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Indoor Passive Panel Technologies: Test Methods to Evaluate Toluene and Formaldehyde Removal and Re- emission, and By-product Formation

Zuraimi Sultan, Robert Magee, Gregory Nilsson, Chantal Arsenault

15 December 2015

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Executive Summary

This test method was developed by the National Research Council Canada (NRC) to determine the initial performance of indoor passive panel technologies (IPPT) in their removal of formaldehyde and toluene gas as well as assess re-emissions of captured gases and harmful by-product formation. This new protocol builds on existing sorption-based standards to evaluate performance of both sorptive- and PCO-based IPPT in removing indoor formaldehyde and toluene. Considering that some PCO-based IPPT may be influenced by sorptive effect, this new protocol differentiates removal performance attributed to light illumination and sorption. This protocol uses an improved chamber with proper control of air velocity and turbulence level to simulate indoor conditions instead of a photoreactor chamber. In addition, the chamber utilises indoor lighting (as opposed to UV) as a source of illumination to better represent indoor applications. By testing by-product formation, this new protocol is the first to address protection of building occupants to harmful pollutant exposures.

The project was funded by the Government of Canada's Clean Air Regulatory Agenda to develop three protocols for evaluating the effectiveness of "IAQ Solutions". It was prepared by NRC researchers under the guidance of a Technical Advisory Committee (TAC) assembled for this task, whose members included participants representing Federal and Provincial Agencies, Industry Associations, Non-Governmental Organizations (NGOs), Municipal governments, and Standards Association from Canada. The protocol also considered consultations of stakeholders comprising builders, researchers, industry partners and health professionals. The contributions of the TAC members and stakeholders to this work are gratefully acknowledged. Compliance to the test method and to the data interpretation developed in this test method is voluntary.

Members of the **Technical Advisory Committee** on IAQ Solutions, NRC-Construction Indoor Air Initiative:

TAC Member	Agency / Organization
Zuraimi M Sultan, <i>Chair</i>	National Research Council Canada
Glenn Curtis <i>Vice-chair</i>	Heating, Refrigeration & Air-Conditioning Institute of Canada (HRAI); S&P Canada Ventilation Products Inc.
Regina De La Campa	Canada Mortgage and Housing Corporation (CMHC)
Eomal Fernando	CSA (Canadian Standards Association) International
Nihat Rahman	EXOVA Canada Inc.
Aaron Wilson	Health Canada
Gemma Kerr	InAIR Environmental Ltd
Gregory Nilsson	National Research Council Canada
Robert Magee	National Research Council Canada
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Indoor Passive Panel Technologies: Test Methods to Evaluate Toluene and Formaldehyde Removal and Re-emission, and By-product Formation

1. Introduction

1.1 Preface

This test method describes procedures for determining initial performance of indoor passive panel technologies in removing airborne volatile organic compounds (VOCs) concentrations as well as assesses re-emissions of captured pollutants and by-product formation. The protocol was developed by the National Research Council of Canada's Construction Portfolio under the guidance of a Technical Advisory Committee (TAC) formed to develop a series of evaluation protocols for "IAQ Solutions".

Indoor passive panel technologies (IPPT) are defined as indoor building materials which are intentionally designed to remove pollutants on their surfaces without requiring additional energy input beyond normal building operations. They include specially designed wallboards, wallpapers, carpets, floorings, paint products, acoustic tiles and other building materials used indoors. IPPT includes those that rely on one of two mechanisms namely sorption and photocatalytic oxidation (PCO). For sorption-based IPPTs, the process involves adsorption and chemisorption principles. For PCO-based IPPTs, the process involves illuminating building materials that contain a photocatalyst or have photocatalytic films, usually made from semi-conducting metal oxides, with indoor light (Section 7.1.2).

Limited standards are available to evaluate performance of IPPTs for building interior applications (a summary of the main IPPT performance aspects covered by the existing standards is given in Section 7). While these limited standards address important indoor pollutant removal performance aspects, none deal with other specific performance for indoor applications aspects such as:

1. Testing harmful by-product formation to protect human health;
2. Optimized testing for long term performance of IPPTs (28 days per sample is deemed too long);
3. Testing removal performance of IPPT under soiling effects or other surface treatments (e.g. paints, wallpapers);
4. Testing for re-emission of captured VOC;
5. Testing of heterogeneous reactions between captured VOCs with ozone to form harmful by-products;
6. Testing IPPT using wall-ceiling-floor scale materials in a full scale (room size) chamber;
7. Testing of IPPT samples using a chamber with proper controlled air velocity and turbulence that is representative of the indoor environment;

8. PCO based samples are not evaluated in a chamber that represent indoor environment (mixing reactor, controlled air velocity and turbulence) and illuminated with visible light using conventional indoor lighting source (instead of UV source);
9. Sorptive effects of PCO based samples are inadequately addressed.

A stakeholder questionnaire survey comprising participants from builders, researchers, industry partners and health professionals was conducted from June to October 2012 to identify gaps, prioritize areas of the IPPT test method development and seek industry consensus. Among the various IAQ performance aspects discussed, stakeholders recommended evaluation of long term performance testing, by-product formation testing, full scale (room size) material testing, environmental and soiling conditions impacting removal performance as high priority areas. They also recommended indoor ozone, formaldehyde and toluene as pollutants that need to be addressed when evaluating IAQ performance of IPPT. A TAC meeting was convened in November 2012 to identify critical performance scope for protocol development. Under the guidance of the TAC, suggestions were reduced to three priority areas based on feasibility, practicality and resource availability considerations. In particular, the TAC recommended addressing the following priorities:

1. testing performance of sorptive-and PCO-based IPPTs in removing formaldehyde and toluene under the same protocol;
2. characterizing by-product release of contaminants from the IPPT; and
3. testing re-emission of captured VOC.

This new protocol builds on existing sorption-based standards to evaluate performance of both sorptive- and PCO-based IPPT in removing indoor formaldehyde and toluene. Considering that some PCO-based IPPT may be influenced by sorptive effect, this new protocol differentiates removal performance attributed to light illumination and sorption. This protocol uses an improved chamber with proper control of air velocity and turbulence level to simulate indoor conditions instead of a photoreactor chamber. In addition, the chamber utilises indoor lighting (as opposed to UV) as a source of illumination to better represent indoor applications. By testing by-product formation, this new protocol is the first to address protection of building occupants to harmful pollutant exposures. In summary, by building on limited standardized methods and improving specific techniques and chamber, this protocol introduced novel tests which have the potential to facilitate adoption by industry/standardization bodies and enhance product evaluation. The developed IPPT protocol will be used for both residential and commercial office buildings application.

1.2 Scope

This protocol describes a method for evaluating the performance of IPPT used in commercial office and residential buildings. Specifically, it examines the following performance aspects of passive panels:

- testing performance of sorptive-and PCO-based IPPTs to remove formaldehyde and toluene;

- evaluating amounts of re-emission of captured formaldehyde and toluene; and
- evaluating emission rates of by-products from the IPPT.

The IPPT test sample shall be a part or component that is representative of the IPPT building material and representative of how it is used in the indoor environment.

2. Reference Publications

ASTM D5116-2010 - *Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products*

ASTM D5197-2009e1 - *Standard Test Method for Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology)*

ASTM D6196-03-2009 - *Standard Practice for Selection of Sorbents, Sampling, and Thermal Desorption Analysis Procedures for Volatile Organic Compounds in Air*

ASTM D6345-2010 - *Standard Guide for Selection of Methods for Active, Integrative Sampling of Volatile Organic Compounds in Air*

ASTM E 741-2011 *Test Method for “Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*

Aiello M, McLaren R. (2009) “Measurement of airborne carbonyls using an automated sampling and analysis system.” *Environ Sci Technol.* 43(23):8901-7.

Gilbert NL, Guay M, Miller JD, Judek S, Chan CC, Dales RE. (2005’) “Levels and determinants of formaldehyde, acetaldehyde, and acrolein in residential indoor air in Prince Edward Island, Canada.” *Environmental Research*, 99(1): 11-7.

Gunschera J, Andersen JR, Schulz N, Salthammer T (2009) *Surface-catalysed reactions on pollutant-removing building products for indoor use.* *Chemosphere*, 75: 476-482.

Health Canada (2006) *Residential Indoor Air Quality Guideline - Formaldehyde*

Health Canada (2010) *Residential Indoor Air Quality Guideline - Ozone*

Health Canada (2012) *Residential Indoor Air Quality Guideline - Toluene*

Ifang S, Gallus M, Liedtke S, Kurtenbach R, Wiesen P, Kleffmann J (2014)

Standardization methods for testing photo-catalytic air remediation materials: Problems and solution. *Atmospheric Environment*, 91, 154-161

ISO Standard 16000-23 *Performance test for evaluating the reduction of formaldehyde concentrations by sorptive building materials*

ISO Standard 16000-24 *Performance test for evaluating the reduction of volatile organic compounds concentrations (except formaldehyde) by sorptive building materials*

ISO Standard 22197-1 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 1: Removal of nitric oxide.*

ISO Standard 22197-2 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 2: Removal of acetaldehyde.*

ISO Standard 22197-3 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 3: Removal of toluene.*

ISO Standard 22197-4 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 4: Removal of formaldehyde.*

ISO Standard 22197-5 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 5: Removal of methyl mercaptan.*

ISO Standard 10677 *Fine ceramics (advanced ceramics, advanced technical ceramics) — Ultraviolet light source for testing semiconducting photocatalytic materials.*

Lajoie P, Aubin D, Gingras V, Daigneault P, Ducharme F, Gauvin D, Fugler D, Leclerc JM, Won D, Courteau M, Gingras S, Héroux MÈ, Yang W, Schleibinger H. (2015) *The IVAIRE project - a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes.* Indoor Air. 25(6):582-97.

Liu LJ, Koutrakis P, Leech J, Broder I. (1995) "Assessment of ozone exposures in the greater metropolitan Toronto area." Journal of Air & Waste Management Association, 45: 223–34.

Nazaroff, W.M. (2000) *Effectiveness of air cleaning technologies.* Proceedings of Healthy Buildings 2000, Espoo, Finland, 2:49–54.

Reardon J. (2007) "Assessment of Natural Ventilation for Canadian Residential Buildings." Client Report B-3316.1a Institute for Research in Construction, National Research Council of Canada

Weschler CJ. (2000) "Ozone in indoor environments: concentration and chemistry." Indoor Air, 10(4): 269-88.

Zhang, J.S.; Shaw, C.Y.; Kanabus-Kaminska, J.M.; MacDonald, R.A.; Magee, R.J.; Luszyk, E.; Weichert, H.J. (1996) *Study of air velocity and turbulence effects on organic compound emissions from building materials/furnishings using a new small test chamber* ASTM Symposium on Methods for Characterizing Indoor Sources and Sinks (Washington, DC, USA, 1994) pp. 184-199 NRCC-38478 IRC-P-3877 ASTM-STP-1287

Zhang JS, Shaw CY, Nguyen-Thi LC, Macdonald RA, Kerr G (1995). *Field measurements of boundary layer flows in ventilated rooms.* ASHRAE Transactions, 101 (Pt 2) 1-9.

Zuraimi MS, Magee R, Nilsson G. (2011). *IAQ Solutions and Technologies: Review and Selection for Protocol Development*, pp. 1-173, March-31-11 (NRCC-54495) <http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc54495.pdf>

3. Terminology

3.1 Definition

Challenge gas - mixture of air and pollutant(s) of known concentration prepared from a standard gas or a zero-calibration gas, to be used for the performance test of an IPPT material

Clean air – air which is supplied into the pretreatment, conditioning or airflow chamber that is particle, VOC and ozone filtered. Air is considered "clean" if the background conditions described in Section 5.1.5 is achieved.

Dark condition - test condition with no light illumination on the test samples using the light source for testing and room lighting

Photocatalyst - substance that performs one or more functions based on oxidization and reduction reactions under photoirradiation, including decomposition and removal of air and water contaminants, deodorization, and antibacterial, self-cleaning and antifogging actions

Photocatalytic materials - materials in which or on which the photocatalyst is added by coating, impregnation, mixing, etc.

Test chamber concentration – (indoor air) concentration of challenge gas measured at the outlet of a test chamber, derived by dividing the mass of the challenge gas sampled at the outlet of the chamber by the volume of sampled air.

3.2 Other Abbreviations

A	surface area
ASTM	American Society for Testing and Materials
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BR	by-product emission rate
C	concentration
CIE	International Commission on Illumination
cfm	cubic feet per minute
DC	direct current
DNPH	2,4-Dinitrophenylhydrazine
ER	Emission rate
GC/MS	gas chromatograph/mass spectrometer
HPLC	high performance liquid chromatography
IPPT	indoor passive panel technology
ISO	International Organization for Standardization
k_d	deposition velocity
L	litres
L/s	litres per second
LOD	Limit of detection
mg/h	milligrams per hour
N	air exchange rate
Pa	Pascals
PCO	photocatalytic oxidation
PTFE	polytetrafluoroethylene
ppb	parts per billion
Q	airflow rate
Re	Re-emissions of captured pollutant from IPPT
RH	relative humidity
RoS	range of slope
RR_A	area specific removal rate
TLT	threshold limit wavelength of transmission
t_e	time elapsed to reach IPPT breakthrough
UV	ultra-violet

VOC	volatile organic compounds
VVOC	very volatile organic compounds
VR_A	area specific ventilation rate
W/m²	watts per meter square
ε	effectiveness
μg/m³	microgram per cubic meter
°C	degrees centigrade
lx	lux

3.3 Overview of Test Methods

A constant concentration challenge method will be used to evaluate removal of toluene or formaldehyde by the IPPT. For sorptive-based IPPTs, known amount of formaldehyde or toluene are introduced to achieve the desired target concentrations at the inlet port of the chamber and maintained for a period of at least 96 hours. After 96 hours, the challenge injection is stopped. By comparing formaldehyde or toluene concentrations at the inlet and outlet ports of the chamber, the removal performance of the IPPT is calculated by determining the area specific removal rate and area specific ventilation rate.

For light-based IPPTs, the test above is modified to consider key aspects of PCO function. A known amount of formaldehyde or toluene is introduced to achieve the target concentrations at the inlet port of the chamber under dark conditions while still monitoring concentrations at the outlet port. Upon confirmation that the IPPT has minimal sorptive effects, the test specimen will be irradiated at a constant illumination using fluorescent lights for 72 hours. After 72 hours of light irradiation, the challenge injection is stopped and light turned off. By comparing formaldehyde or toluene concentrations at the inlet and outlet ports of the chamber during illumination, the removal performance of the IPPT is calculated by determining the area specific removal rate and area specific ventilation rate.

The sorption-based test is extended to evaluate the effects of re-emissions of captured pollutants. After challenge injection had ceased, the inlet and outlet concentrations of formaldehyde and toluene will be monitored for a further 72 hours. Re-emission of formaldehyde or toluene is calculated by comparing outlet concentrations at 168 hours with the amount captured during the injection phase of the test.

The light-based IPPT test is used to evaluate the by-product formation of IPPT. Under constant toluene concentration challenge and fluorescent lights irradiation, formaldehyde and ozone formation will be evaluated. By comparing formaldehyde and ozone concentrations at the inlet and outlet ports of the chamber, the by-product formation rate is calculated.

4. Facilities and Instruments for Determining Performance

4.1 Controlled Airflow Chamber

The chamber to be used to evaluate performance of IPPT shall be airtight, able to control the environmental conditions such as temperature and relative humidity, airflow rate amounts, air velocity and turbulence levels over the IPPT material surface and light

irradiation of the IPPT surface. For this protocol, the chamber used was a modified small chamber assembly designed to test VOC emissions from small building materials under controlled air velocity and turbulence conditions (Figure 1) (Zhang et al., 1996). It consists of an inner and an outer chamber, all made of electro-polished stainless steel. The outer chamber has inner dimensions of 1 by 0.8 by 0.5 m high (internal volume: 0.4 m³).

The control of humidity over the IPPT sample surface is achieved by maintaining the humidity of the supply air to the outer chamber. Temperature control is obtained by maintaining the ambient room environmental set point values. The humidity sensors located inside the outer chamber provide feedback signals directly to the controller. Pressure difference between the outer chamber and the room is monitored using differential pressure sensor.

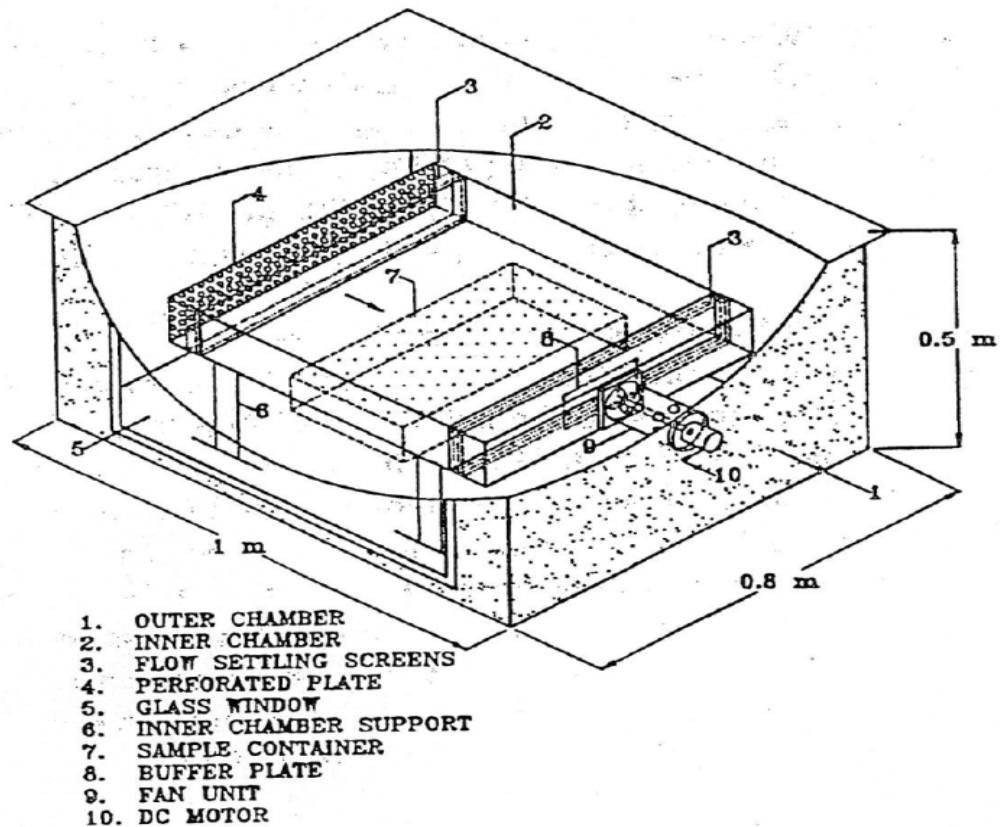


Figure 1 - Schematic of the outer and inner chamber assembly

The control of the air velocity and turbulence level over the IPPT sample surface is achieved by using an inner chamber. As shown in Figure 1, the inner chamber has three sections: an upstream section consisting of a perforated plate and several screens for settling the flow and controlling the turbulence level, a middle section with relatively uniform air flow for exposing the IPPT sample surface, and a downstream section consisting of several screens settling the flow and a buffer plate. The buffer plate is located in the downstream section in front of a stainless steel tube-axial fan. This fan consists of blades, a cylindrical duct with holes downstream of the fan blades, and a shaft driven by a DC motor. The fan draws air through the inner chamber and discharges

through the holes into the outer chamber. The air velocity over the IPPT sample surface is controlled by adjusting the voltage supplied to the DC motor, while turbulence level is controlled by varying the number and diameter of the holes on the perforated plate, and/or the number of screens in the upstream section of the inner chamber. All components for inner chamber are made of stainless steel. In order to minimize background contamination, the DC motor is located outside of the outer chamber, and a PTFE sealed bearing is used for supporting the shaft that drives the fan blades.

The chamber to be used shall be operated slightly above atmospheric pressure to avoid influence from the laboratory atmosphere and is considered sufficiently airtight if: 1) the air leakage is less than 0.5 % of the chamber volume per minute at an overpressure of 1000 Pa; or 2) the air leakage is less than 5 % of the supply airflow rate.

The chamber shall be operated to achieve the standard test condition as in Section 5.1.5 using an electropolished stainless steel plate as a reference. The chamber sink effects on the injected formaldehyde or toluene shall be evaluated using ASTM D5116 standard (ASTM, 2010). The edges of the IPPT test reference plate shall be sealed with low VOC aluminum tape.

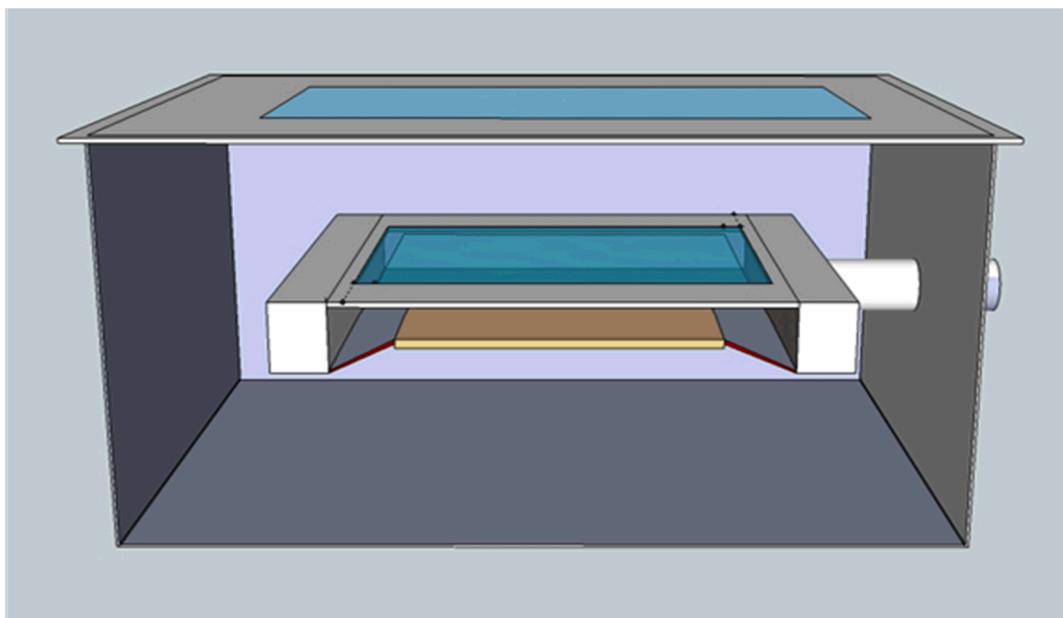


Figure 2 - Schematic of the outer and inner chamber assembly illustrating the optical windows for indoor lighting irradiation

To accommodate testing of PCO-based IPPT, the top section of the inner and outer chambers shall be fabricated with optical windows for indoor lighting photoirradiation of the IPPT sample. The optical windows for the inner and outer chamber shall be made of borosilicate glass that absorbs minimal light at wavelengths longer than 300 nm. An indoor light source fixture shall be installed outside, above the 0.4 m³ outer chamber. The height of the indoor light source fixture shall be adjusted to provide an irradiance of 1000 ± 100 lx on the IPPT sample surface. The schematic for the chamber required to

meet the requirements for evaluating PCO-based IPPT samples is shown in Figure 2. An example of an actual installation of the IPPT test chamber is shown in Figure 3.

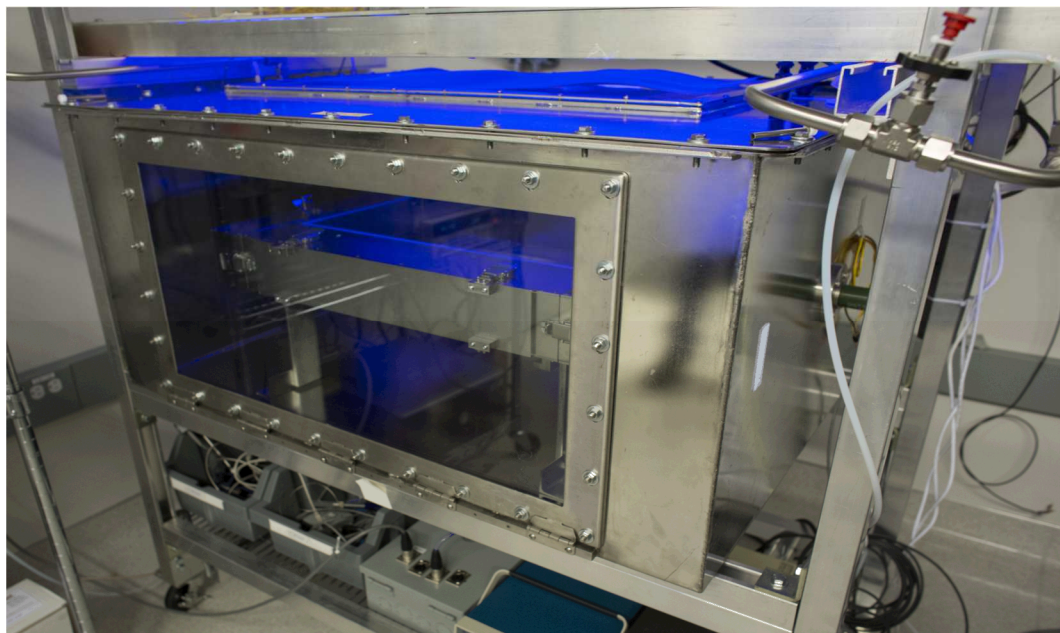


Figure 3 - Example of an actual installation of the IPPT test chamber

4.2 Preconditioning Room or Chamber

The IPPT test sample shall be preconditioned according to ASTM D5116 standard (ASTM, 2010) before testing to improve test repeatability. Preconditioning can be conducted in an electropolished stainless steel chamber that can maintain the same temperature and relative humidity as the test condition for a minimum of 48 hours. For this protocol, the preconditioning temperature and relative humidity shall be $23.0 \pm 2^{\circ}\text{C}$ and $50 \pm 5\%$ respectively. The chamber shall be supplied with clean air to prevent contamination of the IPPT test sample.

4.3 UV Pretreatment Chamber

The IPPT test sample shall be UV pretreated to decompose residual organic matter within the material¹. The pretreatment chamber shall be constructed from stainless steel while allowing for UV photoirradiation of the IPPT sample. The test specimen shall be irradiated with a UV lamp for a minimum of 16 hours. The UV irradiance on the surface of the test specimen shall be between 10 to 20 W/m^2 . The temperature and relative humidity shall be $23.0 \pm 2^{\circ}\text{C}$ and $50 \pm 5\%$ respectively while being supplied with clean air to prevent contamination of the IPPT test sample. The pretreatment chamber shall be shielded from external light.

4.4 Light Sources, Filters, Equipment and Indoor Lighting Conditions

¹ For example, photochemical binder degradation in some test samples may produce small radicals which generate VOCs by recombination (Gunschera et al., 2009). If this process is not isolated in the test protocol, the performance of toluene or formaldehyde removal by some IPPTs may be underestimated.

4.4.1 Light sources and filters

4.4.1.1 Indoor light source

The light source for indoor lighting environment shall be a halophosphate or triphosphor fluorescent lamp with a correlated colour temperature between 3800 to 4500 K. When a triphosphor fluorescent lamp is used for evaluating, the fluorescent lamp of the CIE 1974 general colour rendering index (Ra) defined by CIE 13.3 higher than 80 shall be selected. The test sample shall be irradiated uniformly through the window by the light source. The light source that requires warming up shall consider the use of black opaque cloth, shutter or blinds. The distance between the light source and the chamber shall be adjusted so that the illuminance on the IPPT test sample surface is 1000 ± 100 lx. The irradiance at 9 points on IPPT test sample (see 5.1.5) shall also be constant within ± 10 %. The illuminance shall be measured with an illuminance meter which has been calibrated by a calibration laboratory or manufacturer. The illuminance shall be maintained at 1000 ± 100 lx throughout the illumination phase of the tests. The chamber shall be shielded from external light if necessary.

4.4.1.2 UV sharp cut-off filter

Two types of UV sharp cut-off filters shall be used for testing: 1) a transmittance of 0.1 % or less at 400 nm, threshold limit wavelength of transmission (TLT) of 420 ± 5 nm, range of slope (RoS) of 25 ± 5 nm and average transmittance higher than 80 % between 450 to 780 nm (Type A); and 2) a transmittance of 0.1 % or less at 380 nm, threshold limit wavelength of transmission (TLT) is 415 ± 5 nm, range of slope (RoS) is 30 ± 5 nm and average transmittance higher than 80 % between 420 nm to 780 nm (Type B). When using the filter of different transmittance for testing, spectral transmittance shall be reported with a product name, product number, manufacturer, and thickness.

4.4.2 Indoor lighting conditions and selection of UV sharp cut-off filters

To set three kinds of indoor lighting conditions (condition A, condition B, condition C), the method of selecting the UV sharp cut-off filter shall be given as follows:

Condition A

Condition A is an indoor lighting condition by luminaire that transmits optical radiation of longer wavelength than 400 nm. For this condition, the type A filter shall be used.

Condition B

Condition B is an indoor lighting condition by luminaire that transmits optical radiation of longer wavelength than 380 nm. For this condition, the type B filter shall be used.

Condition C

Condition C is an indoor lighting condition by luminaire without any UV sharp cut-off filter.

4.4.3 UV and visible light measuring equipment

The visible light shall be measured in illuminance (lx) by using an illuminance meter. The illuminance meter shall be calibrated.

The UV light in the pretreatment chamber shall be measured in irradiance (W/m^2) by using a UV radiometer. The UV radiometer shall be calibrated.

4.5 Temperature and Relative Humidity

Temperature measurements in the airflow chamber shall be recorded using one of the following instruments: a) Resistance Temperature Detectors (RTD); b) thermistors; or c) thermocouples. Temperature sensors shall be calibrated and have an accuracy of least $\pm 0.5^\circ\text{C}$.

Humidity in the airflow chamber shall be recorded using either dew point or relative humidity sensors. Sensors employed shall be calibrated and have a minimum accuracy to provide a humidity reading of $\pm 5\%$ RH.

The temperature and humidity sensors shall be mounted such that measurements are taken near the midpoint of the airstream in the inner chamber and that their location and design shall be such that the airflow over the test sample is not affected.

4.6 Differential Pressure

The airflow chamber differential pressure (pressure relative to the ambient pressure outside the chamber), shall be monitored using pressure transducers capable to provide a minimum accuracy of $\pm 1\%$ of reading.

4.7 Data Acquisition System (DAS)

A DAS system shall be installed to automatically record all test parameters and conditions at the levels of accuracy and precisions outlined above. Sampling frequency of the DAS shall be sufficient to provide data at 1 minute increments at minimum. DAS readings are to be verified using handheld monitors that are calibrated to traceable standards. Reported values are to be converted to measured parameters using calibration curves developed for individual sensors.

4.8 Chamber Air Exchange Rate and Air Mixing

The chamber air exchange rate measurements shall be determined using concentration decay of tracer gas technique. Sulphur hexafluoride is recommended as a tracer gas. The procedure, similar to ASTM E 741 Test Method for "Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution" (ASTM, 2011) is recommended for chamber air exchange rate analysis. The airflow chamber air exchange rates can be used to determine its air tightness.

The airflow chamber shall have proper mixing verified via protocols described in ASTM D 5116 (2010) and ASHRAE Standard 129 (ASHRAE, 1997). A mixing level of higher than 80% shall be considered satisfactory.

4.9 Air Velocity

Prior to the test, air velocities over the installed IPPT sample in the inner chamber shall be determined using an omni-directional anemometer or directionally-sensitive anemometers. Examples of instruments measuring air velocity include hot-wire anemometer, hot-sphere and thermistor anemometer, ultrasonic anemometer, and laser-

doppler anemometer. The instrument should be able to measure air velocity within the range of 0.1 to 2 m/s at an accuracy of ± 0.05 m/s or $\pm 5\%$ of reading, whichever is greater. The resolution of the instrument should be at least 0.01 m/s. The response time of the instrument should be 0.2 seconds minimum. An averaging time of 1 min is appropriate for air velocity measurements. Measurements of air velocity over the installed IPPT sample shall be done with the inner chamber sealed.

4.10 Ozone Monitor

Ozone monitor employed in this test shall have a limit of detection of 2 ppb ozone at minimum and an accuracy of $\pm 2\%$ of reading. Chemiluminescence and UV-based detectors are suitable. All air sampling lines connected to the ozone monitor shall be made of Teflon (PTFE). Sample results shall be logged internally by the monitor or recorded at a minimum sampling interval of 1 minute. Paired analyzers (identical in design and sampling flow rate) can be used in order to conduct simultaneous inlet and outlet air sampling. The use of a single ozone monitor is allowed if background concentration of ozone is taken at the inlet side for at least 10 minutes at the beginning of the test.

4.11 Air Sampling and Analysis of Toluene

Air sampling from the inlet and outlet of the airflow chamber shall be conducted according to guidelines provided in ASTM D6196. The use of Tenax TA sorbent tubes for sampling is recommended and shall be in accordance to ASTM D6345. Sample analysis technique shall be consistent with the objective of determining toluene concentrations present in the collected air samples. For this purpose, GC/MS analysis is recommended. The selected sampling and analytical methods should have sufficient sensitivity and accuracy to provide a detection limit of $2 \mu\text{g}/\text{m}^3$ for toluene.

Air sampling pumps and controllers should be capable of accurately determining sampling volumes using the selected sorbent tubes within 5%.

4.12 Air Sampling and Analysis of Formaldehyde

Air sampling from the inlet and outlet of the airflow chamber shall be conducted according to guidelines provided in ASTM D5197. Sample analysis technique shall be consistent with the objective of determining the formaldehyde concentrations present in the collected air samples. For this purpose, HPLC analysis of DNPH derivatives following the ASTM 5197 procedure is recommended. The selected sampling and analytical methods should have sufficient sensitivity and accuracy to provide a detection limit of $2 \mu\text{g}/\text{m}^3$ for formaldehyde.

Air sampling pumps and controllers should be capable of accurately determining sampling volumes using the selected sorbent tubes within 5%.

5. Test Methods

5.1 General

5.1.1 Descriptions of IPPT Test Material Collection, Packaging, Transportation, and Storage

The test report shall include a detailed description of the procedure for the collection, packaging, transportation, and storage of the IPPT test materials to be tested. The intent is to avoid contamination of the IPPT test material while keeping the procedure practical. The procedure for material collection, packaging, transportation, and storage from the ISO 16000-11 is recommended.

A detailed description of IPPT test sample information including the product description, manufacturing history (site and date), IAQ related claims and photographs of the test sample. Complete all required information using the forms provided in Section 6.2.

5.1.2 IPPT Test Sample Preparation

The IPPT test sample shall be a part or component that is representative of the IPPT building material and representative of how it is used in the indoor environment. A loading ratio of the IPPT test sample ranging from 0.2 to 1.0 m²/m³ shall be used for this protocol. Treatment methods (e.g. priming, painting, spraying and plastering) on the IPPT material shall be reported. Detailed treatment materials and process must reflect typical usage and be agreed to by the client. The edges of the IPPT test sample shall be sealed with aluminum tape. A specimen holder shall be used such that the bottom surface of the test specimen shall be sealed from contact with the chamber air.

5.1.3 UV Pretreatment

If photocatalytic removal behavior is to be determined, then the IPPT test sample shall be irradiated with an ultraviolet lamp for a minimum of 16 hours in the UV pretreatment chamber to decompose residual organic matter on the sample for tests 1 to 3. The UV irradiance at the IPPT test sample surface shall be between 10 – 20 W/m². The chamber temperature and relative humidity shall be 23.0 ± 2 °C and 50 ± 5 % respectively while being supplied with clean air to prevent contamination of the IPPT test sample.

5.1.4 Preconditioning

The IPPT test sample, after completion of any treatment process and cutting/edge sealing for IPPT chamber loading, shall be preconditioned for a minimum of 48 hours. The temperature and relative humidity of the preconditioning chamber shall be 23.0 ± 2 °C and 50 ± 5 % respectively. The preconditioning chamber or room shall be supplied with clean air to prevent contamination of the IPPT test sample.

5.1.5 Background Condition

For performance assessment related to toluene or formaldehyde removal (Tests 1a and 1b), all the measurements shall be conducted in the airflow chamber under the following conditions:

- The air within the airflow chamber temperature shall be 23.0 ± 2 °C with relative humidity (RH) of 50 ± 5 %
- The air leakage of the airflow chamber shall be less than 0.5 % of its volume per minute at an overpressure of 1000 Pa or less than 5 % of the supply airflow rate.
- The air exchange rate of the airflow chamber shall be 0.5 ACH.

- The air velocity 1 – 2 cm above the IPPT surface at nine locations shall be within 0.1 – 0.3 m/s (see Figure 4).
- The lux levels above the IPPT surface at nine locations when the indoor lighting source is turned on shall be within 1000 lx \pm 100 lx (see Figure 4).
- The background chamber concentrations of the following parameters shall be:
 Ozone: < 5 ppb
 Formaldehyde²: < 10 $\mu\text{g}/\text{m}^3$
 Toluene³: < 10 $\mu\text{g}/\text{m}^3$

Background levels shall be determined from sampling the air at the chamber outlet. If the background levels are above these values, corrective actions to reduce their concentrations shall be taken before test commencement. These could be in the form of removal of potential sources or introducing new activated carbon filter in the inlet air supply line.

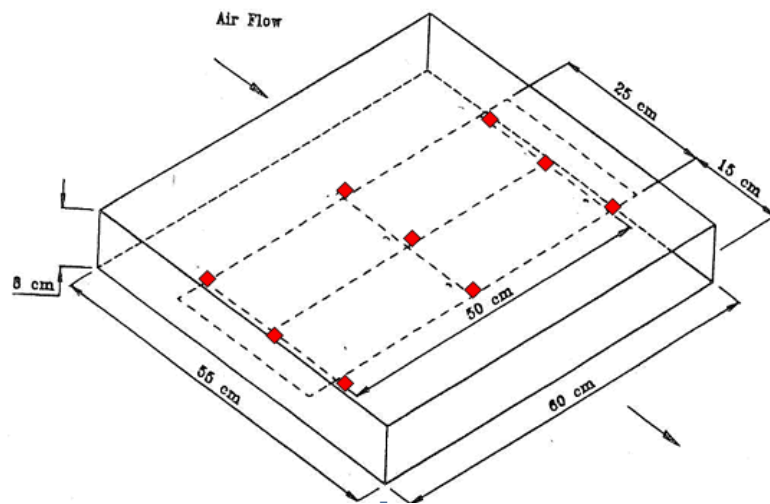


Figure 4 - Locations for air velocity and light measurements (red diamonds)

5.2 Tests 1 and 2: Initial removal of formaldehyde or toluene

5.2.1 Intent:

The intent of this test is to determine the initial removal of formaldehyde or toluene performance using IPPT test sample in the chamber. This test requires that formaldehyde or toluene be introduced into the airflow chamber at a constant emission rate and sampling be conducted in the chamber inlet and outlet air. The IPPT test sample shall be described as whether it is PCO- or sorptive-based. For a PCO-based IPPT, the procedure to evaluate formaldehyde and toluene removal shall be evaluated using Test 1a and 2a respectively. For a sorptive-based IPPT, the procedure to evaluate formaldehyde and toluene removal shall be evaluated using Test 1b and 2b respectively. If the PCO-based IPPT sample is expected to exhibit sorptive characteristics, the test

² for formaldehyde removal, re-emissions and by-product formation tests

³ for toluene removal and re-emission tests

shall require an initial sorptive phase followed by a light-activated phase to differentiate uptake rates between sorption and light.

5.2.2 Tests 1a and 1b: Testing Initial Removal of Formaldehyde

5.2.2.1 Test 1a: Formaldehyde removal and re-emission using PCO-based IPPT

- The IPPT test sample shall be UV pretreated and preconditioned as in Sections 5.1.3 and 5.1.4 respectively.
- With the indoor lighting source turned on, measure the lux levels at the 9 locations of inner chamber.
- Place the IPPT test sample in the middle of the inner chamber such that its surface is flush with the inner chamber floor.
- Measure the air velocity at the 9 locations at a height of 1-2 cm above the IPPT test sample with the inner chamber sealed.
- Seal the inner and outer chambers.
- Background conditions for the airflow chamber shall be as specified in Section 5.1.5.
- With the formaldehyde injection stream bypassing the test chamber, stabilize the injection until stable levels of approximately $100 \mu\text{g}/\text{m}^3$ ($\pm 10\%$) can be achieved. Commence injection of formaldehyde in the inlet of airflow chamber under dark condition and continue injection while maintaining stable levels of approximately $100 \mu\text{g}/\text{m}^3$ ($\pm 10\%$) in the chamber inlet.
- Sample the inlet and outlet air of the airflow chamber at the 24 hour mark under dark condition. If the removal of formaldehyde via sorption by test sample is more than 10% (see section 6.2):
 - Record that the PCO-based IPPT sample has sorptive capability.
 - The test under dark condition shall be continued for 96 hours to evaluate sorptive effects.
 - Air samples from the inlet and outlet chamber shall be taken at 48, 72 and 96 hrs under dark condition.
 - Immediately after the 96 hrs samples have been taken, the IPPT test sample shall be irradiated using the indoor lighting source with the illuminance on the test sample surface at $1000 \text{ lx} \pm 100 \text{ lx}$.
 - Sample the inlet and outlet air of the airflow chamber 120, 144 and 168 hrs after the IPPT test sample was irradiated.
 - Immediately after the 168 hrs samples have been taken, discontinue formaldehyde injection into the airflow chamber and turn off the indoor lighting source. Air samples from the inlet and outlet of the chamber shall be taken at 192, 216 and 240 hrs.

- After 240 hrs, flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber formaldehyde level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.
- If the removal of formaldehyde via sorption by test sample is equal or less than 10% (see section 6.2) after the 24 hours test under dark condition:
 - The IPPT test sample shall be irradiated using the indoor lighting source with the illuminance on the IPPT test sample surface at $1000 \text{ lx} \pm 100 \text{ lx}$.
 - Sample the inlet and outlet air of the airflow chamber 48, 72 and 96 hrs after the IPPT test sample was irradiated.
 - Immediately after the 96 hours of sample have been taken, discontinue formaldehyde injection into the airflow chamber and turn off the indoor lighting source.
 - Flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber formaldehyde level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.
- For all air samples, the following shall be recorded: sample location (inlet, outlet); sampling time; sampling tube make/model/serial number; sampling system components (pump/controllers); sampling rate (mL/min), (at least 200 mL/min), sampling start and stop time/date, sampling personnel name and discrete sample code (including Test ID and sample number). Laboratory blank samples shall be collect by briefly opening and closing clean cartridges co-located with air sample tubes during testing period.

5.2.2.2 Test 1b: Formaldehyde removal and re-emission using sorptive-based IPPT

- The IPPT test sample shall be preconditioned as in Section 5.1.4.
- Place the IPPT test sample in the middle of the inner chamber such that its sorptive surface is flush with the inner chamber floor.
- Measure the air velocity at the 9 locations at a height of 1-2 cm above the IPPT test sample with the inner chamber sealed.
- Seal the inner and outer chambers.
- Background conditions for the airflow chamber shall be as specified in Section 5.1.5.
- With the formaldehyde injection stream bypassing the test chamber, stabilize the injection until stable levels of approximately $100 \mu\text{g}/\text{m}^3 (\pm 10 \%)$ can be achieved. Commence injection of formaldehyde in the inlet of airflow chamber and continue injection while maintaining stable levels of approximately $100 \mu\text{g}/\text{m}^3 (\pm 10 \%)$ in the chamber inlet.
- Sample the inlet and outlet air of the airflow chamber. Air samples from the inlet and outlet airflow chamber shall be taken at 24, 48, 72 and 96 hrs after the IPPT test sample was placed in the chamber.

- After 96 hours, discontinue formaldehyde injection into the airflow chamber. Sample the inlet and outlet air of the airflow chamber. Air samples from the inlet and outlet airflow chamber shall be taken at 120, 144 and 168 hrs.
- After 168hrs, flush the chamber with clean air for at least 2.5 hrs at $N=1\text{ h}^{-1}$ to bring the chamber formaldehyde level below $10\text{ }\mu\text{g}/\text{m}^3$ and terminate the test.
- For all air samples, the following shall be recorded: sample location (inlet, outlet); sampling time; sampling tube make/model/serial number; sampling system components (pump/controllers); sampling rate (mL/min), (at least 200 mL/min), sampling start and stop time/date, sampling personnel name and discrete sample code (including Test ID and sample number). Laboratory blank samples shall be collected by briefly opening and closing clean cartridges co-located with air sample tubes during testing period.

5.2.3 Tests 2a and 2b: Testing initial removal of Toluene

5.2.3.1 Test 2a: Toluene removal and re-emission using PCO-based IPPT

- The IPPT test sample shall be UV pretreated and preconditioned as in Sections 5.1.3 and 5.1.4 respectively.
- With the indoor lighting source turned on, measure the lux levels at the 9 locations of inner chamber.
- Place the IPPT test sample in the middle of the inner chamber such that its surface is flush with the inner chamber floor.
- Measure the air velocity at the 9 locations at a height of 1-2 cm above the IPPT test sample with the inner chamber sealed.
- Seal the inner and outer chambers.
- Background conditions for the airflow chamber shall be as specified in Section 5.1.5.
- With the toluene injection stream bypassing the test chamber, stabilize the injection until stable levels of approximately $100\text{ }\mu\text{g}/\text{m}^3$ ($\pm 10\%$) can be achieved. Commence injection of toluene in the inlet of airflow chamber under dark condition and continue injection while maintaining stable levels of approximately $100\text{ }\mu\text{g}/\text{m}^3$ ($\pm 10\%$) in the chamber inlet.
- Sample the inlet and outlet air of the airflow chamber at the 24 hour mark under dark condition. If the removal of toluene via sorption by test sample is more than 10% (see section 6.2):
 - Note that the PCO-based IPPT sample has sorptive capability.
 - The test under dark condition shall be continued for 96 hours to evaluate the sorptive effects (Test 1b).
 - Air samples from the inlet and outlet chamber shall be taken at 48, 72 and 96 hrs under dark condition.

- Immediately after the 96 hrs samples have been taken, the IPPT test sample shall be irradiated using the indoor lighting source with the illuminance on the IPPT test sample surface at $1000 \text{ lx} \pm 100 \text{ lx}$.
- Sample the inlet and outlet air of the airflow chamber 120, 144 and 168 hrs after the IPPT test sample was irradiated.
- Immediately after the 168hrs samples have been taken, discontinue toluene injection into the airflow chamber and turn off the indoor lighting source. Air samples from the inlet and outlet of the chamber shall be taken at 192, 216 and 240 hrs.
- After 240 hrs, flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber toluene level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.
- If the removal of toluene via sorption by test sample is equal or less than 10% (see section 6.2) after the 24 hours test under dark condition:
 - The IPPT test sample shall be irradiated using the indoor lighting source with the illuminance on the IPPT test sample surface at $1000 \text{ lx} \pm 100 \text{ lx}$.
 - Sample the inlet and outlet air of the airflow chamber 48, 72 and 96 hrs after the IPPT test sample was irradiated.
 - Immediately after the 96 hours of sample have been taken, discontinue toluene injection into the airflow chamber and turn off the indoor lighting source.
 - Flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber toluene level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.
- For all air samples, the following shall be recorded: sample location (inlet, outlet); sampling time; sampling tube make/model/serial number; sampling system components (pump/controllers); sampling rate (mL/min), (50 – 200 mL/min), sampling start and stop time/date, sampling personnel name and discrete sample code (including Test ID and sample number). Laboratory blank samples shall be collect by briefly opening and closing clean cartridges co-located with air sample tubes during testing period.

5.2.3.2 Test 2b: Toluene removal and re-emission using sorptive - based IPPT

- The IPPT test sample shall be preconditioned as in Section 5.1.4.
- Place the IPPT test sample in the middle of the inner chamber such that its sorptive surface is flush with the inner chamber floor.
- Measure the air velocity at the 9 locations at a height of 1-2 cm above the IPPT test sample.
- Seal the inner and outer chambers.
- Background conditions for the airflow chamber shall be as specified in Section 5.1.5.

- With the toluene injection stream bypassing the test chamber, stabilize the injection until stable levels of approximately $100 \mu\text{g}/\text{m}^3$ ($\pm 10\%$) can be achieved. Commence injection of toluene in the inlet of airflow chamber and continue injection while maintaining stable levels of approximately $100 \mu\text{g}/\text{m}^3$ ($\pm 10\%$) in the chamber inlet.
- Sample the inlet and outlet air of the airflow chamber. Air samples from the inlet and outlet airflow chamber shall be taken at 24, 48, 72 and 96 hrs after the IPPT test sample was placed in the chamber.
- After 96 hours, discontinue toluene injection into the airflow chamber. Sample the inlet and outlet air of the airflow chamber. Air samples from the inlet and outlet airflow chamber shall be taken at 120, 144 and 168 hrs.
- After 168 hrs, flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber toluene level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.
- For all air samples, the following shall be recorded: sample location (inlet, outlet); sampling time; sampling tube make/model/serial number; sampling system components (pump/controllers); sampling rate (mL/min), (50 – 200 mL/min), sampling start and stop time/date, sampling personnel name and discrete sample code (including Test ID and sample number). Laboratory blank samples shall be collected by briefly opening and closing clean cartridges co-located with air sample tubes during testing period.

5.2.4 Data Analysis and Reporting

The removal performance indices for the IPPT measured from Tests 1 and 2 are the area specific removal rate (RRA) and the equivalent area specific ventilation rate (VRA). These are given in equations 1 and 2.

$$RR_A = (C_i - C_o) Q / A \quad \text{Equation 1}$$

Where RR_A is the area specific removal rate in $\mu\text{g}/\text{h}/\text{m}^2$; C_i is the inlet concentration of formaldehyde or toluene in $\mu\text{g}/\text{m}^3$; C_o is the outlet concentration of formaldehyde or toluene in $\mu\text{g}/\text{m}^3$; Q is the airflow rate of the chamber; and A is the surface area of the IPPT test sample.

$$VR_A = (C_i / C_o - 1) Q / A \quad \text{Equation 2}$$

Where VR_A is the area specific ventilation rate in $\text{m}^3/\text{h}/\text{m}^2$;

For sorptive based IPPT, report the average RR_A and VR_A between 48 and 96 hours.

For PCO based IPPT, if the test sample does not exhibit sorptive capacity, report the average RR_A and VR_A between 48 and 96 hours. If the test sample exhibit sorptive capacity, report the difference in average RR_A and VR_A between 120 and 168 hours with average RR_A and VR_A between 48 and 96 hours.

During the time period used to calculate the average RR_A and VR_A for sorptive based IPPT, if the final C_o concentration differ by more than half of its initial concentration,

calculate the time elapsed from the beginning of the test before half of the final C_o concentration has been reached. The time elapsed, t_e , is referred to as the time to reach breakthrough performance.

If the area specific removal rate is being compared with a reference sample (e.g. stainless steel, non-IPPT material or any material requested by manufacturer), the relative performance of the IPPT test sample can be determined by calculating its effectiveness, ε (Nazaroff, 2000). The effectiveness of the IPPT that relates the contaminant concentrations with and without IPPT (RR_A and $RR_{A, \text{ref}}$ respectively) can be expressed by the following equation:

$$\varepsilon = (RR_{A, \text{ref}} - RR_A) / RR_A \quad \text{Equation 3}$$

For evaluating re-emissions of captured formaldehyde or toluene from IPPT under Tests 1b and 2b, calculate the percentage (Re) of re-emitted toluene or formaldehyde at 168 hrs using the following equation:

$$\text{Re} = ([C_{o, 168h} - C_{i, 168h}] / [C_i - C_o]_{48h-96h}) 100 \% \quad \text{Equation 4a}$$

Where $C_{i, 168h}$ and $C_{o, 168h}$ are the respective inlet and outlet concentrations of formaldehyde or toluene at 168 hrs and $[C_i - C_o]_{48h-96h}$ are the average difference in inlet and outlet concentrations of formaldehyde or toluene between 48 hrs and 96 hrs.

For evaluating re-emissions of captured formaldehyde or toluene from PCO-based IPPT having sorptive properties under Tests 1a and 2a, calculate the percentage (Re) of re-emitted toluene or formaldehyde at 240 hrs using the following equation:

$$\text{Re} = ([C_{o, 240h} - C_{i, 240h}] / [C_i - C_o]_{48h-96h}) 100 \% \quad \text{Equation 4b}$$

Where $C_{i, 240h}$ and $C_{o, 240h}$ are the respective inlet and outlet concentrations of formaldehyde or toluene at 240 hrs and $[C_i - C_o]_{48h-96h}$ are the average difference in inlet and outlet concentrations of formaldehyde or toluene between 48 hrs and 96 hrs.

5.2.4.1 Test 1a or 2a: Calculation and expression of results

Calculate the area specific removal rate (RR_A) and the equivalent area specific ventilation rate PCO-based IPPT test sample. Report the average RR_A and VR_A between 48 and 96 hours if the 24 hours removal of formaldehyde or toluene via sorption by test sample is equal to or less than 10% (see section 6.2). If the 24 hours removal of formaldehyde or toluene via sorption by test sample is more than 10% (see section 6.2), report the difference between the average RR_A and VR_A measured between 120 and 168 hours with that measured between 48 and 96 hours.

If a reference material is tested, calculate the effectiveness using Equation 3.

Calculate the percentage of captured formaldehyde or toluene released at 240 hrs if IPPT sample exhibits sorptive capabilities.

5.2.4.2 Test 1a or 2a: Reporting

Describe in detail the air sampling equipment used (pumps, flow controllers, timing devices, sample collection media and its handling/preparation including cleaning).

Describe the analytical systems used for formaldehyde or toluene sample analysis (including analytical instrumentation, analysis conditions, calibration, and integration parameters). Report the blank - corrected values expressed as $\mu\text{g}/\text{m}^3$ (formaldehyde or toluene mass on sample cartridge – mass in blank cartridge) / sample volume) and limit of detection, LOD, ($\mu\text{g}/\text{m}^3$: assume a 1 L sample for toluene and 15 L sample for formaldehyde).

Describe the illumination on the IPPT test sample surface, indoor lighting conditions (condition A, condition B, condition C), air flow rate, air temperature and relative humidity of the airflow chamber and the surface area of the exposed IPPT test sample. Record the inlet and outlet formaldehyde or toluene concentrations

Use tables provided in Section 6 to record formaldehyde or toluene initial removal rate performance.

5.2.4.3 Test 1b or 2b: Calculation and expression of results

Calculate the area specific removal rate (RR_A) and the equivalent area specific ventilation rate sorptive-based IPPT test. Report the time elapsed if breakthrough is observed.

If a reference material is tested, calculate the effectiveness using Equation 3. Calculate the percentage of re-emitted toluene or formaldehyde at 168 hrs.

5.2.4.4 Test 1b and 2b: Reporting

Describe in detail the air sampling equipment used (pumps, flow controllers, timing devices, sample collection media and its handling/preparation including cleaning).

Describe the analytical systems used for formaldehyde or toluene sample analysis (including analytical instrumentation, analysis conditions, calibration, and integration parameters). Report the blank - corrected values expressed as $\mu\text{g}/\text{m}^3$ (formaldehyde or toluene mass on sample cartridge – mass in blank cartridge) / sample volume) and limit of detection, LOD, ($\mu\text{g}/\text{m}^3$: assume a 1 L sample for toluene and 15 L sample for formaldehyde).

Describe the air flow rate, air temperature and relative humidity of the airflow chamber and the surface area of the exposed IPPT test sample. Record the inlet and outlet formaldehyde or toluene concentrations.

Use tables provided in Section 6 to record formaldehyde or toluene initial removal rate performance.

5.3 Test 3: By-product formation

5.3.1 Intent:

The intent of this test is to determine if PCO-based IPPT would generate harmful by-products in the airflow chamber. This test is similar to Test 2a with the exception that it requires ozone and formaldehyde measurements to be conducted and only toluene as a challenge VOC.

5.3.2 Tests 3: Testing ozone and formaldehyde formation

- The IPPT test sample shall be UV pretreated and preconditioned as in Sections 5.1.3 and 5.1.4 respectively.
- With the indoor lighting source turned on, measure the lux levels at the 9 locations of inner chamber.
- Place the IPPT test sample in the middle of the inner chamber such that its surface is flush with the inner chamber floor.
- Measure the air velocity at the 9 locations at a height of 1-2 cm above the IPPT test sample.
- Seal the inner and outer chambers.
- Background conditions for the airflow chamber shall be as specified in Section 5.1.5.
- Commence injection of toluene in the inlet of airflow chamber under dark condition and continue injection until stable levels of approximately $100 \mu\text{g}/\text{m}^3$ ($\pm 10\%$) have been maintained in the inlet of the airflow chamber.
- Sample the inlet and outlet air of the airflow chamber at the 24 hour mark under dark condition. If the removal of toluene via sorption by test sample is more than 10% (see section 6.2):
 - Record that the PCO-based IPPT sample has sorptive capability.
 - The test under dark condition shall be continued for additional 72 hours to evaluate the sorptive effects (Test 1b).
 - Toluene samples from the inlet and outlet chamber shall be taken at 24, 48, 72 and 96 hrs under dark condition.
 - Immediately after the 96 hrs samples have been taken, the IPPT test sample shall be irradiated using the indoor lighting source with the illuminance on the IPPT test sample surface at $1000 \text{ lx} \pm 100 \text{ lx}$.
 - Sample the inlet and outlet air for toluene of the airflow chamber at 120, 144 and 168 hrs after the IPPT test sample was irradiated.
 - Immediately after the 168 hrs samples have been taken, discontinue toluene injection into the airflow chamber, turn off the indoor lighting source and flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber toluene level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.
 - Formaldehyde as a by-product sampling: Air samples from the inlet and outlet airflow chamber shall be taken at 0, 24, 48, 72, 96, 102, 120, 144 and 168 hrs.
 - Ozone as a by-product sampling: Turn on two ozone monitors and allow the monitors to warm up for the period recommended by the manufacturer, and

then confirm that both units are recording the same background ozone concentration (± 2 ppb). Connect using PTFE air sampling lines from the two ozone monitors to the inlet and outlet airflow chamber.

- If only one ozone monitor is used, measure the inlet concentration for 10 minutes before the toluene injection and use the average value as the background concentration. Connect the air sampling line from the ozone monitor to the outlet airflow chamber.
- Record ozone levels throughout the experiment at a minimum sampling interval of 1 minute. Plot ozone data (background corrected if one monitor is used) and calculate average values and standard deviations.
- If the removal of toluene via sorption by test sample is equal to or less than 10% (see section 6.2) after 24 hours under dark condition:

- The IPPT test sample shall be irradiated using the indoor lighting source with the illuminance on the IPPT test sample surface at $1000 \text{ lx} \pm 100 \text{ lx}$.

- Sample the inlet and outlet air of the airflow chamber for toluene at 24, 48, 72 and 96 hrs after the IPPT test sample was irradiated.

- Immediately after the 96 hours of sample have been taken, discontinue toluene injection into the airflow chamber, turn off the indoor lighting source, flush the chamber with clean air for at least 2.5 hrs at $N=1 \text{ h}^{-1}$ to bring the chamber toluene level below $10 \mu\text{g}/\text{m}^3$ and terminate the test.

- Formaldehyde as a by-product sampling: Air samples from the inlet and outlet airflow chamber shall be taken at 0, 24, 30, 48, 72 and 96 hrs after the IPPT test sample was irradiated. For all air samples, the following shall be recorded: sample location (inlet, outlet); sampling time; sampling tube make/model/serial number; sampling system components (pump/controllers); sampling rate (mL/min), (50 – 200 mL/min), sampling start and stop time/date, sampling personnel name and discrete sample code (including Test ID and sample number). Laboratory blank samples shall be collected by briefly opening and closing clean cartridges co-located with air sample tubes during testing period.

- Ozone as a by-product sampling: Turn on two ozone monitors and allow the monitors to warm up for the period recommended by the manufacturer, and then confirm that both units are recording the same background ozone concentration (± 2 ppb). Connect using PTFE air sampling lines from the two ozone monitors to the inlet and outlet airflow chamber.

If only one ozone monitor is used, measure the inlet concentration for 10 minutes before the toluene injection and use the average value as the background concentration. Connect the air sampling line from the ozone monitor to the outlet airflow chamber.

Record ozone levels throughout the experiment at a minimum sampling interval of 1 minute. Plot ozone data (background corrected if one monitor is used) and calculate average values and standard deviations.

- For all toluene and formaldehyde air samples, the following shall be recorded: sample location (inlet, outlet); sampling time; sampling tube make/model/serial number; sampling system components (pump/controllers); sampling rate (mL/min), (50 – 200 mL/min), sampling start and stop time/date, sampling

personnel name and discrete sample code (including Test ID and sample number). Laboratory blank samples shall be collected by briefly opening and closing clean cartridges co-located with air sample tubes during testing period.

5.3.3 Test 3: Reporting

Describe in detail the air sampling equipment used (pumps, flow controllers, timing devices, sample collection media and its handling/preparation including cleaning).

Describe the analytical systems used for formaldehyde or toluene sample analysis (including analytical instrumentation, analysis conditions, calibration, and integration parameters). Report the blank - corrected values expressed as $\mu\text{g}/\text{m}^3$ (formaldehyde or toluene mass on sample cartridge – mass in blank cartridge) / sample volume) and limit of detection, LOD, ($\mu\text{g}/\text{m}^3$: assume a 1 L sample for toluene and 15 L sample for formaldehyde).

Describe the illumination on the IPPT test sample surface, air flow rate, air temperature and relative humidity of the airflow chamber and the surface area of the exposed IPPT test sample. Record the inlet and outlet formaldehyde or toluene concentrations as well as ozone concentrations.

Calculate formaldehyde and ozone formation rates using the tables in Section 6.

5.3.3.1 Formaldehyde

Calculate the area specific emission rate (BR_f) of formaldehyde as a result of by-product formation of the IPPT test sample using the following equation:

$$BR_f = Q (C_o - C_i) / A \quad \text{Equation 5}$$

Where BR_f is the formaldehyde by-product formation rate, Q is the airflow rate of the airflow chamber, A is the area of the exposed IPPT sample, C_i is the inlet formaldehyde concentration after the IPPT test sample was irradiated and C_o is the outlet formaldehyde concentration after the IPPT test sample was irradiated.

Next, calculate the expected 'standard' emission rate which will give a Health Canada recommended residential IAQ guideline steady state formaldehyde concentration of 40 ppb ($50 \mu\text{g}/\text{m}^3$) in a typical Canadian room using equation 6:

$$E_{std,f} = \left(C_{std,f} - C_{out,f} \right) \cdot N_C \cdot V_C \quad \text{Equation 6}$$

Where $E_{std,f}$ is the 'standard' emission rate for formaldehyde (mg/h), $C_{std,f}$ is the 'standard' concentration for formaldehyde served as the threshold guideline (mg/m³), $C_{out,f}$ is the outdoor concentration for formaldehyde during summer (mg/m³), V_C is the interior volume of a typical Canadian room (m³) and N_C is the ventilation rate of a typical Canadian room (h⁻¹)

Median ambient concentration of 0.575 ppb (0.77 µg/m³) was provided by Aiello and McLaren (2009). Typical values of Canadian residential room volume are obtained from the intervention field study conducted in Quebec City (Lajoie et al., 2015). Data obtained from 83 houses recorded mean volume of 28 m³. Reardon (2007) measured ventilation rates 3848, 12735 and 4162 buildings from Ottawa Vancouver, and Saskatoon respectively. Reported mean ventilation rates for the 3 respective cities were 0.4, 0.4 and 0.3 h⁻¹. Gilbert et al (2006) measured mean ventilation rates of 0.2 h⁻¹ in 96 Quebec City homes while the intervention field study conducted in Quebec City recorded 0.3 h⁻¹. The average of the ventilation rates data from these cities is used (0.3 h⁻¹).

Using the above values, the calculated $E_{std,f}$ amounts to 0.41 mg/h.

Evaluation Criteria:

The increase in formaldehyde emission as a byproduct should be below 'standard' emission rate that is calculated from the Health Canada recommended residential IAQ guideline steady state formaldehyde concentration of 40 ppb in a typical Canadian room. This 'standard' emission rate has to be normalized to the expected area of IPPT covering. Therefore the evaluation criteria are dependent on whether the IPPT is used for wall, ceiling or floor surfaces. For this protocol, the total wall, ceiling and floor areas are obtained from the Quebec City study (Lajoie et al., 2015). The respective areas for walls, ceiling and floor are 32.7, 11.8 and 11.8 m².

- For wall based IPPT:
 - Pass: By-product emission rate, ER < 12.5 µg/h/m²
 - Fail: By-product emission rate, ER ≥ 12.5 µg/h/m²
- For ceiling or floor based IPPT:
 - Pass: By-product emission rate, ER < 34.7 µg/h/m²
 - Fail: By-product emission rate, ER ≥ 34.7 µg/h/m²

5.3.3.2 Ozone

Calculate the area specific emission rate (BR_o) of ozone as a result of by-product formation of the IPPT test sample using the following equation:

$$BR_o = Q (C_o - C_i) / A$$

Equation 7

Where BR_o is the ozone by-product formation rate, Q is the airflow rate of the airflow chamber, A is the area of the exposed IPPT sample, C_i is the inlet ozone concentration after the IPPT test sample was irradiated and C_o is the outlet ozone concentration after the IPPT test sample was irradiated.

Next, calculate the expected 'standard' emission rate which will give a Health Canada recommended residential IAQ guideline steady state ozone concentration of 20 ppb (40 $\mu\text{g}/\text{m}^3$) in a typical Canadian room using equation 8:

$$E_{std,o} = C_{std,o} \left(k_d \cdot \frac{A_C}{V_C} + N_C \right) \cdot V_C - C_{out,o} \cdot N_C \cdot V_C \quad \text{Equation 8}$$

Where $E_{std,o}$ is the 'standard' emission rate for ozone (mg/h), $C_{std,o}$ is the 'standard' concentration for ozone served as the threshold guideline (mg/m³), $C_{out,o}$ is the daytime outdoor concentration for ozone during summer (mg/m³), k_d is the the ozone deposition velocity (m/h), A_C is the interior surface area of a typical Canadian room (m²), V_C is the interior volume of a typical Canadian room (m³) and N_C is the ventilation rate of a typical Canadian room (h⁻¹)

The calculation of $E_{std,o}$ is to be determined assuming the following conditions: 1) outdoor ozone concentration during daytime in summer, 2) building ventilation rates in a typical Canadian room during summer, 3) typical room volume of Canadian room, 4) ozone deposition velocity and interior area and volume is representative of that in a typical Canadian room.

Liu et al (1995) conducted an ozone exposure assessment study in Toronto, Ontario, during the winter and summer of 1992. Indoor, outdoor and personal exposure measurements were taken weekly during the winter and daily in the summer in 40 homes. They reported mean daytime home outdoor ozone concentration during summer of 19.1 ppb (38.2 $\mu\text{g}/\text{m}^3$). A typical value of Canadian residential room volume of 28 m³ is obtained from the intervention field study conducted in Quebec City where 83 rooms were evaluated (Lajoie et al., 2015). The average ventilation rate of 0.3 h⁻¹ is used from data of Canadian houses of various cities is used (Reardon, 2007; Gilbert et al, 2006; Lajoie et al., 2015). Weschler (2000) summarized ozone deposition velocities and A_C/V_C values measured from 22 studies where 4 involves residences. The average product of deposition velocity with A_C/V_C for the 4 residential studies is 4.6 h⁻¹.

Using the above values, the calculated $E_{std,o}$ amounts to 5.2 mg/h.

Evaluation Criteria:

The increase in ozone emission as a by-product should be below 'standard' emission rate that is calculated from the Health Canada recommended residential IAQ guideline steady state ozone concentration of 20 ppb in a typical Canadian room. This 'standard' emission rate has to be normalized to the expected area of IPPT covering. Therefore the evaluation criteria is dependent on the whether the IPPT is used for wall, ceiling or floor surfaces. For this protocol, the total wall, ceiling and floor areas are obtained from the Quebec City study (Lajoie et al., 2015). The respective areas for walls, ceiling and floor are 32.7, 11.8 and 11.8 m².

- For wall based IPPT:
 - Pass: By-product emission rate, $BR_o < 160 \mu\text{g} / \text{h}/\text{m}^2$
 - Fail: By-product emission rate, $BR_o \geq 160 \mu\text{g} / \text{h}/\text{m}^2$
- For ceiling or floor based IPPT:
 - Pass: By-product emission rate, $BR_o < 440 \mu\text{g} / \text{h}/\text{m}^2$
 - Fail: By-product emission rate, $BR_o \geq 440 \mu\text{g} / \text{h}/\text{m}^2$

6. Test Report

The test report shall include the following information:

- IPPT Test Sample Description
- IPPT Test Sample Production Date
- IPPT Test Sample Receipt Date
- IPPT Test Sample Source
- IPPT Test Sample Technology (Sorbptive; PCO; both)
- Description of IPPT Test Sample Collection and Handling
- IPPT Test Sample Age at Test Start
- Document any IAQ-related claims made for the IPPT Test Sample
- Record information from any certificates on performance attached or supplied with the IPPT Test Sample
- Photograph of the IPPT Test Sample
- Test Laboratory Details
- Evaluation Test Reports (Results)
- Evaluation Summary

6.1 Sample Test Report

A) IPPT Test Sample Description:

Name: _____

Production Date: _____

Receipt Date: _____

Test Start Date: _____

Test Sample Age at Test Start: _____

IPPT Test Sample Technology (Sorptive; PCO; both):

- Sorptive-based ☐
- PCO-based ☐
- Sorptive and PCO-based ☐

Description of IPPT Test Sample Collection and Handling

- Test Sample Source: _____
- Test Sample Handling: _____
- Test Sample treatment methods and materials:

- Test Sample Details:
 - Final Dimensions, l x w x d (mm): _____
 - Mass, Initial / Final (g): _____
 - Specimen Density (g/cm³): _____
 - Exposed Surface(s): _____
 - Exposed Surface Area (m²): _____

IAQ-related performance claims from Manufacturer's advertising/operational literature:

- _____
- _____
- _____
- _____

IPPT Test Sample Photos and Diagrams:

B) Test Lab Details:

Lab Name and Location: _____

Contact Name: _____

6.2 Sample Evaluation Test Reports

6.2.1 Evaluation Test 1a Report: Formaldehyde removal using PCO-based IPPT

Test Sample: (Specimen/Reference)

a) Airflow Chamber Conditions

- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____
- Air leakage (%) : _____
- Air-exchange rate (h^{-1}) : _____
- Surface air velocity (ms^{-1}) : _____ \pm _____
- Background formaldehyde ($\mu\text{g}/\text{m}^3$): _____

b) UV Pretreatment Results:

- Total UV-pretreatment time (hr): _____
- Surface UV irradiance (W/m^2): _____ \pm _____
- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____

c) Preconditioning Results:

- Total preconditioning time (hr): _____
- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____

d) Test Results:

- Removal via sorption under dark condition

Table 1. Removal via sorption under dark condition

	Formaldehyde concentration		Removal via sorption of IPPT test sample
	inlet ($\mu\text{g}/\text{m}^3$)	outlet ($\mu\text{g}/\text{m}^3$)	(inlet-outlet / inlet) x 100 %
Test Result:			

- Indoor lighting condition (A/B or C): _____
- Formaldehyde removal testing under indoor lighting
Surface indoor lighting lux level: _____ \pm _____

Table 2. Formaldehyde concentrations under indoor lighting condition testing

	Formaldehyde concentration		Area specific removal rate (RR _A)	Area specific ventilation rate (VR _A)
Test Result:	inlet (µg/m ³)	outlet (µg/m ³)	RR _A (µg/h /m ²)	VR _A (m ³ /h /m ²)
24 hours				
48 hours				
72 hours				
96 hours				
120 hours				
144 hours				
168 hours				

Average area specific removal rate ($\mu\text{g/h /m}^2$): \pm
 Average area specific ventilation rate ($\mu\text{g/h /m}^2$): \pm ⁴

Effectiveness (if reference test performed): _____

Re-emission (Re): ____% (if removal via sorption under dark condition > 10%)

⁴ Calculate area specific removal rate and area specific ventilation rate attributed to light irradiance only (see Section 5.2.4).

6.2.2 Test 1b Report: Formaldehyde removal using sorptive-based IPPT

Test Sample: (Specimen/Reference)

a) Airflow Chamber Conditions

- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____
- Air leakage (%) : _____
- Air-exchange rate (h^{-1}) : _____
- Surface air velocity (ms^{-1}) : _____ \pm _____
- Background formaldehyde ($\mu\text{g}/\text{m}^3$): _____

b) Preconditioning Results:

- Total preconditioning time (hr): _____
- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____

c) Test Results:

Table 3. Formaldehyde concentrations under testing

	Formaldehyde concentration		Area specific removal rate (RR_A)	Area specific ventilation rate (VR_A)
Test Result:	inlet ($\mu\text{g}/\text{m}^3$)	outlet ($\mu\text{g}/\text{m}^3$)	RR_A ($\mu\text{g}/\text{h} / \text{m}^2$)	VR_A ($\text{m}^3/\text{h} / \text{m}^2$)
24 hours				
48 hours				
72 hours				
96 hours				

Average area specific removal rate ($\mu\text{g}/\text{h} / \text{m}^2$): _____ \pm _____

Average area specific ventilation rate ($\mu\text{g}/\text{h} / \text{m}^2$): _____ \pm _____

Effectiveness (if reference test performed): _____

Re-emission (Re): _____ %

Time elapsed, t_e , (if breakthrough noted): _____

6.2.3 Test 2a Report: Toluene removal using PCO-based IPPT

Test Sample: (Specimen/Reference)

a) Airflow Chamber Conditions

- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____
- Air leakage (%) : _____
- Air-exchange rate (h^{-1}) : _____
- Surface air velocity (ms^{-1}) : _____ \pm _____
- Background toluene ($\mu\text{g}/\text{m}^3$): _____

b) UV Pretreatment Results:

- Total UV-pretreatment time (hr): _____
- Surface UV irradiance (W/m^2): _____ \pm _____
- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____

c) Preconditioning Results:

- Total preconditioning time (hr): _____
- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____

d) Test Results:

- Removal via sorption under dark condition

Table 4. Removal via sorption under dark condition

	Toluene concentration		Removal via sorption of IPPT test sample
	inlet ($\mu\text{g}/\text{m}^3$)	outlet ($\mu\text{g}/\text{m}^3$)	(inlet-outlet / inlet) x 100 %
Test Result:			

- Indoor lighting condition (A/B or C): _____
- Toluene removal testing under indoor lighting
Surface indoor lighting lux level: _____ \pm _____

Table 5. Toluene concentrations under indoor lighting condition testing

	Toluene concentration		Area specific removal rate (RR _A)	Area specific ventilation rate (VR _A)
Test Result:	inlet (µg/m ³)	outlet (µg/m ³)	RR _A (µg/h /m ²)	VR _A (m ³ /h /m ²)
24 hours				
48 hours				
72 hours				
96 hours				
120 hours				
144 hours				
168 hours				

Average area specific removal rate ($\mu\text{g/h /m}^2$): ±

Average area specific ventilation rate ($\mu\text{g/h /m}^2$): ±⁵

Effectiveness (if reference test performed): _____

Re-emission (Re): _____% (if removal via sorption under dark condition > 10%)

⁵ Calculate area specific removal rate and area specific ventilation rate attributed to light irradiance only (see Section 5.2.4).

6.2.4 Test 2b Report: Toluene removal using sorptive-based IPPT

Test Sample: (Specimen/Reference)

a) Airflow Chamber Conditions

- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____
- Air leakage (%) : _____
- Air-exchange rate (h^{-1}) : _____
- Surface air velocity (ms^{-1}) : _____ \pm _____
- Background toluene ($\mu\text{g}/\text{m}^3$): _____

b) Preconditioning Results:

- Total preconditioning time (hr): _____
- Relative humidity (%) : _____ \pm _____
- Temperature (°C) : _____ \pm _____

c) Test Results: Toluene removal testing

Table 6. Toluene concentrations under testing

	Toluene concentration		Area specific removal rate (RR_A)	Area specific ventilation rate (VR_A)
Test Result:	inlet ($\mu\text{g}/\text{m}^3$)	outlet ($\mu\text{g}/\text{m}^3$)	RR_A ($\mu\text{g}/\text{h} / \text{m}^2$)	VR_A ($\text{m}^3/\text{h} / \text{m}^2$)
24 hours				
48 hours				
72 hours				
96 hours				

Average area specific removal rate ($\mu\text{g}/\text{h} / \text{m}^2$): _____ \pm _____

Average area specific ventilation rate ($\mu\text{g}/\text{h} / \text{m}^2$): _____ \pm _____

Effectiveness (if reference test performed): _____

Re-emission (Re): _____ %

Time elapsed, t_e , (if breakthrough noted): _____

6.2.5 Test 3 Report: By-product formation

Test Sample: (Specimen/Reference)

a) Airflow Chamber Conditions

- Relative humidity (%) : _____ \pm _____
- Temperature ($^{\circ}\text{C}$) : _____ \pm _____
- Air leakage (%) : _____
- Air-exchange rate (h^{-1}) : _____
- Surface air velocity (ms^{-1}) : _____ \pm _____
- Background concentrations
 - Toluene ($\mu\text{g}/\text{m}^3$): _____
 - Ozone (ppb): _____
 - Formaldehyde ($\mu\text{g}/\text{m}^3$): _____

b) UV Pretreatment Results:

- Total UV-pretreatment time (hr): _____
- Surface UV irradiance (W/m^2): _____ \pm _____
- Relative humidity (%) : _____ \pm _____
- Temperature ($^{\circ}\text{C}$) : _____ \pm _____

c) Preconditioning Results:

- Total preconditioning time (hr): _____
- Relative humidity (%) : _____ \pm _____
- Temperature ($^{\circ}\text{C}$) : _____ \pm _____

d) By-product formation results:

- Formaldehyde

Table 7. Formaldehyde as a by-product formation under indoor lighting illumination

Time after irradiance	Formaldehyde concentration		By-product formation rate (BR_f)
Test Result:	inlet ($\mu\text{g}/\text{m}^3$)	outlet ($\mu\text{g}/\text{m}^3$)	BR_f ($\mu\text{g}/\text{h}/\text{m}^2$)
6 hours			
24 hours			
48 hours			
72 hours			

Average by-product formation rate ($\mu\text{g}/\text{h}/\text{m}^2$) : _____ \pm _____

Evaluation Criteria:

Formaldehyde (as a by-product) formation rate < 'standard' emission rate: (**Pass** / **Fail**): _____

- Ozone

Table 8. Ozone as a by-product formation under indoor lighting illumination

	Ozone concentration		By-product formation rate (BR _o)
Test Result:	inlet (µg/m ³)	outlet (µg/m ³)	BR _o (µg/h/m ²)
Average			

Inlet measurements:

Time start: _____

Time end: _____

Outlet measurements:

Time start: _____

Time end: _____

Average by-product formation rate (µg/h/m²): _____ ± _____

Evaluation Criteria:

Ozone (as a by-product) formation rate < 'standard' emission rate: (**Pass** / **Fail**): _____

6.3 Evaluation Summary

Test 1: Formaldehyde Removal Performance

- **Test 1a: Tested as PCO-based IPPT** (Yes / No): _____
 - Removal via sorption under dark condition: _____
 - Formaldehyde area-specific removal rate (PCO): _____
 - Formaldehyde area-specific ventilation rate (PCO): _____
 - Effectiveness: _____
 - Reference material for effectiveness: _____
 - Re-emissions of formaldehyde: _____
- **Test 1b: Tested as sorptive-based IPPT** (Yes / No): _____
 - Formaldehyde area-specific removal rate (sorptive): _____
 - Formaldehyde area-specific ventilation rate (sorptive): _____
 - Effectiveness: _____
 - Reference material for effectiveness: _____
 - Re-emissions of formaldehyde: _____
 - Elapsed time: _____

Test 2: Toluene Removal Performance

- **Test 2a: Tested as PCO-based IPPT** (Yes / No): _____
 - Removal via sorption under dark condition: _____
 - Toluene area-specific removal rate (PCO): _____
 - Toluene area-specific ventilation rate (PCO): _____
 - Effectiveness: _____
 - Reference material for effectiveness: _____
 - Re-emissions of toluene: _____
- **Test 2b: Tested as sorptive-based IPPT** (Yes / No): _____
 - Toluene area-specific removal rate (sorptive): _____
 - Toluene area-specific ventilation rate (sorptive): _____
 - Effectiveness: _____
 - Reference material for effectiveness: _____
 - Re-emissions of toluene: _____
 - Elapsed time: _____

Test 3: By-product Formation

- Formaldehyde (as a by-product) formation rate: (Pass / Fail) _____
- Ozone (as a by-product) formation rate: (Pass / Fail) _____

Appendix A - INFORMATIVE

Technologies

Indoor passive panel technologies (IPPT) are commercially available building materials specially designed to reduce indoor concentrations of chemical and biological contaminants via physical and/or chemical processes. Depending on processes, IPPTs have various indoor pollutant capture, retention strength and pollutant capacity.

The reduction of indoor pollutant concentration using IPPT does not rely on increased ventilation that is normally associated with increased energy consumption. IPPT has the ability to improve indoor air quality with little reliance on energy. This is because there are no added mechanical forces involved in the uptake of pollutants onto the surfaces. As an alternative to conventional active (flow through) pollutant removal systems, IPPT remove indoor pollutants through pollutant contact via normal airflows in the occupied space of buildings.

There are several IPPT based processes involved in the removal of indoor pollutants. These process include sorptive based IPPTs and PCO based IPPTs. Sorptive based IPPTs rely on adsorption and chemisorptions processes. PCO based IPPTs rely on the use of photocatalysts on building materials illuminated with either ultraviolet or indoor light radiation.

Sorptive – based IPPT process

For chemical pollutants such as volatile organic compounds (VOCs), their sorption through IPPT can be brought about by adsorption, absorption and chemisorption processes. These are described below.

Adsorption: This process results from the electrostatic interaction between the VOC and the IPPT material. This process creates a film of the VOC (adsorbate) on the surface of the IPPT (adsorbent). Solid adsorbents used in IPPT-based building materials include activated charcoal and several other materials such as silica gel, activated alumina, zeolites, porous clay minerals, and molecular sieves. These materials are useful as adsorbents due to their large internal surface area, stability, and low cost.

Absorption: This process is where the VOC molecules enter IPPT material with the VOC molecules taken up by the IPPT volume, not by the surface (as in the case for adsorption).

Chemisorption: This process involves electron transfer and is essentially a bond-forming chemical reaction between the adsorbent and the adsorbate. Chemical reaction occurs with the VOC and the IPPT (elements or with other reactive reagents which are manufactured into the IPPT based materials). The sorbent forms chemical bonds with the VOC, which in turn, binds it to the sorbent substrate or converts it into more benign chemical compounds. Once bound, the contaminant is chemically altered and cannot escape back into the air stream.

Some issues associated with sorptive based IPPT:

1. Some sorptive IPPTs adsorb effectively certain gaseous indoor air pollutants (e.g. volatile organic compounds), but will not efficiently adsorb very volatile organic compounds (VVOCs) and low molecular weight gases such as formaldehyde.

2. The rate of adsorption (efficiency) decreases with the amount of pollutant captured -- thus sorptive based IPPT has fixed adsorption capacities.
3. Some sorptive-based IPPT may re-emit captured VOCs upon saturation becoming a pollution source themselves. In addition, certain environmental conditions (elevated temperatures, relative humidity, air velocity) may cause re-emissions.
4. Surface treatment (e.g. paint, prime, wallpaper) or particle soiling on IPPT surfaces may affect the performance by hindering contact between pollutant and IPPT material.
5. Captured VOCs of certain classes, such as unsaturated hydrocarbons, within the IPPT may react heterogeneously with reactive airborne pollutants in the air (e.g. ozone). The reactions may form harmful by-products such as formaldehyde and ultrafine particles.

PCO-based IPPT process

For chemical pollutants such as VOCs, PCO is used for their removal via a process of shining ultraviolet light (UV) or visible light onto a catalytic surface composed of a metal oxide (e.g. TiO₂). Theoretically, this process creates a chemical reaction that converts airborne VOCs into less harmful substances. The photocatalyst absorbs photons of ultraviolet light or visible light to drive oxidation and reduction reactions on the catalyst surface. Highly reactive species (hydroxyl radicals and super-oxide ions) formed from these reactions oxidize VOCs to carbon dioxide and water.

Traditionally, PCO technology relying on traditional photocatalysts such as TiO₂ and ZnO requires UV light for activation thus making it appealing for outdoor applications. However, the band edges of these photocatalysts lie in the UV region which makes them inactive under visible light irradiation. New catalytic surfaces employing surface modification via organic materials/semiconductor coupling and band gap modification through doping with metals and nonmetals or creation of oxygen vacancies and oxygen sub-stoichiometry can use visible light to make it possible for this technology to be used for indoor applications.

Some issues associated with PCO based PP:

1. PCO based IPPT may not just produce hydroxyl radicals and superoxide ions, but also produce ozone and formaldehyde. These reaction by-products are associated with human health effects when inhaled and are regulated by Health Canada.
2. Surface treatment (e.g. paint, prime, wallpaper) or particle soiling on IPPT surfaces may affect the performance by hindering contact between pollutant and IPPT material.
3. Environmental conditions (temperatures, relative humidity) may affect performance.
4. PCO based IPPT may not perform effectively under indoor lighting conditions due to very low UV levels.

Existing standardization related to IPPT performance

Currently, available standards to test performance of indoor passive panel technologies to remove chemical pollutants are sorptive- and PCO-based IPPT standards. These are discussed below:

Sorptive – based IPPT standards

ISO has published 2 standards to evaluate reducing formaldehyde and volatile organic compounds concentrations (ISO standard 16000-23 and ISO standard 16000-24). These 2 standards measure performance of sorptive building materials to reduce formaldehyde or

volatile organic compounds concentrations. The test includes an assessment of both the initial performance of the material and how long that performance is maintained. The performance of sorptive building materials is evaluated by sorption flux, equivalent ventilation rate and saturation mass per area (capacity). Performance test to evaluate saturation mass per area typically takes 28 days per sample.

1. ISO standard 16000-23 Indoor Air – Part 23: Performance test for evaluating the reduction of formaldehyde concentrations by sorptive building materials.
2. ISO standard 16000-24 Indoor Air – Part 24: Performance test for evaluating the reduction of volatile organic compounds concentrations (except formaldehyde) by sorptive building materials.

PCO-based IPPT standards

Currently, there is no standard to evaluate PCO-based IPPT performance for indoor applications. ISO has published 6 standards using PCO based passive panels technologies illuminated using ultraviolet light. These are given below.

The 22197 series (1 to 5) deal with the removal of 5 gaseous pollutants (nitric oxide, acetaldehyde, toluene, formaldehyde and methyl mercaptan) for passive panels based on photocatalytic oxidation technologies illuminated by ultraviolet light radiation. For these standards, performances of test materials will be evaluated with respect to their ability reduce target concentrations by measuring removal amount of the pollutants in a test chamber. The language and technical information used in these standards is not optimized for building science application.

ISO 22197-1 and ISO 22197-2 cover a little on by-product formation by computing, respectively, the amount of nitrogen dioxide (NO₂) and carbon dioxide (CO₂) converted from the challenge pollutants. However, the main purpose of this is not for preventing harmful exposure to humans but to determine the complete mineralization of target pollutants through passive panels use.

The companion standard 10677 describes the light source which is used for the performance test of photocatalysts excited by ultraviolet radiation. It is to be noted that since these standards deal with ultraviolet radiation, typical indoor lighting may not have sufficient energy to excite the PCO based passive panels. This may render the application of these standards incomplete.

1. ISO standard 22197 – Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 1: Removal of nitric oxide.
2. ISO standard 22197 – Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 2: Removal of acetaldehyde.
3. ISO standard 22197 – Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 3: Removal of toluene.
4. ISO standard 22197 – Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for air-purification performance of semiconducting photocatalytic materials — Part 4: Removal of formaldehyde.

5. ISO standard 22197 – Fine ceramics (advanced ceramics, advanced technical ceramics)
— Test method for air-purification performance of semiconducting photocatalytic materials — Part 5: Removal of methyl mercaptan.
6. ISO standard 10677 – Fine ceramics (advanced ceramics, advanced technical ceramics)
— Ultraviolet light source for testing semiconducting photocatalytic materials.

Test chamber used in IPPT standards

VOC removal by PCO-based IPPT is a surface reaction process consisting of two steps: 1) the VOCs have to transfer to the reaction surface; and 2) the VOCs are decomposed by the photocatalyst. Thus, the VOC convective mass transfer rate, the reaction rate and the reaction surface area are the most important performance parameters of a PCO based IPPT.

VOC removal by sorptive-based IPPT, on the other hand, is dependent on 3 steps: 1) the VOCs have to transfer to the surface; 2) the VOCs are adsorbed or absorbed onto the IPPT; and 3) the VOCs are transferred into the interior surface or converted to different constituents. Here, the VOC mass transfer coefficient, the adsorption or absorption characteristics of the IPPT, the diffusion resistance of the interior surface of the IPPT or chemisorption rate and chemisorption surface area within the IPPT are the most important performance parameters of a sorptive based IPPT.

The common parameter impacting VOC removal process using PCO-based and sorptive-based IPPTs is the mass transfer coefficient. This parameter is dependent on ambient airflow conditions measured by air velocity and turbulence level. In real buildings, ambient airflow conditions over typical material surfaces include stagnant, laminar and turbulent flows. In order to evaluate the independent performance of IPPT in removing VOC in a test chamber, control of air velocity and turbulence over the IPPT material surface is needed. Installing a fan in the test chamber may result in an excessively high mass transfer coefficient on the IPPT surface, which may over- or under-estimate the IPPT performance under actual indoor conditions⁶.

The test chamber used to evaluate the performance of PCO-based IPPTs in standards described in 7.2.2 is based on the use of photoreactor and not a mixing chamber. The main limitation of using a photoreactor is that it involves laminar flow conditions (Ifang et al., 2014). Firstly, the air flow near the interior surfaces of typical indoor environments are not laminar (Zhang, et al., 1995). Secondly, in a laminar flow photoreactor the transport of pollutants to the IPPT surface will lead to the formation of concentration gradients. Thus, the chemical reaction may become much lower than that expected from the measured causing in an underestimation of the real surface uptake kinetics.

Existing test chamber used in the standards uses UV illumination as opposed to indoor lighting illumination. UV levels in indoor environment are very low due to poor transmission through windows and lack of indoor sources.

Thus, it is necessary to have a protocol that test pollutant removal by PCO-based IPPT in a test chamber that replicates typical indoor conditions, especially with regards to commonly used indoor lighting sources. However, such a method has yet to be established.

⁶ High mass transfer coefficient may increase the adsorption process and in turn, increase the VOC removal using sorptive based IPPT. In a PCO-based IPPT however, a high mass transfer coefficient may shorten the residence time for VOC reaction with the photocatalyst, leading to incomplete mineralisation and increased by-product formation.

Summary of new IPPT protocol development needs and consultation

A summary of the main IPPT performance aspects covered by the above standards is given in Table 9. While these standards address some important indoor pollutant removal performance aspects for sorptive-based IPPT and outdoor pollutant removal of PCO-based passive panel technologies, the following performance aspects are lacking:

1. Testing harmful by-product formation from the use of PCO based IPPT to protect human health;
2. Testing removal performance of IPPT under soiling effects or other surface treatments (e.g. paints, wallpapers);
3. Testing for re-emission of captured VOC under varying environmental conditions;
4. Testing of heterogeneous reactions between captured VOCs (unsaturated hydrocarbons) with ozone to form harmful by-products;
5. Testing IPPT using wall-ceiling-floor scale materials in a full scale (room size) chamber;
6. Test chamber that replicates conditions found near surfaces of indoor environments; and
7. Test chamber does not employ indoor lighting illumination to simulate indoor performance.

A consultation comprising participants from builders, researchers, industry partners and health professionals was then conducted to consider stakeholder needs, gaps, prioritize areas and consensus. This was followed up with a TAC meeting to identify critical performance scope for the development of new protocol. Under the guidance of the TAC, consultation suggestions were reduced to three priority areas based on feasibility, practicality and resource availability considerations. It was finalised that the new protocol has to build on existing sorption-based standards to evaluate performance of both sorptive- and PCO-based IPPT in removing key indoor pollutants relevant for built environments in Canada. Considering that some PCO-based IPPT may be influenced by sorptive effect, the new protocol has to differentiate removal performance attributed to light illumination and sorption. The new protocol also needs to utilise an improved chamber with proper control of air velocity and turbulence level to simulate indoor conditions instead of a photoreactor chamber. In addition, the new protocol must utilise a chamber that employs indoor lighting (as opposed to UV) as a source of illumination to better represent indoor applications. The new protocol must address protection of building occupants to harmful pollutant exposures through use of PCO based IPPT by testing by-product formation.

Guideline values for individual organic compounds, formaldehyde and ozone

Ozone Guideline:

Health Canada (2010) Residential Maximum Exposure Limit for Ozone (8 h exposure): 20 ppb (40 $\mu\text{g}/\text{m}^3$)

Formaldehyde Guideline:

Health Canada (2006) Residential Indoor Air Quality Guideline – Formaldehyde (8 h exposure): 40 ppb (50 $\mu\text{g}/\text{m}^3$)

Toluene Guideline:

Health Canada (2011) Residential Indoor Air Quality Guideline – Toluene (24 h exposure): 600 ppb (2300 $\mu\text{g}/\text{m}^3$); (8 h exposure): 4000 ppb (15000 mg/m^3)

Importance and relevance associated with current IPPT standards/protocols:

Health Canada has provided residential IAQ guidance in terms of recommended exposure limits for formaldehyde, toluene and ozone. The removal performance of IPPT using formaldehyde and toluene as challenge pollutants and their possible re-emissions are addressed in Tests 1 and 2 of this protocol. The by-product formation as measured in Test 3 of this protocol evaluates exposures to formaldehyde and ozone.

Table 9. Overview of Existing IPPT Performance Standards

Existing Standard	Performance Aspect		
	Removal indices	Long term performance indices	Equivalent Ventilation indices
ISO 16000-23: Performance test for evaluating the reduction of formaldehyde concentrations by sorptive building materials	<ul style="list-style-type: none"> Sorption flux (F_m) = $(C_{in}-C_{out})Q/A$ where Q =air flow rate of test chamber; A = surface area of test specimen 	<ul style="list-style-type: none"> Total mass per area of sorption at the halflife time (\bar{n}) = $\bar{a}(F_m \times \bar{A}t_{e,i})$ & $\bar{A}t_{e,i} = t_{e,i} - t_{e,i-1}$ (t_e = elapsed time) 	<ul style="list-style-type: none"> Equivalent vent. rate per area (F_v) = $[(C_{in}/C_{out})-1]Q/A$
ISO 16000-24: Performance test for evaluating the reduction of volatile organic compounds concentrations (except formaldehyde) by sorptive building materials	<ul style="list-style-type: none"> Sorption flux (F_m) = $(C_{in}-C_{out})Q/A$ where Q =air flow rate of test chamber; A = surface area of test specimen 	<ul style="list-style-type: none"> Total mass per area of sorption at the halflife time (\bar{n}) = $\bar{a}(F_m \times \bar{A}t_{e,i})$ & $\bar{A}t_{e,i} = t_{e,i} - t_{e,i-1}$ (t_e = elapsed time) 	<ul style="list-style-type: none"> Equivalent vent. rate per area (F_v) = $[(C_{in}/C_{out})-1]Q/A$
ISO 22197-1: Test method for air-purification performance of semiconducting photocatalytic materials — Part 1: Removal of nitric oxide.	<ul style="list-style-type: none"> NO_x Ads (n_{ads}) = $f/22.4 \int (C_{in,NO} - C_{out,NO})dt - \int C_{NO_2}dt$ NO amt removed (n_{NO}) = $f/22.4 \int (C_{in,NO} - C_{out,NO})dt$ Net amT NOx rem (n_{NOx}) = $n_{ads} + n_{NO} - n_{NO_2} - n_{des}$ where f=air flow rate of test chamber; C_{NO_2} = conc of NO_2 formed. 	<ul style="list-style-type: none"> NO_x amount desorbed (n_{des}) = $f/22.4 \int C_{out,NO_2}dt + \int C_{NO_2}dt$ 	
ISO 22197-2: Test method for air-purification performance of semiconducting photocatalytic materials — Part 2: Removal of acetaldehyde.	<ul style="list-style-type: none"> Removal percentage (R_A) = $100 \times (C_{in}-C_{out})/ C_{in}$ Amount removed (n_A) = $R_A \times (C_{in} \times f \times 1.016 \times 60)/(100 \times 22.4)$ where f=air flow rate of test chamber 		
ISO 22197-3: Test method for air-purification performance of semiconducting photocatalytic materials — Part 3: Removal of toluene.	<ul style="list-style-type: none"> Removal percentage (R_A) = $100 \times (C_{in}-C_{out})/ C_{in}$ Amount removed (n_A) = $R_A \times (C_{in} \times f \times 1.016 \times 60)/(100 \times 22.4)$ where f=air flow rate of test chamber 		
ISO 22197-4: Test method for air-purification performance of semiconducting photocatalytic materials — Part 4: Removal of formaldehyde.	<ul style="list-style-type: none"> Removal percentage (R_A) = $100 \times (C_{in}-C_{out})/ C_{in}$ Amount removed (n_A) = $R_A \times (C_{in} \times f \times 1.016 \times 60)/(100 \times 22.4)$ where f=air flow rate of test chamber 		
ISO 22197-5: Test method for air-purification performance of semiconducting photocatalytic materials — Part 5: Removal of methyl mercaptan.	<ul style="list-style-type: none"> Removal percentage (R_A) = $100 \times (C_{in}-C_{out})/ C_{in}$ Amount removed (n_A) = $R_A \times (C_{in} \times f \times 1.016 \times 60)/(100 \times 22.4)$ where f=air flow rate of test chamber 		