emissions. Only a range of Volatile Organic Compounds (VOCs) from n-hexane to n-hexadecane, including aldehydes are included. Considerations for reducing chemical emissions and for improving the work environment are given in Annexes A and B.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16000-2, *Indoor air — Part 2: Sampling strategy for formaldehyde*

ISO 16000-3, *Indoor air — Part 3: Determination of formaldehyde and other carbonyl compounds in indoor and test chamber air — Active sampling method*

ISO 16000-4, *Indoor air — Part 4: Determination of formaldehyde — Diffusive sampling method*

ISO 16000-5, *Indoor air — Part 5: Sampling strategy for volatile organic compounds (VOCs)*

ISO 16000-6, *Indoor air — Part 6: Determination of organic compounds (VVOC, VOC, SVOC) in indoor and test chamber air by active sampling on sorbent tubes, thermal desorption and gas chromatography using MS or MS FID*

ISO 16017-1, *Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 1: Pumped sampling*

ISO 16017-2, *Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 2: Diffusive sampling*

ISO 16200-1, *Workplace air quality — Sampling and analysis of volatile organic compounds by solvent desorption/gas chromatography — Part 1: Pumped sampling method*

ISO 16200-2, *Workplace air quality — Sampling and analysis of volatile organic compounds by solvent desorption/gas chromatography — Part 2: Diffusive sampling method*

ISO/TR 27628, *Workplace atmospheres — Ultrafine, nanoparticle and nano-structured aerosols — Inhalation exposure characterization and assessment*

ISO 28439, *Workplace atmospheres — Characterization of ultrafine aerosols/nanoaerosols — Determination of the size distribution and number concentration using differential electrical mobility analysing systems*

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions from ISO/ASTM 52900 and the following are applied.

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
volatile organic compound
VOC
organic compound that is emitted from the test specimen and all those detected in the chamber outlet air

Note 1 to entry: Due to practical reasons to be taken into account for test chambers, this definition differs from that defined in ISO 16000-6:2004. In ISO 16000-6, the definition is based on the boiling point range (50 °C to 100 °C) to (240 °C to 260 °C).

Note 2 to entry: The emission test method described in ISO 16000-9 is optimum for the range of compounds specified by the definition of total volatile organic compounds (TVOC).

[SOURCE: ISO 16000-9:2006, 3.15]

3.2
aldehydes
organic compounds containing formyl families

Note 1 to entry: Formaldehyde, acetaldehyde and vanillin are members of aldehyde families.

[SOURCE: ISO 21366:2019, 3.8]

3.3
ultrafine particles
UFP
particles with a particle diameter less or equal 0,1 µm

[SOURCE: ISO/IEC 28360-1:2021, 4.36]

3.4
breakthrough volume
volume of test atmosphere that can be passed through a sorbent tube before the concentration of eluting vapour reaches a predefined limit value of the applied test concentration

Note 1 to entry: For hazardous substances in air, 5 % of the applied test concentration is a generally applied limit value.

[SOURCE: ISO 16017-1:2000, 3.1, modified — The definition was slightly reworded.]

3.5
active sampling
active sampling method in which sampling for collecting chemical substances is performed within an hour

3.6
real-time sampling
real-time sampling method in which measuring the total number concentration of aerosol particles is performed consecutively

4 Hazardous substance targets and major factors

VOCs, aldehydes, and UFP are currently identified as some of the potentially hazardous substances emitted during operation of material extrusion type AM machines in schools and public places. The material extrusion type AM machines which are currently used for AM process with filaments (ABS, PA, PC, etc.) can change the concentration of hazardous substances depending on the process and environment of the non-industrial places. The risk of each hazardous substance can be confirmed by referring to the hazard statement of the MSDS of the substance.

Since the following factors can increase the concentration of hazardous substances in that place, appropriate countermeasures are needed. See Annex A for information on considerations to reduce the emission concentrations of hazardous substances in the non-industrial place.

The factors are specified as follows:

— printer-related factors (e.g. design - open frame, enclosed);

— feedstock-related factors (e.g. type of polymer, colour, infill materials);

— process-related factors (e.g. extruder temperature, bed temperature, infill density);

— environmental-related factors (e.g. room size, presence of doors/windows, ventilation, temperature, humidity).

5 Relevant test standards

This document covers three main classes (VOCs, aldehydes, and UFP) of hazardous substances that can be emitted in case of using material extrusion type 3D printers and filaments. Table 1 provides a list of these hazardous substances and the recommended sampling strategy and test methods for their analysis in a workplace or indoor environment. Users should be aware that each type of emission can vary individually depending on the duration of machine operation, type of filaments, temperature, humidity of the place, etc. As such they shall each be monitored individually and proper care should be taken to ensure the monitoring plan covers the worst-case scenarios. Currently, there is no test method to measure VOCs, aldehydes, and UFP simultaneously or for an extended period (such as the entire additive manufacturing process). Therefore, the non-industrial places where material extrusion type 3D printers are in operation require an integrated analysis method to monitor each substance that is relevant to the process.

Table 1 — Relevant test standards for some hazardous substances

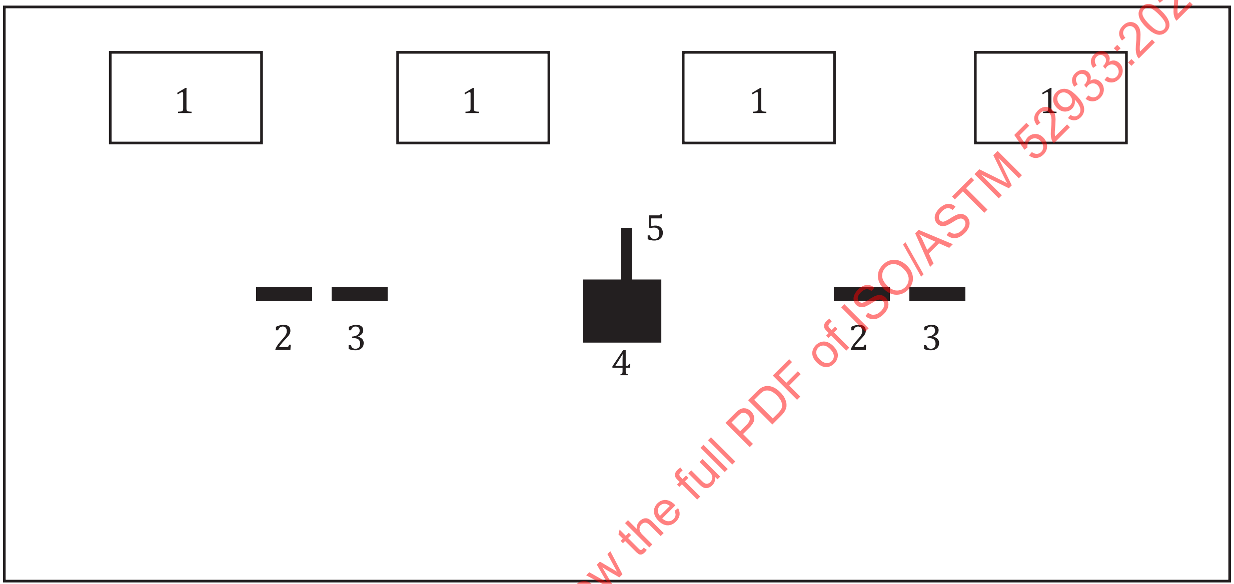
Requirements	VOCs	Aldehydes	UFPs
Sampling method	ISO 16000-5 ISO 16000-6 ISO 16017-1 ISO 16017-2 ISO 16200-1	ISO 16000-2 ISO 16000-3 ISO 16000-4 ISO 16200-2	ISO/TR 27628 ISO 28439
Analysis method	ISO 16000-6 ISO 16017-1 ISO 16017-2	ISO 16000-4	ISO/TR 27628 ISO 28439

6 Sampling conditions

6.1 Sampling location

Sampling of hazardous substances during the AM process shall be carried out simultaneously and the VOCs, aldehydes sampler and the UFP analysis equipment shall be placed in separate spaces to sample each of the substances. Figure 1 shows an example of one possible spacing of samplers relative to 3D printers. Two VOCs and aldehyde sampler shall be installed for cross-check. In addition, the sampler location is usually installed at the centre of the non-industrial place and is installed at 1,0 m to 1,8 m height from the floor.

UFP sampling tube shall consist of a conductive silicon tube or stainless steel, not exceeding 3 m in length, and avoid bends in the tube.



Key

1 material extrusion 3D printer (example)

2 VOCs sampler

3 aldehyde sampler

4 UFP analytical equipment

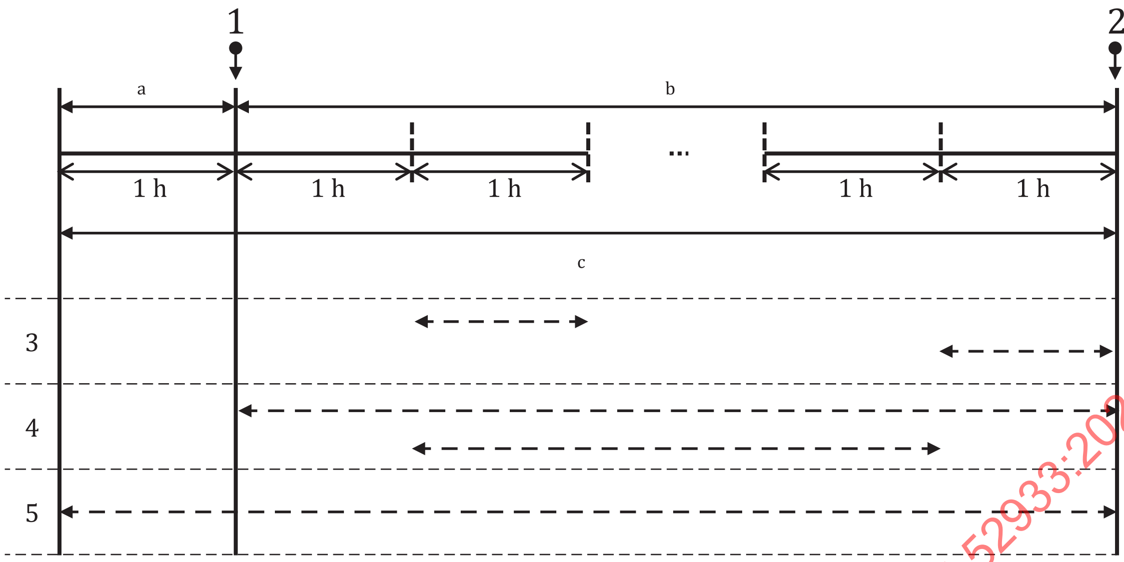
5 UFP sampling tube

Figure 1 — Schematic diagram of the non-industrial place for sampling strategy

In case of UFP analytical equipment that condenses nanoparticles by using butanol, isopropanol, and other organic solutions, the substances can be spontaneously volatilized in the non-industrial place while the equipment is in operation. Accordingly the final concentration of VOCs would be affected. Therefore, UFP analytical equipment that uses organic solvents, should be placed outside the additive manufacturing site, ensuring no occurrence of cross-contamination from outside.

6.2 Sampling planning

The sampling conditions need requirements shown in Figure 2 according to the active, time-integrated and real-time sampling methods.



Key

1 start to operate the 3D printer
2 suspend the 3D printer
3 example of active method
4 example of time-integrated method
5 example of real-time method
a Pre-operation phase.
b Operation phase.
c Sampling phase.

Figure 2 — Sampling planning in the non-industrial place

a) Pre-operation phase

As a preparation step for feeding the filament before the operation of the 3D printer, it is necessary to open doors and windows and operate the ventilation system for 60 min or longer to emit the toxic substances released from this process. If external air quality is rather suspicious, the place should be ventilated through a forced circulation way or mechanical circulation equipment instead of opening the windows.

b) Operation phase

In the operation phase, where the 3D printers are running, all doors and windows shall be closed to prevent the external air from coming in. If there is a ventilation system or a heating or cooling facility in the non-industrial place, run the printer under the same condition as usual. However, if the test is expected to be conducted under the most adverse condition in the non-industrial place, the ventilation and air conditioning systems can be shut down during the evaluation.

c) Sampling phase

In this phase, each of the hazardous substances is sampled. This phase is divided into active, time-integrated, and real-time sampling methods according to the sampling strategy:

— active method.

The sampling of VOCs and aldehydes is performed only for one hour in a specific phase among the operation phase b) during the 3D printer operation.

— time-integrated method.

The sampling of VOCs and aldehydes is performed consecutively at one hour intervals in operation phase b) after the 3D printer is operated.

— real-time methods.

To measure the amount of UFP generated during operation, start collecting gases from phase a) to phase b) consecutively and perform collecting for more than 30 min after suspending the 3D printers.

7 Measurement methods

7.1 Active and time-integrated methods

7.1.1 Purpose

The active and time-integrated methods are intended to measure VOCs and aldehydes. Active sampling method using pumps and sorbent is recommended for assessing the highest concentration of hazardous substances or a specific concentration during operation. The method of active sampling was selected based on ISO 16000-6, ISO 16017-1, and ISO 16000-3.

7.1.2 VOCs analysis

7.1.2.1 Sampling

Connect Tenax ® TA[1)] as a sorbent tube, to a pump that is capable of collecting VOCs at a constant speed of (50 to 200) ml/min and install the sampler according to 6.1 For time-integrated method, collect vapours at a flow rate of (50 to 80) ml/min consecutively on an hourly basis. For a active method, collect vapours at the same flow rate only for one hour within the operation phase (b) shown in Figure 2.

In case of sampling high concentration (100 nl/l to 500 nl/l) ozone atmospheres, Tenax ® should be used with an ozone scrubber because benzaldehyde, phenol and acetophenone artifacts would be formed via oxidation of the polymer Tenax®.

Due to continuous nozzle heating during operation of the 3D printer, the room temperature inside the non-industrial place may continue to rise. As a result, this may cause continuous increase of the emission of VOCs and aldehyde from 3D printers and surrounding building materials.

Eventually, the concentration increase over time during printing may cause breakthrough of absorbent. Therefore, two pumps should be used simultaneously at different flow rates in order to avoid sampling failure due to the breakthrough volume.

To identify any breakthrough volume of the sorbent tube, connect the two sorbent tubes using a union to set the flow rate of the pump at 80 ml/min.

The other pump should be simultaneously collected at 50 ml/min in case of a sampling failure due to the breakthrough volume.

See ISO 16000-6 and ISO 16017-1 for information on the VOCs safe sampling volume concerning the breakthrough volume.

For the time-integrated method, sampling shall be done consecutively on an hour basis until the suspension of the printers. For the active method, sampling shall be done for at least one hour before the suspension of AM machines unless there are specific requirements from AM users.

All the sorbent tubes should be sealed using metal screw-cap fittings with PTFE ferrules and stored in an air-tight container at room temperature.

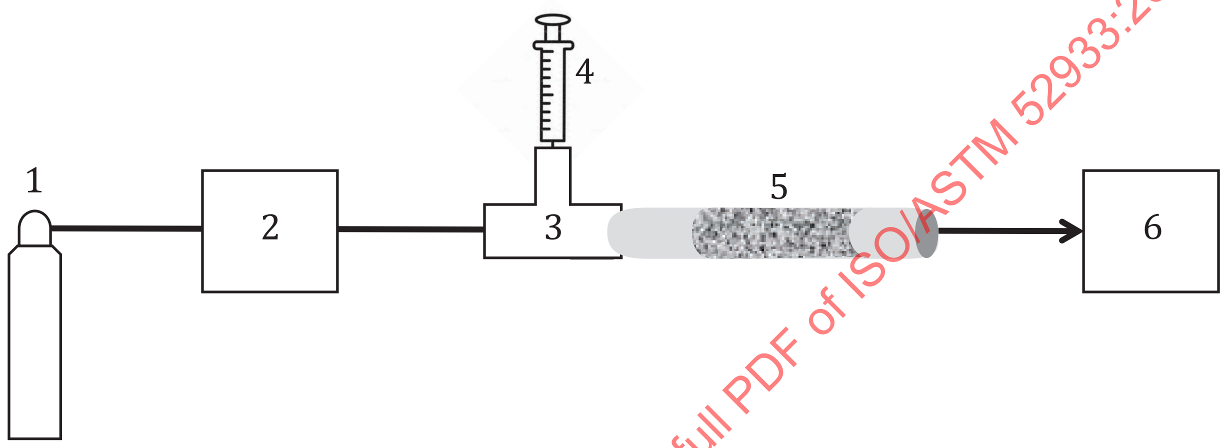
1) Tenax ® TA is a trademark of *"Tenax international B.V"*. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named.

The temperature inside the non-industrial place may arise during operation of the 3D printer, which may result in a change in the actual sampling volume collected. Therefore, the actual volume of VOCs sampling shall be adjusted to the temperature of 25 °C and pressure of 101,3 kPa by keeping track of the temperature and pressure every hour in the non-industrial place.

7.1.2.2 Preparation of calibration curve

When preparing the calibration curve by manufacturing a liquid standard solution, ISO 16000-6:2021, 6.4 can be referred to. However, if a standard gas mixtures (e.g. 1 µmol/mol containing toluene, within 10 % as tolerance) is used, a calibration curve can be prepared as follows:

a) prepare a heat-treated sorbent tube to flow at a constant flow rate of (50 to 100) ml/min using inert purge gases (e.g. nitrogen and helium) as shown in Figure 3;



Key

1 purge gas
2 mass flow regulator
3 T-type connector
4 gas-type syringe
5 Tenax-TA
6 pump

Figure 3 — Example of manufacturing a standard sorbent tube using standard gas mixtures

b) calculate a linear equation of $y = ax$ by using the toluene mass (ng) of analyte present in each sorbent tube injected and the toluene total ion chromatogram area of the GC-chromatogram as shown in Figure 4. However, the correction coefficient (r^2) shall be determined as 0,999 or higher.

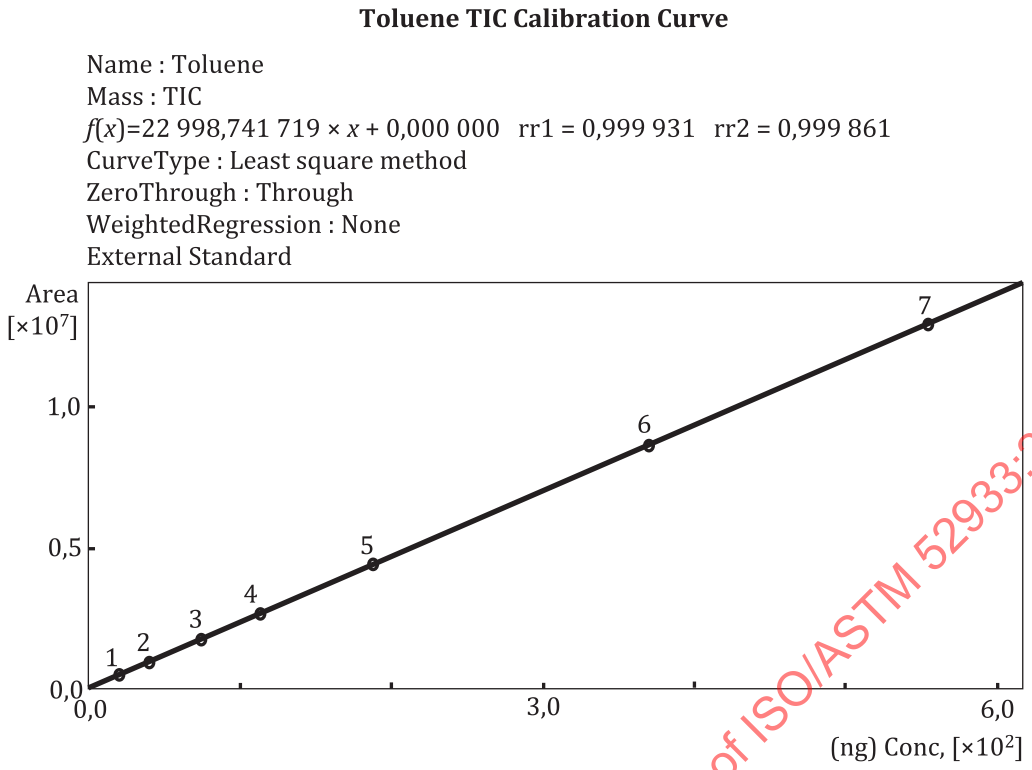


Figure 4 — Example of creating a calibration curve

7.1.2.3 Analysis method

VOCs, collected via a sorbent tube during operation of the 3D printer in the non-industrial place, are analysed by using a GC/MS analysis equipment specified in ISO 16000-6.

7.1.2.4 Determination of VOCs concentration

$$C_{\mathrm{m}} = \frac{\dfrac{A_{\mathrm{s}_1} + A_{\mathrm{s}_2}}{2} - A_{\mathrm{b}}}{V_{(25\ ^\circ\mathrm{C},\ 1\ \mathrm{atm})}} \qquad (1)$$

where

C_m	is the mass concentration of VOCs analyte collected from the sorbent tube, in µg/m^3;
A_{s_1}, A_{s_2}	are the mass in nanograms of VOCs analyte collected from the sorbent tube, in ng;
A_{b}	is the mass in nanograms of VOCs analyte collected from the blank sorbent tube, in ng;
$V_{(25\ ^\circ\mathrm{C},\ 1\ \mathrm{atm})}$	is the sampling volume at 25 °C and 101,3 kPa, in l.

The sampling volume of VOCs shall be adjusted to conditions of the temperature of 25 °C and the pressure of 101,3 kPa according to the following formula.

$$V_{(25\ ^\circ\mathrm{C},\ 1\ \mathrm{atm})} = V \times \frac{298}{T} \times \frac{p}{101{,}3} \qquad (2)$$

where

$V_{(25\,°C,\,1\,atm)}$	is the sampling volume corrected to 25 °C and 101,3 kPa, in l;
V	is the sampling volume of the air sampled, in l;
T	is the average indoor temperature over the course of the sampling, in Kelvin (K);
p	is the average indoor pressure over the course of the sampling, in kPa.

The relative percentage difference of the two VOCs samples analysed under the same condition shall not exceed 20 %.

The average concentration of VOCs emitted from the non-industrial place is determined as follows. The maximum concentration of VOCs in the non-industrial place can be checked through the concentrations ($C_{m_1} - C_{m_n}$) of each phase sampled continuously on a regular basis

$$\overline{C_{\text{voc}}} = \frac{C_{\text{m}_1} + C_{\text{m}_2} + \ldots + C_{\text{m}_\text{n}}}{n} \quad (3)$$

where

$\overline{C_{\text{voc}}}$	is the average mass concentration of VOCs analyte collected, in µg/m^3;
C_{m_1}	is the mass concentration of VOCs analyte collected from the sorbent tube for first 1 h while selected time-integrated method period in µg/m^3;
C_{m_2}	is the mass concentration of VOCs analyte collected from the sorbent tube for second 1 h while selected time-integrated method period in µg/m^3;
C_{m_n}	is the mass concentration of VOCs analyte collected from the sorbent tube for last 1 h while selected time-integrated method period in µg/m^3;
n	is the total number of samples from C_{m_1} to C_{m_n} .

7.1.3 Aldehyde method

7.1.3.1 Sampling

Connect a cartridge coated with 2,4-dintrophenyhydrazine with an ozone scrubber and use a pump that is capable of collecting aldehydes at a constant speed of (0,5 to 1,2) l/min to collect aldehydes of air. Each sampler installed according to 6.1 should be pumped at a flow rate of (0,5 to 1,0) l/min to sample continuously on an hourly basis for the time-integrated method.

As with VOCs sampling in 7.1.1, the increased concentration of the sample resulting from the rising indoor temperature may cause the cartridge to reach the breakthrough volume. It is better to use two union-connected cartridges to prevent sampling failure, and the flow rate of the pump shall be 1,0 l/min to check if there is any breakthrough volume.

For the time-integrated method, sampling shall be done consecutively on an hour basis until the suspension of 3D printers. For the active method, sampling shall be done for at least one hour before the suspension of AM machines. All cartridges shall be sealed by using caps and kept refrigerated until the start of analysis.

According to ISO 16000-3:2022, 5.1, acrolein and crotonaldehyde cannot be accurately quantified by the method. Inaccurate results for these compounds can result from the formation of multiple derivative peaks and the instability of the peak ratios.

The actual volume of aldehyde sampling shall be adjusted to the temperature of 25 °C and pressure of 101,3 kPa just as VOCs sampling in 7.1.1.

7.1.3.2 Preparation of calibration curve

When preparing the calibration curve, ISO 16000-3:2022, 10.3.3 can be referred to.

7.1.3.3 Analysis method

Aldehyde collected via DNPH cartridge during operation of the 3D printer in the non-industrial place is analysed in accordance with ISO 16000-3:2022, 8.3.

7.1.3.4 Determination of aldehyde concentration

Refer to ISO 16000-3 for the type of aldehyde compound and analysis method. The Formula (4) below only relates to formaldehyde.

$$\overline{C_{\text{ald}}} = \frac{C_{\text{a}_1} + C_{\text{a}_2} + \ldots + C_{\text{a}_n}}{n} \quad (4)$$

where

- $\overline{C_{\text{ald}}}$ is the average mass concentration of formaldehyde analyte collected, in ng/ml;
- C_{a_1} is the concentration of formaldehyde analyte collected from the DNPH cartridge for 1 h since the start of the 3D printer operation, in ng/ml;
- C_{a_2} is the concentration of formaldehyde analyte collected from the DNPH cartridge for 1 h after 2 h of 3D printer operation, in ng/ml;
- C_{a_n} is the concentration of formaldehyde analyte collected from the DNPH cartridge for 1 h before the stopping of 3D printer, in ng/ml;
- n is the total number of samples from C_{a_1} to C_{a_n}.

The relative percentage difference of the two aldehyde samples analysed under the same condition shall not exceed 20 % as given by Formula (5):

$$C_a = \frac{\left(\frac{A_{s_1} + A_{s_2}}{2} - A_b\right) \times L}{V_{(25\,°\text{C},\,1\,\text{atm})} \times 1{,}000} \quad (5)$$

where

- A_{s_1}, A_{s_2} are the concentrations of formaldehyde analyte extracted from the DNPH cartridge, in ng/ml;
- A_{b} is the concentration of formaldehyde analyte extracted from the blank DNPH cartridge, in ng/ml;
- $V_{(25\,°\text{C},\,1\,\text{atm})}$ is the sampling volume corrected to 25 °C and 101,3 kPa, in l;
- L is the final volume extracted with acetonitrile, in ml.

The actual volume of aldehyde sampling shall be adjusted to the temperature of 25 °C and the pressure of 101,3 kPa by using Formula (3).

NOTE DNPH cartridge means an air-sampling media device for sampling carbonyls, which is coated with 2,4-dinitrophenylhydrazine.

7.2 Real-time method

7.2.1 Purpose

The real-time method is intended to measure fine particles and ultra-fine particles while using the material extrusion 3D printers in the non-industrial places. The calculation methods for particle concentration are based on the ISO/IEC 28360-1 and RAL-UZ 205[8].

7.2.2 Sampling

The measurement of particles emitted from non-industrial places where the material extrusion type 3D printers are used is continuously sampled from the pre-operation stage to the operation phase in Figure 2. Aerosol measurement instruments should be able to measure total particle number concentration over time.

To measure particle concentration, a condensed particle counter (CPC) and/or a combination of a differential mobility analysing system (DMAS) and a light scattering air particle counter (LSAPC) should be used as aerosol instruments. A CPC detection efficiency for greater than 10 nm in diameter shall be equal to or higher than 50 %. In the case of the combination of aerosol instruments, consistency between the two different aerosol measurement instruments shall be checked and comparable.

To check the consistency between the two different aerosol measurement instruments, the example is as follows. The CPC should be capable of counting particle sizes ranging from 7 nm to 3 µm at least. The DMAS can measure particle number distribution for particle optical diameter of 7 nm to 420 nm and the LSAPC should measure particle number distribution for particle optical diameter of 300 nm to 3 µm. Thus, the combination of DMAS and LSAPC can be capable of counting particle sizes ranging from 7 nm to 3 µm. Therefore, the result of the total particle number concentration result of a CPC and the combination of a DMAS and a LSAPC are comparable. The comparison results of the classified particles by their size should be correlated.

7.2.3 Determination of particles concentration

The arithmetic average particle concentration, C_{av}, is calculated by using the particle number concentration based on time and the index n which stands for the number of measured values between emission time t_{stop} - t_{start}, as given by Formula (6):

$$C_{av} = \frac{\sum_{i=1}^{n} \left(C_{p,i} \right)}{n} \tag{6}$$

where C_{av} is the arithmetic average of accumulated particle number concentration from t_{start} to t_{stop}, in cm^{-3};

The total particle number shall be calculated by the sum of each particle number concentration over the extruding phase.

The formula for calculating the total particle concentration and the total particle number emitted from the material extrusion type 3D printer using CPC can be equally applied to the measurement of the particle concentration of a specific size as follows. In order to analyse the emission amount for specific particle size, DMAS measuring equipment can be used, and particles of 100 nm or less, which are commonly emitted in the material extrusion type 3D printer, can be calculated for each specific size with Formula (7):

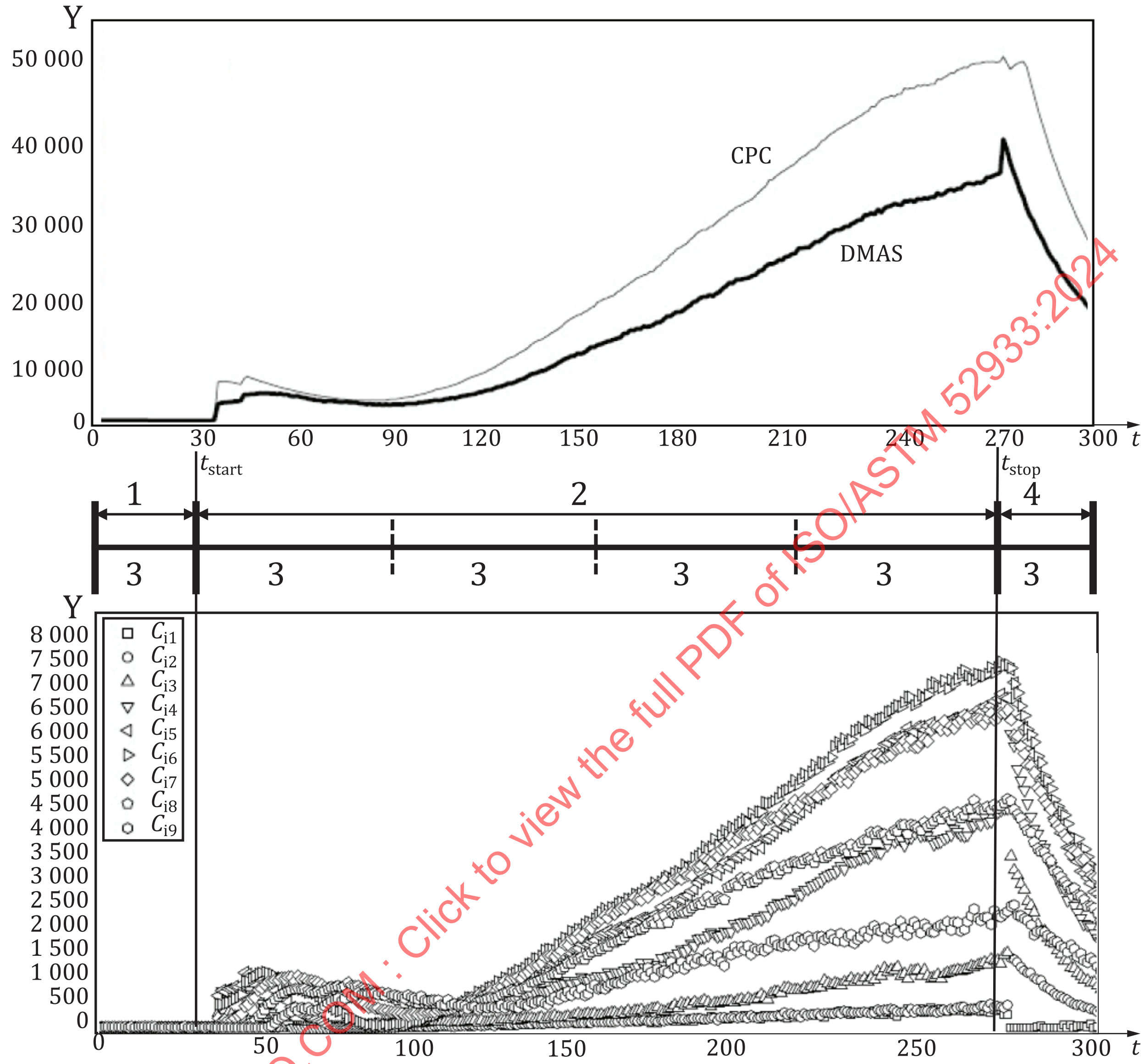
$$C_{av,size} = \frac{\sum_{i=1}^{n} \left(C_{p,size,i} \right)}{n} \tag{7}$$

where

$C_{av,size}$ is the arithmetic average of accumulated particle number concentration for specific particle size from t_{start} to t_{stop}, *in* cm^{-3};

$C_{p,size,i}$ is the accumulated particle number concentration for n^{th} of specific particle size, in cm^{-3}.

Figure 5 is an example of using each CPC and DMAS measuring equipment when the material extrusion type 3D printer is used in a non-industrial space. The upper graph is about the total particle concentration, and the bottom is an example of concentration for each specific size particle.



Key

t	time (min)
Y	number concentration (#·cm^{-3})
1	pre-extruding phase
2	extruding phase
3	sampling phase
4	post-extruding phase

NOTE This method requires the extruding phase to last at least 240 min for the calculation

Figure 5 — Total particle and specific size particle concentration diagram

8 Test report

The following information shall be recorded and included:

a) a reference to this document, i.e. ISO/ASTM 52933:2024;

b) the date of the test

c) name of the responsible person

d) information of the sampling location:

1) name and full address of the test location.

2) the size of the sampling area [e.g. 5 m (width) × 10 m (depth) × 3 m (height)];

3) distance of samplers from the AM machines;

4) specification of AM machines (model name, the number of each models, etc.)

5) parameters of AM machines (description of printed sample design, extrusion temperature, part bed temperature, etc.)

6) specifications of materials (the exact name, manufacture, SDS, etc.)

7) height of samplers from the floor;

8) sampling start time and end time.

e) applied measurement methods (active method, time-integrated method, real-time method);

f) descriptions of the sampling procedure:

1) sampling plans for pre-operation phase;

2) environmental conditions for operation phase(temperature, relative humidity);

3) the characteristics of sampling area(windows and doors(open/closed), mechanical air exchange and room air change rate per hour)

4) sampling plans and sampling strategy for sampling phase.

g) sampling method used for VOC and aldehydes:

1) sorbents used;

2) sampling volume and flow rate of pump;

3) sampling start time and duration.

h) description of the aerosol measurement instrument used:

1) manufacturer, model and serial number;

2) name and version of the software;

3) date of last factory calibration and maintenance (date, time and results of last field calibration);

4) aerosol measuring system set-up values used for measurement (count mode, sampling flow rate, reaction velocity, etc.);

5) particle size range.

i) description of the analysis procedure:

1) VOC and aldehyde measuring equipment used;

2) standard gas volume injected for calibration curve;

3) detection limits of VOC, aldehydes and particular matter;

j) test results:

1) average mass concentration of VOCs presented in the sorbent tube, in µg/m^3 (see 7.1.2.4);

2) average concentration of formaldehyde analyte presented in the DNPH cartridge, in ng/ml (see 7.1.3.4);

3) total number concentration of particles, in #·cm^{-3} (see 7.2.3);

4) any unusual features observed;

5) any deviations from the procedure.

Annex A
(informative)

Considerations for reducing the emission of hazardous substances

A.1 Environment in the non-industrial place

A.1.1 General

Since the emission concentration of UFP and chemical compounds (VOCs and aldehydes) may vary depending on environmental and cleaning conditions of the educational place, machine users make efforts in order to reduce hazardous substances before machine operation, during machine operation, and after machine operation.

A.1.2 Before material extrusion process

Dust in the educational place may be combined with ultrafine particles generated during machine operation, which increase the number of ultrafine particles in the place. In addition, the cleaning of the educational place should be performed before starting working the machine because the concentration of initial chemical compounds can increase depending on the cleaning conditions of the place where the machine is operated.

When cleaning, it is recommended to clean the floor and windows of the educational place by removing dust with a vacuum cleaner and a water mop.

A.1.3 During material extrusion process

There is a possibility that ultrafine particles and chemical compounds emitted during machine operation within a closed space continuously increase according to the operation time. Therefore, the mechanical ventilation system should be operated during operation of the material extrusion 3D printer. It is preferable to ventilate the air in the educational place by opening the windows and doors regularly considering the outdoor air if there is no mechanical ventilation system in the place.

A.1.4 After material extrusion process

After the operation of the material extrusion 3D printers is completed, the concentration of hazardous substances will decrease over time. However, since ultrafine particles and chemical compounds are likely to stay in the air for a long time, the mechanical ventilation equipment should be operated for a constant period after the 3D printer is shut down. Enabling natural ventilation by opening windows and doors is also recommended at the same time.

A.2 Material extrusion - 3D printer

Most of desktop-3D printers can be used regardless of the filament type of each manufacturer with the exception of some manufacturers. The emission of ultrafine particles and chemical compounds may vary depending on the nozzle temperature and nozzle thickness set-up values since the melting tolerance temperature range provided by the manufacturers are different while machine users can set up different operation values.

Therefore, the following factors in Table A.1 should be considered in advance and the machine operating conditions should be planned according to the operating conditions of the desktop 3D printer, so as not to affect the quality of the final product.

Table A.1 — Machine set-up items and considerations

Set-up items	Considerations
Nozzle temperature (°C)	Although the same filament is used, the acceptable of melting temperature range varies depending on the nozzle set-up conditions. The higher the nozzle temperature, the higher the possibility of ultrafine particle emission increases[e.g. Melting temperature of ABS filament is (210 to 250) °C]. (See Table A.2)
Nozzle thickness (mm)	Depending on the machine manufacturer, the nozzle thickness set-up values can be different. Therefore, the thicker the nozzle thickness, the higher the possibility of ultrafine particle emission increases.
Nozzle cleaning status	If the filament is stuck around the nozzle after feeding filament, the emission of ultrafine particles can increase at the beginning of the machine operation.
Type of filament (ABS, TPU, PA, PLA, etc.)	If the VOCs content per filament is high, the concentration of VOCs emission increases.
Infill density (%)	Infill density can be set up with different filling percentage depending on the slicing program. In general, the lower the infill density, the higher particle emission is observed.
Infill pattern	There are many different infill patterns depending on the slicing program. It is recommended setting up the infill pattern for the highest density in consideration of the infill density because the infill pattern for the lowest density tends to emit more particles.
Internal cleaning status	After the machine starts, the emission of hazardous substances may increase depending on the filament residues remaining inside the machine and cleaning conditions.

Table A.2 shows a relationship between particle number concentration and nozzle temperature for several filaments. This is an example from the reference, so it shall not be used as health and safety guidelines. In the reference for Table A.2 (in Table A.1), Several papers have measured the particle concentration with respect to nozzle temperature. Each printing scenario (equipment, material, process) can be evaluated independently to gauge levels of particle concentration.

Table A.2 — Example of relationship between particle number concentration and nozzle temperature for several filaments (example)[12]

Material	Nozzle temperature °C		
	220	230	240
	particle number concentration (N_{peak}, part.cm^{-3})		
PLA	(5,15 ± 0,55) × 10^{3}	(8,21 ± 3,27) × 10^{3}	(4,87 ± 2,29) × 10^{4}
WOOD1	(1,45 ± 0,88) × 10^{4}	(3,95 ± 2,20) × 10^{4}	(9,27 ± 1,95) × 10^{4}
WOOD2	—	(6,97 ± 2,26) × 10^{5}	(9,51 ± 2,45) × 10^{5}
COPPER	(3,61 ± 1,5) × 10^{5}	(4,53 ± 3,37) × 10^{5}	(6,67 ± 0,63) × 10^{5}
BAMBOO	(1,11 ± 0,02) × 10^{5}	(4,13 ± 0,09) × 10^{5}	(9,54 ± 3,83) × 10^{5}
FLEX PLA	—	—	(2,53 ± 0,39) × 10^{4}
CP	(8,93 ± 0,74) × 10^{4}	(1,78 ± 0,02) × 10^{5}	(5,62 ± 0,85) × 10^{5}
CP-CARBON	(1,09 ± 0,15) × 10^{5}	(2,30 ± 0,44) × 10^{5}	(4,84 ± 0,40) × 10^{5}
PA	Negligible	(1,28 ± 0,68) × 10^{4}	(1,41 ± 0,28) × 10^{4}
TPU	Negligible	(1,78 ± 1,03) × 10^{4}	(5,78 ± 1,88) × 10^{4}

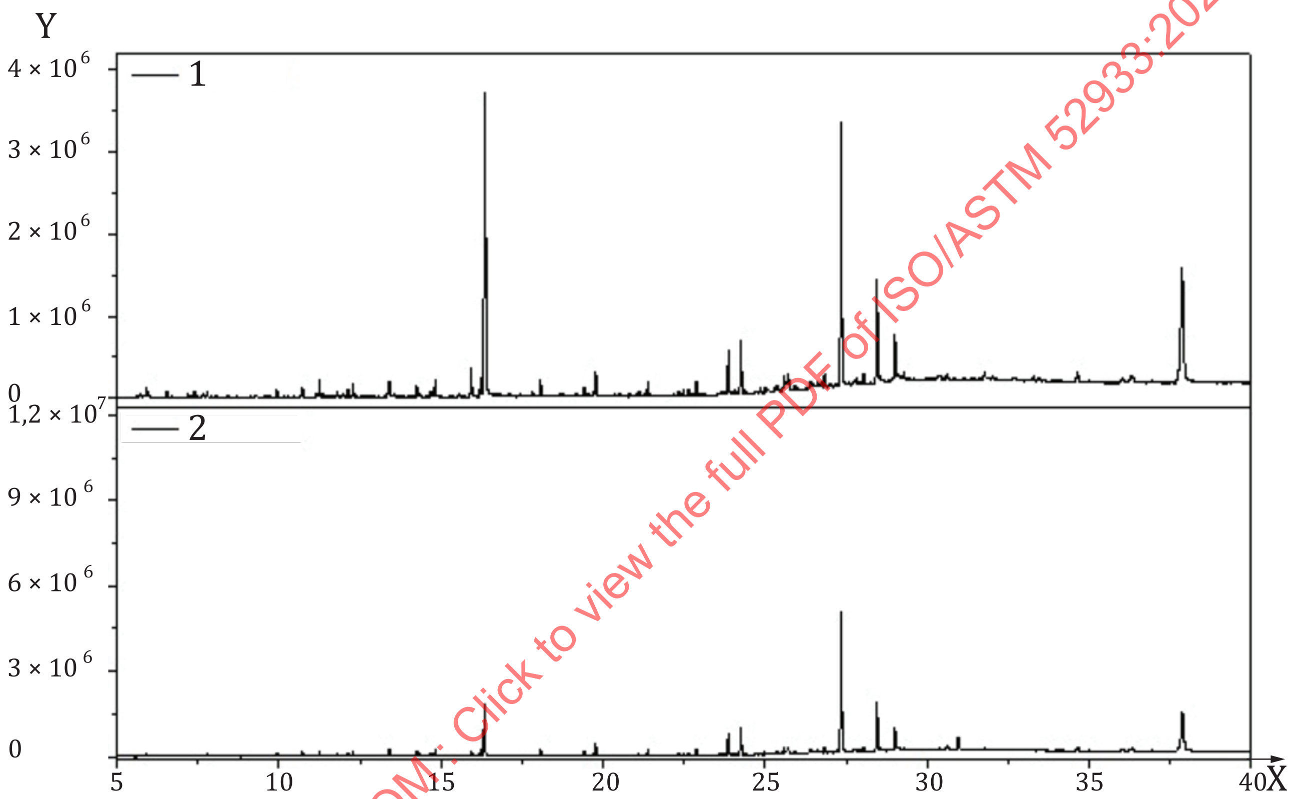
A.3 Filament

The filaments of MEX type 3D printer are made of various organic compounds depending on the type of materials. The emission concentration of chemical compounds(VOCs and Aldehydes) may be affected depending on the type and content of the main substances of filaments. Therefore, the customer should check the major chemical composition and content of the filament based on SDS provided by the manufacturer when choosing the filament.

In addition, filament selection should take into consideration the TLV(Threshold Limit Values) of chemical substances provided by the ACGIH besides OSHA's PELs (Permissible Exposure Limits) and DFG's MAKs(Maximum Concentrations at the Workplace) for the anticipated substances that can be released into the air during additive manufacturing process melting filament.

A.4 Additive manufactured product

Figure A.1 below shows that the VOCs content in the final product manufactured by raw filament is higher than the VOCs content of the raw material. It means that when the final product is placed in the open space of the educational place, VOCs may be released into the air and deteriorate air quality. Therefore, the raw filament should be kept in sealed state when users make their first purchase and keep the final products in an enclosed container or in a separate space rather than in the educational place.



Key

X retention time
Y absolute intensity
1 PLA-after
2 PLA-before

Figure A.1 — The chromatogram of the raw filament and final product analysed by GC-MS

A.5 Environmental status consideration in the non-industrial place

A.5.1 Ventilation status

AIVC (air infiltration and ventilation centre), ASHRAE, and other advanced organizations have set ventilation performance and installation standards in accordance with the building equipment standard of their respective countries and set the minimum ventilation standard in buildings to maintain indoor air quality. However, the emission of chemical compounds and ultrafine particles would be significantly different depending on the selection of the number of desktop 3D printers and filaments for an educational place. Local and national regulations for installing ventilation standards apply. Additionally, natural ventilation or simple mechanical equipment (e.g. portable local exhaust ventilation unit) should be installed in order to evaluate the adequacy of ventilation in the non-industrial place depending on the number of operations of the desktop 3D printers. Ventilation conditions and average air retention time for contaminants in the air can be assessed in accordance with ISO 16000-8.

A.5.2 Temperature and humidity control

MEX type 3D printers maintain the nozzle temperature at over 200 °C depending on the type of filaments and operate the machine for one hour for a short time and 6 h or longer depending on the educational environment. For this reason, there would be a rise in temperature and a decrease in humidity depending on the space, environment, and number of machine operations. Therefore, it is recommended to install a temperature and humidity control mechanism such as a thermo-hygrostat so that the temperature and humidity in the place should be maintained constantly. If it is difficult to install such equipment, it should be managed to maintain constant temperature and humidity through natural ventilation.

A.5.3 Facilities and equipment

Building materials (paint, wallpaper, wooden furniture, etc.) are basically used for the facility of MEX type 3D printers at the educational place. These building materials are characterized by the continuous release of chemical compounds according to the environmental conditions of the place. Therefore, the building materials in the place should be installed at a minimum, and the desk used for the 3D printers should be composed of materials made of non-volatile organic compounds as much as possible. If the material is made of wood, the material should be purchased considering the test result of the chemical compounds through GREENGUARD AGBB, California Air Resources Board, EN 16516 and the other relevant test evaluation.

A.6 Other considerations

The Table A.3 is from NIOSH Nanotechnology Research Center (NTRC). It includes health and safety questions with different control options and information to reduce exposure to potential hazards.

Table A.3 — 3D Printing with filaments: health and safety questions to ask (NTRC)

Considerations	Questions	Information to reduce exposure
Characterization of potential hazards	a) What are the potential hazards associated with 3D printing? b) Are there known health effects from the filaments (for example, see safety data sheets)? c) What is the form of work environment (for example, open or isolated area)?	a) **Potential hazards may include :** — Breathing and skin contact with volatile organic chemicals(VOCs) and particulates(printing) and other chemicals(post-printing) — Hot surfaces and moving parts b) **Printing considerations:** — Printing material(e.g., use polylactic acid[PLA] filament rather than acrylonitrile butadiene styrene[ABS] if possible) — Filaments with additives(e.g., metals, nanomaterials, carbon fibers) — Frequency and duration of printing — Manufacturer's recommendations for bed and nozzle temperatures