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Won, D. Y.; Schleibinger, H.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20374515
Research Report (National Research Council Canada. Institute for Research in Construction); no. IRC-RR-323, 2011-12-01

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National Research Council Canada
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D. Won and H. Schleibinger

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Date of issue: December 2011

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Summary

A scan of commercial off-the-shelf (COTS) sensors is provided for three indoor pollutants (formaldehyde, volatile organic compounds and radon) based on the information from the literature and manufacturers obtained between July 2008 and February 2009. The performance requirements for sensors are also proposed for a meaningful operation in sensor network systems aimed for ventilation and indoor air quality (V&IAQ) controls. Several COTS sensors meeting the proposed requirements are identified for formaldehyde and radon in this report. The identified formaldehyde COTS detectors have a resolution of 5 to 10 ppb, a detection range of 0 to 1 ppm, and a response time of a few to 30 minutes, and are priced between CDN $1,000 and $7,000. Several real-time continuous radon sensors also meet the pre-defined performance requirements, including a detection range between 20 and 5,000 Bq/m^3, a resolution of 10 Bq/m^3, and a response time of 2 days, and are priced between CDN $300 and $1,100. No commercial volatile organic compound (VOC) sensors meet the established requirements for VOCs. Several of the identified formaldehyde COTS sensors will be validated in NRC's labs for their actual sensitivity and selectivity.

Table of Contents

List of Tables:

Commercial IAQ Sensors and Their Performance Requirements for Demand-Controlled Ventilation

1. Introduction

Sensor-based demand controlled ventilation (DCV) aims to lower energy costs while maintaining the required indoor air quality (IAQ). The reliable sensing technology for continuous monitoring of indoor air quality is the vital component of a successfully operating DCV system. Issues associated with the stability of the sensor calibration and maintenance are the main reasons for the underutilization of DCV (Clark, 2009) as well as the cost. If accurate and reliable sensors would be available for continuous real-time IAQ monitoring, demand controlled ventilation could be easily realized based on the sensor output.

In 2005, the Institute for Research in Construction (IRC) of the National Research Council Canada (NRC) published a report with the title of "The State of-the-Art in Sensor Technology for Demand-Controlled Ventilation" (Won and Yang, 2005). The report provided the status of sensor technologies and commercially available sensors with the focus on the application to ventilation control based on indoor air quality parameters. Later in 2008, the Information and Communications Technology (ICT) Sector of NRC launched a multi-institute project called "ICT sector indoor air quality project". The major goal of the project was to develop new indoor air quality sensor system technologies to minimize energy use, while optimizing or maintaining occupants' health. The final outcome of the project would be a demonstration of an integrated indoor air quality sensor system with networking and closed loop ventilation system actuation.

Within the scope of the project many sub-tasks were identified. In the area of sensor development, the key objectives were:

1. Investigating the potential improvement of commercial sensors and
2. Developing new prototype sensors.

The subtasks associated with the improvement of commercial sensors were to:

1.1 Select two or three relevant IAQ parameters and establish the performance requirements for the sensors

1.2 Select (a) commercial sensor(s) meeting the performance requirements and which can be improved for demand-controlled ventilation purposes

1.3 Develop a lab-based sensor evaluation station, with the capacity to verify the performance of the selected commercial sensors

1.4 Characterize the performance of the selected commercial sensors in the lab-based sensor evaluation station (bench-top scale test)

1.5 Select a commercial sensor among those evaluated in the bench-top scale test and perform a scale-up test for the ventilation control in a full-scale chamber at IRC's building (M-24).

This report focuses on the tasks 1.1 and 1.2: developing IAQ sensor requirements and selecting commercial IAQ sensors for future laboratory testing.

2. Specifications of Sensors for IAQ Control

The sensors recommended for demand-controlled ventilation (DCV) in the previous review report (Won and Yang, 2005) include CO_2, relative humidity, formaldehyde, TVOC (total volatile organic compounds), radon and airborne particles. The selection of the IAQ parameters was based on three criteria: performance of sensors (detection range, resolution), cost of sensors, and potential risk of exceeding IAQ guidelines.
The first two parameters (CO_2 and relative humidity) were excluded from further discussion, as they are the surrogate of the indoor air pollutants. The parameter 'airborne particles' is also excluded since particle concentrations are often lower indoors than outdoors. The selected parameters are therefore formaldehyde, TVOC, and radon. Formaldehyde, benzene (a VOC) and radon are known to be carcinogenic. WHO recently published guidelines for these three contaminants for the protection of public health risks due to a number of chemicals commonly present in indoor air (WHO, 2010).

In this chapter, performance requirements for sensors that can be used for a DCV system are discussed and proposed. The identified commercial off-the-shelf (COTS) sensors are compared in the following chapter against these performance criteria.

2.1 Sensitivity requirements for IAQ sensors

The sensitivity requirements are expressed as the desired detection range and the resolution. The desired detection range needs to reflect the typical indoor levels in non-industrial buildings and guideline values, if they are existent at all. The desired resolution was defined to be the half the lower value of the desired detection rage. If the resulting resolution was considered to be too low to achieve with the current technology, it was determined to be the same as the lower value of the detection range.

The references used for developing the detection range are the Health Canada guidelines (Health Canada, 2009, Health Canada, 2006, Health Canada, 1995) and typical indoor air levels of VOCs (Table A. 1) published by the Association of Ecological Research Institutes (AGÖF) in Germany. In Canada, indoor air concentration measurements with respect to volatile organics or very volatile organics ('semi organic') gases like formaldehyde are only anecdotal or outdated. The most comprehensive overview exists in Germany, based on many thousands of measurements over a decade.

The resulting sensitivity requirements are suggested in Table 1. While the priority is to detect individual compounds, requirements are also provided for alternatives, i.e., detecting a set of chemicals. For example, if it is difficult to measure formaldehyde alone due to cross-sensitivity, the next step is to detect the sum of low-molecular aldehydes (formaldehyde, acrolein, and acetaldehyde) or the sum of selected aldehydes (formaldehyde, acrolein, acetaldehyde, propanal, pentanal, hexanal, octanal, octenal, and benzaldehyde). The same principle applies to VOCs. The priority is to detect toluene as it is prevalent indoors and can represent aromatic compounds. If it is not feasible to detect toluene alone, detecting the sum of aromatic VOCs or even sum of all VOCs (also known as TVOC – total volatile organic compounds) is suggested as alternatives. In spite of the carcinogenic concern, benzene has the fourth priority as it is typically at very low concentration indoors.

Table 1: Performance requirements for IAQ sensors

		Detection Range	Response Time	Resolution
Aldehydes	Formaldehyde[1]	12 – 500 µg/m^3 10 – 400 ppb	10 – 30 min	12 µg/m^3 10 ppb
	Σ Aldehydes[2]	25 – 500 µg/m^3 20 – 400 ppb	10 – 30 min	12 µg/m^3 10 ppb
	C-2 Aldehydes[3]	25 – 500 µg/m^3 20 – 400 ppb	10 – 30 min	12 µg/m^3 10 ppb
VOCs	Toluene[4]	100 – 5,000 µg/m^3 25 – 1,300 ppb	1 – 2 h	50 µg/m^3 12 ppb
	Aromatic VOC[5]	100 – 5,000 µg/m^3 25 – 1,300 ppb	1 – 2 h	50 µg/m^3 12 ppb
	'TVOC'[6]	100 – 5,000 µg/m^3 25 – 1,300 ppb	1 – 2 h	100 µg/m^3 25 ppb
	Benzene[7]	5 – 100 µg/m^3 2 – 30 ppb	1 h	5 µg/m^3 2 ppb
Radon	Radon[8]	20 – 5,000 Bq/m^3	2 d	10 Bq/m^3

[1] Health Canada's guideline for formaldehyde: < 123 µg/m^3 (1 h) & < 50 µg/m^3 (8 h) (Health Canada, 2006);

[2] If formaldehyde (c1), acrolein (c2), and acetaldehyde (c3) are present: $c1/C1 + c2/C2 + c3/C3 \leq 1$; C1=120, C2=50, C3=9,000 µg/m^3 (Health Canada, 1995);

[3] Formaldehyde, acrolein, acetaldehyde, propanal, pentanal, hexanal, octanal, octenal, benzaldehyde;

[4] Guideline expected by Health Canada within the next years; guideline available in other countries

[5] Sum of aromatic VOCs: benzene, toluene, xylenes, di/tri methyl benzenes, ethyl benzene, styrene, etc.;

[6] TVOC has an open definition, depending on detection method, either

- GC/MS or FID: The sum of VOCs, sampled on Tenax TA, which elute between and including n-hexane and n-hexadecane, are detected with a flame ionization detector (TVOC-FID) or mass spectrometric detector (TVOC-MS) (ISO, 2004), or
- Photoionization detection method, etc.

General experience:

- TVOC < 200 µg/m^3 = normally no health complaints,
- TVOC should not exceed 1,000 µg/m^3;

[7] Benzene is human carcinogenic and no safe level of exposure can be recommended. It is expedient to reduce indoor exposure levels as low as possible (WHO, 2010).

[8] The average residential radon concentration in Canadian homes is approximately 28 Bq/m^3 (Tracy, 2006) and the guideline value set by Health Canada is 200 Bq/m^3 (Health Canada, 2009).

2.2 Cross-sensitivity criteria for IAQ sensors

In general, cross-sensitivity (also referred to as specificity or interference) is the major issue for developing and operating sensors, besides sensitivity. Minimizing cross-sensitivity is important for an indoor air quality sensor, as indoor air contains a variety of volatile organic compounds in the part per billion (ppb) range (Moritz and Breuer, 2008). The requirement for cross-sensitivity is largely depending on the concentration ratios to other interfering VOCs. For most organic pollutants such as VOCs, concentrations in indoor air are significantly higher than outdoor air, often up to 10 to 100 times higher, and often the VOC spectrum between indoor and outdoor is different. The cross-sensitivity is explained in more details using two examples involving formaldehyde and toluene.

2.2.1 Cross-sensitivity requirements for formaldehyde sensors

Table 2 presents the cross-sensitivity requirements for selected alcohols and carbonyl compounds that have similar chemical properties to formaldehyde, and therefore may interfere with formaldehyde measurements. Assuming that the cross-sensitivity should be less than the error bound of a formaldehyde sensor, the cross-sensitivity requirements can be calculated based on Eq. 1 or Eq. 2.

$$C_i * \frac{S_i}{100} < C_{HCHO} * \frac{A_C}{100} \qquad \text{Eq. 1}$$

$$S_i < \frac{C_{HCHO} * A_C}{C_i} \qquad \text{Eq. 2}$$

where C_i is the concentration of an interfering gas (μg/m^3), S_i is the tolerable cross-sensitivity (%), C_{HCHO} is the formaldehyde concentration, and A_C is the accuracy of the formaldehyde sensor. It should be noted that the cross-sensitivity requirements would be changed with different levels of typical formaldehyde concentration (C_{HCHO}) and the accuracy of the formaldehyde sensor.

The examples in Table 2 are based on C_{HCHO} of 30 μg/m^3 and A_C of 10%. The concentrations of the interfering gases (2nd column of Table 2) are based on the 90th percentile concentration in typical non-industrial indoor environments in Table A. 1. It was also assumed that the air contains only two chemical compounds that the formaldehyde sensor responds, including formaldehyde and one of the interfering gases in Table 2.

To illustrate how to interpret the cross-sensitivity requirements, the case of formaldehyde and acetaldehyde from Table 2 can be used. With a cross-sensitivity of 4 %, a concentration of 70 μg/m^3 acetaldehyde would result in an additional ~3 μg/m^3 indicated by the formaldehyde sensor, leading to the total concentration of ~33 μg/m^3. Since the sensor accuracy is 10 % (± 3 μg/m^3), this cross-sensitivity effect can be ignored compared to the sensor accuracy. The situation would worsen, if the sensor is cross-sensitive against other or all aldehydes (as often their detection is only based on the interaction with the functional group), or against all carbonyl compounds which includes aldehydes and ketones. Especially the 'smaller' ketones, like dimethyl ketone (acetone) or methyl ethyl ketone (MEK), can deteriorate the functionality and usefulness of the sensor.

Table 2: Cross-sensitivity requirements for formaldehyde sensors *

Interfering Compounds	Concentration (μg/m³) **	Cross-sensitivity Requirements
Acetaldehyde	70	< 4 %
Hexanal	70	< 4 %
Acetone	70	< 4 %
2-Butanone	40	< 8 %
2-Propanol	70	< 4 %
1-Butanol	40	< 8 %
Ethanol	1170	< 0.3 %

* The cross-sensitivity requirements were calculated based on the assumption that the formaldehyde senor has 10% accuracy at 30 μg/m³ formaldehyde.
** Based on 90th percentile concentration in Table A. 1 except for ethanol. The reported ethanol level is based on the results from one study so that the level may change in the future when more data is available.

2.2.2 Cross-sensitivity requirements for toluene sensors

Another example is given in Table 3 for toluene. Eq. 2 was also used to determine the cross-sensitivity requirements for toluene (3rd column of Table 3). It was assumed that the sensor has an accuracy of ± 10 % and the typical toluene concentration was 49 μg/m³. Table 3 presents a list of aromatic compounds that can be found in indoor air and that may have potential for interfering with formaldehyde sensors. The operating concentrations for interfering aromatic compounds are based on the 90th percentile concentrations in typical non-industrial indoor environments in Table A. 1. Again, for this case it was assumed that the air contains only two aromatic compounds indicated by the sensor, including toluene and one of the interfering gases in Table 3. Since a typical level of toluene (49 μg/m³) is higher than other aromatic compounds, the cross-sensitivity requirements for the toluene sensor are more relaxed than those for the formaldehyde sensor.

Table 3: Cross-sensitivity requirements for toluene sensors*

Interfering Compounds	Concentration (μg/m³)	Cross-sensitivity Requirements
Benzene	4	< 123 %
Ethylbenzene	13	< 38 %
m,p-Xylene	38	< 13 %
o-Xylene	14	< 35 %
Styrene	12	< 40 %
1,2,4-Trimethylbenzene	16	< 31 %
1,2,3-Trimethylbenzene	4	< 117 %
1,2,4,5-Tetramethylbenzene	1	< 445 %
1,3,5-Trimethylbenzene	5	< 98 %
2-Ethyltoluene	4	< 123 %
3-Ethyltoluene	10	< 49 %
4-Ethyltoluene	6	< 86 %
4-Cymene	4	< 136 %

* The cross-sensitivity requirements were calculated based on the assumption that the toluene sensor has an accuracy of 10% at 49 μg/m³ of toluene.

3. Market Survey

This chapter is to compare the commercial sensors/monitors in terms of detection range, sensitivity, and cost. The information was obtained from the manufacturer (mostly through their websites or direct contact) or from published literature between July 2008 and February 2009. The keywords used include ‘formaldehyde’, ‘volatile organic compounds’, ‘VOCs’ ‘radon’ combined with either ‘sensor’, ‘monitor’ or ‘indoor air’.

3.1 Formaldehyde sensors

Table 4 presents the results of the market survey of formaldehyde sensors. The findings are:

• Sensor #1: Sensor #1 is an analytical equipment rather than a sensor with a detection limit of 0.05 ppb, which is better than the requirements specified in Table 1, and with a price of ~CDN $60,000.

• Sensor #2: Sensor #2 is based on metal-oxide semiconductor, but it is not available on the market yet.

• Sensors #3 to #13: The remaining commercial products identified in the table can be grouped into electrochemical (EC, Sensors # 3-11) or photoelectric photometry based sensors (PEP, Sensor #12 & 13). Both types of sensors showed similar detection ranges (typically, 0 – 5 or 0 - 10 parts per million (ppm) for EC sensors and 0 – 5 ppm for PEP sensors) and resolution (10 ppb for both). The difference is that electrochemical sensors are more susceptible to interferences from other IAQ pollutants while the interference effects are minimal with PEP sensors (see the interference data in Table 4). On the other hand, it is necessary to replace the coloring tape or tab in the PEP sensors on a regular interval (every measurement or every month). The price of the sensor ranges from CDN $1, 000 to 4,000 for EC sensors and CDN $1,000 to 7,000 for PEP sensors. The cost of consumables for SEP sensors is approximately CDN $120 for a tape and CDN $2 for a tab.

Both types of sensors meet the resolution requirements and cover the detection range requirements identified in Table 1. The response time is not an issue as it is only a few seconds for most EC sensors. The averaging time of PEP sensors is 15 or 30 minutes, which also meet the response time requirements. As a result, it is concluded that the commercial formaldehyde sensors are worthwhile being investigated for the development of a wireless sensor network system for ventilation and IAQ controls. We are recommending that at least one commercial sensor from each group of EC and PEP sensors should be purchased, verified for its performance, and upgraded for continuous monitoring and wireless communication capabilities.

Table 4: Market survey of formaldehyde monitors and sensors

#	Manufacturer/ Distributor	Product	Technology	Range	Accuracy or Resolution	Calibration	Output	Price (CDN$)	Interference
1	AERO-LASER Ltd./ Yankee Environmental Systems	AL4021	"Hantzsch" reaction	**0-20 ppb** **0-200 ppb** **0-2 ppm**	Detection limit: **< 0.05 ppb**	Internal permeation device using KIN-TEK permeation tubes	Analog: 0-5 Volt Digital: via RS 232 interface	$60,000	
2	Synkera	Formaldehyde (air quality) sensors	Metal oxide (tin), built on ceramics-based, nanostructured		Detection limit: 50 ppb				No information available.
3	CEA Instruments, Inc.	Two-wire remote sensor/transmitter CEA 420 series (421-F)	Solid-state diffusion type (resistance change btw two electrodes)	**0-10**, 0-50, 0-100, 0-500, 0-1000 (ppm)	Accuracy: +/- 5% of reading	Calibration / Flow Adapter Cap: $ 35	4-20 mA (optional 12, 24 VDC or 115-220 VAC)	$1,095 - $1,295	
		Series U Single channel wall mounted units (FO-6200)					Optional Recorder Output (4-20 mA or 0-1 VDC): $200	$1,595	
		Series U Portable(FO-6200P)					"	$1,895	
4	Hal Technology, LLC	Handheld HAL-HFX105	Electrochemical sensor	**0-5 ppm**	Resolution: **10 ppb**	Once or twice a year (built-in self-calibration function)	All data can be downloaded onto a PC	$1,100 (w/ temp & RH probe)	Methanol: 1%, Ethanol: 10%, Isopropanol: 2%, CO: 5%, Phenol: 0.2%, Acetaldehyde: 0.5%, H2: 0.5%, H2S: 6%, SO2: 1%, No response: H2O, CO2, acetone
5	Enmet Corporation	Portable Direct Reading Formaldehyde Monitor (Formaldemeter htv)	Electrochemical sensor	0.05-10 ppm (optional high range: 80 ppm)	Precision: 10% at 2 ppm level	In-field formaldehyde calibration standard	All data is stored, downloadable to a PC via RS-232	$2,983	No interference: acetone, acetic acid Acetaldehyde: 12% Butanol & propanol: 5% Glutaraldehyde: 0.1% Ethanol: 8% Methanol: 2% Phenol: 20% & CO: 1%
6	Detcon Inc	DM-7000-CH2O	Electrochemical Fuel Cell	0-100 ppm	Accuracy: +/- 2% of full scale		Linear 4-20 mA DC, RS-485 Modbus-rtu	$1,300 (w/o junction box)	Interference from aldehydes, alcohols, and other reducing gases (acetald: 12%, acetylene: 103%, butadiene: 52%, CO: 30%, ethanol: 55%, methanol: 126%)
7	Environmental Sensors Company	Formaldehyde Z-300 (z-model, handheld)	Electrochemical sensor (w/ chemical filters) - Manual filter change is necessary	0 - 30 ppm	Resolution: 10 ppb	In-field formaldehyde calibration standard	All data can be downloaded onto a PC	$1,500 $1,600 (w/ data logging)	Acetone & diethyl ketone: 2% No interference from MEK, acetaldehyde, acetic acid, ethanol, iso-propanol, & CO
		Formaldehyde Z-300XP (pump-model, portable desktop)	"	"	Resolution: **10 ppb** Accuracy: +/- 0.01%		"	$2,900	
8	Dart Sensors LTD	Formaldehyde (air quality) sensors	Filtering: carbon and glass fiber	**0-5 ppm** 0-25 ppm	Detection limit: 50 ppb	Long term output drift: <10% per year		$35 (sensor element only)	

Table 4 (continued)

#	Manufacturer/ Distributor	Product	Technology	Range	Accuracy or Resolution	Calibration	Output	Price (CDN$)	Interference
9	PPM Technology	Formaldemeter htv-m (hand held & continuous data logger - up to 7 days)	Electrochemical sensor	**0 - 10 ppm** (extended available)	Resolution: **10 ppb** Precision: 2%	In-field formaldehyde calibration standard	All data can be downloaded onto a PC (RS232 interface) Can be connected to a PC via one-to-one **wireless system**	$3,791	No interference: acetone, acetic acid, butanol, propanol Acetaldehyde: 6% Ethanol: 4% Glutaraldehyde: 10% Ethanol: 8% Methanol: 8% Phenol: 10% Ammonia: 5% CO: 1%
		Formaldemeter 400	"	"	"	"	All data can be downloaded onto a PC (RS232 interface) AMS-2 Base unit ($4,000) is needed for continuous monitoring.	$3,000	
		Formaldemeter 400ST	"	"	Resolution: **1 ppb** (available in China only)	"			
10	Interscan Corporation	Portable Analyzer (4000 Series)	Electrochemical voltametric sensor	20-1999, 2.0-199.9, 0.2-19.99, 0.02-1.999, **0.01-1.0 ppm**	Resolution: 1, 0.1, 0.01 ppm; **1 ppb** Accuracy: +/- 2% Repeatability: +/- 0.5% Min detectibility: 1%	Against standard gas mixture, or via Interscan's Electronic Calibration Service	0-100 mV	$4,187 (1 ppm) $4,107 (2 ppm)	Advised against using this sensor for IAQ investigation due to interference issues. Acetald: 6% Acetone: 0.1% Ethanol: 0.8% Glutarald: 0.5% Methanol: 0.2% Isopropanol: 0.1% MEK: 0.1% Propionald: 0.6% Phenol: 0.1% NO2: 3% (negative) NO: 0.2% SO2: 33%
		Single Point Stationary Monitors (LD series)	"	20-1999, 2.0-199.9, 0.2-19.99, 0.02-1.999 ppm	"	"	0-1 V 4 - 20 mA	$6,477 (2 ppm)	
		Rack-mount Analyzers (RM series)	"		"	"	0-100 mV	$6,412 (2 ppm)	
		Three/Four/Five Point Monitoring Systems (PLC series)	"		"	"	4-20 mA	$20,725 (3 points, 2 ppm) $24,189 (4 points, 2 ppm)	
11	Membrapor AG	CH2O/S-10, CH2O/C-10, CH2O/M-10	Electrochemical	**0-10 ppm**	Resolution: **10 ppb**	Max zero shift: 0.25ppm Long-term output drift: <2 % signal loss/month	4600 +/- 1200 nA/ppm	$113 - $130 (sensor element) $145 (transmitter)	H2: 1-3%, CO: 10-18%, Interference from reducing gases (alcohols)
12	RKI instruments	FP-330 (High Sensitivity Formaldehyde Gas Monitor)	Photoelectric photometry method using tape cassette	**0.03-5 ppm** 0.05-10	Resolution: **5 ppb**; Accuracy: +/- 20%	Replace tape every month	4-20 mA	$6,900	No interference by carbonyls (CH3CHO, acetone), alcohols, other HCs & typical gases (CO, CO2, NO2) according to Suzuki et al. (2003)
		FP-30		0-0.4, 0-1 ppm	Accuracy: +/- 10%	Replace the tab every 3/15/30	LCD display	$1,290	
		FP-40		0-0.6 ppm	"	"	"	$1,420	
13	Wingtuf, Japan	Portable Formaldehyde Sensor BHS-01	Photoelectric photometer (chips & reagents)	**0-1 ppm**	Accuracy and selectivity equivalent to JIS K0303 DNPH-HPLC method	Use disposable chip for every measurement	All data can be downloaded to a PC via RS-233		No interference by other aldehydes, acidic or alkaline gas & VOCs

3.2 Volatile organic compounds (VOC) sensors

The market survey results for VOC sensors with handheld or desktop size are summarized in Table 5. The commercial products can be grouped into three categories:

- sensor arrays (Sensors #1 – 2),
- photoionization detector (PID) based sensors (Sensors #3 – 10), and
- solid-state metal oxides semiconductor (MOS) sensors (Sensors #11-16).

The selectivity of sensor arrays (#1 –2) meets the requirements given in Table 1. In particular, zNose model 4200, 4300, and 4500 (sensor #1) are an electronic nose comprised of an array of surface acoustic wave detectors and a GC column for separating individual VOCs. It can identify and quantify hydrocarbons in the range of C4 and C25 with a minimum detection level of 10 ppb for toluene and 42 ppb for benzene. However, the high cost, which is in the range for research grade instrument, can serve as a deterrent to a wider use of the sensor arrays.

The PID sensors (#3 –8) are mostly designed for industrial settings (e.g., hazardous solvent leaks and spills) so that they have compromised sensitivity with a detection range of a few ppm to 15,000 ppm. However, some PID sensors (#9 & 10) have a much narrower detection range (0 – 10 or 20 ppm). The price of PID sensors ranges from CDN $1,500 to $5,000. PID sensors are not specific so that only TVOC levels are reported.

MOS sensors (Sensor #11-16) are more affordable with a price range of several hundred dollars as a semiconductor element (#17) is much cheaper than a PID lamp (#18). The detection range of MOS sensors is from a few ppm to 50 ppm. However, as with PID sensors, MOS sensors are not specific for individual VOCs.

Most commercial VOC sensors have a response time of ~ 1 min, which meets the requirement (1- 2 h) provided in Table 1. While several sensors cover the detection range specified in Table 1 (0 – 1 ppm), the resolution is observed to about 20 times worse than that required (~100 ppb at best vs. ~5 ppb requirement). The PID and MOS sensors report a TVOC level rather than a level of individual chemicals so that they are not suitable for an individual VOC (e.g., toluene) in Table 1. One exception is an electronic nose such as zNose, if the cost is not an issue.

Based on the information in Table 5, it can be concluded that no VOC commercial sensors are sensitive and specific enough to be used for ventilation control. Therefore, no recommendations were made for further investigation of VOC sensors.

Table 5: Market survey of monitors and sensors for volatile organic compounds

#	Manufacturer/ Distributor	Product	Technology	Range	Accuracy or Resolution	Output	Calibration	Price (CDN$)	Size or Weight
1	Electronic Sensor Technology, US	zNose (Model 4200/4300/4500) portable GC for field use w/ internal helium cyliner	GC/SAW (surface acoustic wave detector)	**> 10 ppb** (Individual chemicals from C4 to C25)	Accuracy: < 2% Resolution: **ppb**	RS-232 between controller and 4300	Once every 6 months at $133 for gas sensor (If properly trained, the user can do)	$26,000 - $36,000	Head: 2.6 kg Support: 8.5 kg
2	Air Sense Analytics	GDA 2 (Gas Detector Array) (hand-held)	PID, IMS (ion mobility spectrometer), EC (electrochemical cell), MOS (semiconductor)	0.2 - 200 ppm		works with computer or in stand alone mode, serial port RS-232	mentions a calibration unit but no reference as to how often		395x112x210 mm 4.2 kg (without batteries)
3	Baseline	Model 8800 PID Analyzer	PID (photo ionization detector)	sub ppm - 10,000 ppm	+/- 1 ppm or +/- 15% Detection limit: 0.1 ppm (as isobutylene)	0/4 - 20 mA RS-485, RS-232	Calibration gas		483x222x406 mm (13.64 kg)
4	BW technologies (Honeywell)	GasAlertMicro 5 PID	PID	0-1,000 ppm	Resolution: 1 ppm	Data log (no real time)	calibration at least every 180 days	> $1,500	145x74x38 mm (370 g)
5	MSA Sirius	MultiGas Detector	PID	0 - 200 ppm 200 - 2,000 ppm	0.1 ppm 1 ppm	Data log (no real time)	self calibrating cycles and must be recalibrated with changes of gases	> $4,000	165x92x66 mm (500 g)
6	Instrumentation Northwest, Inc.	Photovac 2020 Photoionization Dector	PID	0.5-2,000 ppm		RS 232 serial output	to be calibrated before each use		"light weight"
7	Drager	Drager Multi-PID 2	PID	0-2,000 ppm		Built in data logger that comes with software to transfer to a PC	self calibrating cycles and must be recalibrated with	$4,000	230x110x80 mm (861 g)
8	Rae Systems	MiniRAE 3000	PID	0-1,000 ppm 1,000-15,000 ppm	0.1 ppm 1 ppm	Real time wireless data transmission with built in RF modem or Bluetooth	Calibration required every time gas type is changed or 30 days	$5,000	255x76x64 mm
9	GrayWolf Sensing Solutions	TG-502 TVOC Probe	PID	0.02 - 20 ppm		Supplied Pocket PC that is connected to PPC afterwards	N/A	$4,537 (T, RH & TVOC)	50x300 mm (453 g)
10	Detcon	PI-500	PID (plug-in miniature PID sensor)	**1-10** ppm (all gases w/ ionization potential<10.6 eV)	+/- 10% of reading or +/- 2% of range	4-20 mA DC		$3,200	210x150 mm
		PI-600 (RS-485 addresable)						$3,400	
		PI-700 (w/ display)						$2,700	

Table 5 (continued)

#	Manufacturer/ Distributor	Product	Technology	Range	Accuracy or Resolution	Output	Calibration	Price (CDN$)	Size or Weight
11	Eco-sensors	C-21 VOC Gas Sensor	Heated metal oxide semiconductor	a few - 50 ppm for most solvent based VOCs	Accuracy: 20%	0-2 VDC	Only mentions to change the battery annually for good practice.	$380	85x35x60 mm (140 g)
12	Kanomax	Aeroqual Series 300/500 Monitor	Semiconductor	0 - 500 ppm toluene	< +/-10 ppm (< 200 ppm), < +/- 10% (200 - 500 ppm) Resolution: 1 ppm	0-5 VDC output Series 500 has Serial RS232	Not listed		193x122x53 mm (< 460 g)
13	Edinburgh Instruments (manufactured by Tongdy, China)	Tongdy VOC Monitor/Controller (F2000IAQ-VOC)	Semiconductor	TVOC: 0 - 30 ppm Temp: 5 - 45 oC RH: 5 - 95%	0.1 ppm (display resolution)	0-10V, Optional RS-485 communication interface	Regular check ups	$160-200	120x90x24 mm (280 g)
		Tongdy VOC Detector (F2000TSM-VOC)	"	TVOC: 0 - 30ppm		Indicator type: 6 indicator lights for 6 levels Transmitter type: 1-10 VDC Optional RS-485 communication interface		$130-160	100x80x28 mm (190 g)
14	Building Automation Products, Inc (BAPI)	Air Quality Sensors	Thermal conductivity (using a heated element)	**TVOC** (not specific)			Not necessary if the environment is clean.	$350 (room mount) $590 (duct mount)	85x85x26 mm
15	Synkera Technologies	VOC Sensor (P/N 707)	Semiconductor	**TVOC** (not specific)		0-5 VDC output			
16	AppliedSensors	IAQ-100 Indoor Air Quality Module	MOS sensor (micro-machined)	Not speicific (CO, CH4, VOCs)					
17	Figaro	VOC sensor (TGS2602)	Metal oxide	Not specific (1 - 30 ppm ethanol)				$20 (sensor element only)	
18	AlphaSense	PID-AH	PID	0.05 - 50 ppm (isobutylene), All VOCs w/ ionization potential < 10.6 eV	Sensitivity: > 20 mV / ppm isobutylene	Voffset (60-100 mV) to Vmax (2.9 to 3.5 V)	Life expectancy: 5 years (excluding lamp & electrode stack)	$740 (PID element only)	

3.3 Radon sensors

The measurement methods of radon, which is a radioactive gas that is released during the decay of uranium, can be classified into two categories: passive integrating radon monitors (activated carbon collectors, electret ion chambers, and alpha track detectors) and passive or active continuous radon monitors (scintillation cell monitors, current and pulse ionization chambers, and semiconductor based monitor) (George, 2008). As ventilation control is based on continuous real-time monitoring, the second category is the focus of this report. For comparison, analytical type monitors are also included.

Table 6 lists radon monitors/sensors with real-time monitoring capability. Most of real-time radon sensors are based on semiconductors or ionization chambers. The radon detectors are diverse in terms of averaging time (1 min – 5 yr), lower detection limit (1- 80 Bq/m^3), upper detection limit (3,700 – 10,000,000 Bq/m^3), sensitivity (0.04 – 11.0 cpm per 100 Bq/m^3) and price ($150 - $20,000). Detectors based on ionization chambers tend to be 2 - 3 times more sensitive than semiconductor-based detectors on average. AlphaGuard PQ2000 provides the best sensitivity of 11 counts per minute (cpm) per 100 Bq/m^3, which is close to the sensitivity level of a scintillation based detector (e.g., sensor #22).

Two detectors (Safety Siren Pro Series III, Ramon 2.2) look promising with an affordable price ($150, $450, respectively) and acceptable level of resolution (1 Bq/m^3), averaging time (2d, 1d), and handheld size. It is concluded that both sensors have a potential for the upgrade to a wireless sensor network system for demand-controlled ventilation with some improvements. For example, the lower detection range of Ramon 2.2 needs to be improved. No information was available for the sensitivity of Pro Series III. It is important to assure that the detectors perform well at the lower detection limit, considering the Health Canada's guideline is 200 Bq/m^3. Chen et al. (2007) reported that readings from the "digital radon detectors" were systematically higher compared to those of the more expensive continuous monitors such as Pylon AB4 (sensor #22 in Table 6) with a standard uncertainty of < 25%. The difference from the true value was worst (123%) at the lower level (8 Bq/m^3) in the field tests involving 26 digital radon detectors at 6 radon concentration levels of 8 to 871 Bq/m^3. Also, it is recognized that large errors in readings may be caused by the electromagnetic interference from household electronic devices (National Collaborating Centre for Environmental Health, 2008).

Table 6: Market survey of real-time radon sensors

#	Manufacturer/ Distributor	Product	Sensor Technology	Measurement Range (Bq/m^3)	Accuracy or resolution (Bq/m^3)	Sensitivity [cpm/(100 Bq/m^3)] *	Sampling	Response time or Sampling Interval	Price (CDN$)	Size or weight
1	GT Analytic (importer)	Ramon 2.2	Semiconductor	30 - 9,999	Accuracy: +/- 20% Resolution: 1 Bq/m^3		passive	2 d to 5 y	$300 - $500	125x75x50 mm (0.2 kg)
2	SMM, Prague	Radim 3A	Semiconductor	30 - 150,000	Accuracy: +/- 20% (37 Bq/m^3)	3.0	"	> 10 min	$7,000	230x170x90 mm (2.5 kg)
3	"	Radim 5	Semiconductor	80 - 50,000	Accuracy: +/- 25% (80 Bq/m^3)	1.1	"	0.5 h		200x100x70 mm (0.5 kg)
4	Sun Nuclear	Sun Nuclear 1027	Semiconductor (diffused junction photo diode)	0.1 - 999 pCi/L (4 - 37,000 Bq/m^3)	Accuracy: +/-25% (37 Bq/m^3)	0.3	"	1 h	$800	203x119x51 mm (0.9 kg)
5	"	Sun Nuclear 1028	Semiconductor	0.1 - 999.9 pCi/L 1 - 9,999 Bq/m^3	"	0.3	"	1 - 24 h	$1,000	117*208*99 mm (1.36 kg)
6	"	Sun Nuclear 1029 (T, RH,& P)	Semiconductor	1,000 - 9,999 pCi/L 10 - 99,999 Bq/m^3	"	0.6	"	0.5 - 24 h	$2,000	117*208*99 mm (1.36 kg)
8	Sarad, Germany	Doseman	Semiconductor	10 - 4,000,000	Resolution: 1 Bq/m^3	0.04 or 0.07	"	1 - 255 min	$3,000 - $6,000	115x60x35 mm (0.25 kg)
9	"	Radon Scout	Semiconductor	0 - 10,000,000		0.4	"	2 h	$3,000 - $5,000	175x135x55 mm (0.8 kg)
7	"	RTM1688-2	Semiconductor	0 - 10,000,000		0.6 or 1.5	active	15 min	$10,000	232x182x135 mm (3.5 kg)
10	"	RTM2100	Semiconductor	0 - 10,000,000		0.3 or 0.7	"	20 - 150 min	$20,000	235x145x255 mm (3.5 kg)
11	"	Indoor Air Sensor	Semiconductor	0 - 10,000,000		0.6 or 1.5	passive	15 or 120 min		225x145x180 mm (2 kg)
12	Durridge, USA	RAD7	Semiconductor	4 - 750,000	Accuracy: +/-10% (148 Bq/m^3)	3.0	active	1 h	$8,000	240x190x270 mm (5 kg)

* Unit: cpm/(100 Bq/m^3) = counts per minute per 100 Bq/m^3

Table 6 (continued)

#	Manufacturer/ Distributor	Product	Sensor Technology	Measurement Range (Bq/m^3)	Resolution (Bq/m^3)	Sensitivity [cpm/(100 Bq/m^3)] *	Sampling	Response time or Sampling Interval	Price (CDN$)	Size or weight
13	Family Safety Products, Inc	Safety Siren Pro Series III	ionization chamber	3.7 - 37,000	Accuracy: +/-12% (980 Bq/m^3)		passive	7 d to 5 y (2 d for 1st reading)	$150	119x79x53 mm (0.34 kg)
14	AccuStar	Radstar RS300	ionization chamber (pulse)	0.5 - 150 pCi/L 19 - 5,000 Bq/m^3		1.2	"	1 h	$1,100	178x203x114 mm (1.13 kg)
15	"	Radstar RS800 (T & RH)	ionization chamber (pulse)	0.5 - 200 pCi/L 18 - 7,200 Bq/m^3		2.4	"	1 h	$5,000	"
16	Saphymo, Germany	Alphaguard PQ2000	ionization chamber	2 - 2,000,000	Resolution: 1 Bq/m^3	11.0	passive	1 h	$8,000	(4.5 kg)
17	Radalink Radon Monitors, USA	Radalink Aircat	ionization chamber	19 - 92,000		2.5	"	1 h	$200/month (for rental)	172x108x99 mm (1.2 kg)
18	RADON v.o.s. corporation, Czech	Radonic 01	ionization chamber	50 - 12,000	Resolution: 2 Bq/m^3		active	10 min display (5 min for 1st reading)	$11,000	270x270x520 mm (4.5 kg)
19	Femto Tech	CRM-510 LP	ionization chamber (pulse)	0.5 - 2,000 pCi/L 18 - 74,000 Bq/m^3		1.8	passive	1 h	$5,500	137x160x190 mm (1.8 kg)
20	RTCA	E-Smart	ionization chamber (current)	0 - 99.9 pCi/L 0 - 3,700 Bq/m^3		1.2	"	1 h	$3,000	184x111 mm (0.65 kg)
21	Gamma Data, Sweden	Atmos 12DPX	ionization chamber (pulse)	2 - 100,000 Bq/m^3	Accuracy: ±20% at 200 Bq/m^3	4.4 **	active	1 min - 24 h (10 min average)	$17,000	385x500x220 mm (14 kg)
22	Pylon, Canada	Pylon CRM, AB-4	Scintillation cell	> 24.8 Bq/m^3		8.9	passive		$8,300	115x105x70 mm (12 kg)

* Unit: cpm/(100 Bq/m^3) = counts per minute per 100 Bq/m^3

** George (2008)

4. Summary and Recommendations

A scan of commercial detectors for three indoor air pollutants (formaldehyde, volatile organic compounds- VOCs, and radon) was provided with respect to detection range, resolution, interference, and cost. The information was collected from manufacturers (websites or direct contact) and literature between July 2008 and February 2009. The keywords used for search include formaldehyde, volatile organic compounds, VOCs, radon, sensor, monitor and indoor air. The performance requirements for IAQ sensors were also established by NRC staff according to the anticipated needs for IAQ control and demand controlled ventilation. The requirements include the detection range, resolution and response time.

Table 7 lists commercial formaldehyde detectors that meet the requirements. They are either electrochemical or photochemical photometry based sensors with a price of CDN $1,000 to $7,000, a resolution of 5 to 10 ppb, and a detection range between 0 and 1 ppm. Several of the identified sensors will be purchased and their performance will be tested in a laboratory setting in the next phase of this study. In particular, the selectivity of formaldehyde sensors will be scrutinized, as the first four sensors are electrochemical sensors that are prone to show cross-sensitivity to various indoor VOCs. For better acceptability in the market for continuous monitoring, the last two sensors (based on photoelectric photometry) should be improved in term of the maintenance frequency (changing the coloring tape or tab).

Table 7: Commercial formaldehyde detectors with a resolution of 10 ppb or better

	Range	Resolution	Interference	Cost	Note
Criteria	*0.01 – 0.4 ppm*	*10 ppb*	*Less than accuracy @ 30 μg/m³ (24 ppb)*		
Hal HFX105	0 – 5 ppm	10 ppb	Interference from other VOCs (e.g, acetaldehyde 0.5%)	$1,100	
Env Sensors Z-300XP	0 – 30 ppm	10 ppb	Interference from other VOCs (e.g, acetone 2%)	$1,500	
PPM htv-m	0 – 10 ppm	10 ppb	Interference from other VOCs (e.g., acetaldehyde 6%)	$3,800	Wireless capability
Intersacn 4000 series	0.01 – 1 ppm	1 or 10 ppb	Interference from other VOCs (e.g., acetaldehyde 6%)	$4,200	IAQ application is discouraged by the manufacturer
RKI FP-30	0.03 – 5 ppm	5 ppb	No interference	$1,290	Photoelectric photometry Coloring tape needs to be replaced every month.
RKI FP-330	0 – 1 ppm	5 ppb	No interference	$6,900	Photoelectric photometry Coloring tab needs to be replaced every time.

Most commercial VOC sensors are based on photoionization detector (PID) and metal oxide sensors (MOS). These commercial sensors can only be used as a TVOC sensor as PID and MOS are not selective for different VOCs. It can be concluded that the current VOC sensors are not sensitive or selective enough to be used for IAQ and ventilation controls in non-industrial settings. For this purpose TVOC sensors need to be improved to achieve better sensitivity. For sensors aimed at detecting individual VOCs such as toluene and benzene, measures to improve selectivity should be introduced. Examples include pre-concentration steps using adsorbents or better identification techniques using sensor arrays.

Commercial radon detectors (real-time continuous digital sensors) are sensitive and selective enough to be applied to IAQ and ventilation controls. The commercial radon sensors that cost less than CDN $1,100 are summarized in Table 8. However, the performances at the lower level need to be investigated as the detection range given by the manufacture is very broad and the typical indoor concentration is low (~ 28 Bq/m^3 on average in Canada) with Health Canada guideline of 200 Bq/m^3.

Table 8: Commercial real-time radon detectors (< $1,100)

	Range (Bq/m^3)	Resolution (Bq/m^3)	Sensitivity [$cpm/(100\ Bq/m^3)$]	Cost	Note
Criteria	*20 – 5,000*	*10*			
Ramon 2.2	30 – 9,999	1	-	$300-$500	Semiconductor, 200 g
Sun Nuclear 1027	4 – 37,000	-	0.3	$800	Semiconductor, 900 g
Safety Siren Pro Series III	4 – 37,000	-		$150	Ionization chamber, 340 g
Radstar RS300	19 – 5,000	-	1.2	$1,100	Ionization chamber, 1130 g

5. Conclusion and Outlook

Concluding all findings, it seems to be very challenging to accurately monitor the concentrations of pollutants in non-industrial settings such as commercial buildings with the identified commercial sensors, since the typical indoor concentrations are close to their detection limits. The focus of the next phase of the study, involving characterizing selected commercial sensors, should include determining

- the accuracy at the detection limits,
- the selectivity under the typical indoor conditions, and
- the long-term performance of commercial detectors should be investigated under various interfering factors (e.g., interference from various VOCs for formaldehyde sensor, electromagnetic interference from household electronic devices for radon sensors).

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Appendix : Typical concentration of volatile organic compounds indoor air

Table A. 1 Levels of Volatile Organic Compounds in Indoor Air

		Compound (Synonyms)	CAS	Normal -Value 50th Percentile [µg/m³] 1	Attention-Value 90th Percentile [µg/m³] 2	Guidance-Value [µg/m³] 3
Alcohols	1	1-Butanol	71-36-3	11	45.7	45
	2	1-Hexanol	111-27-3	0.4	2.1	2
	3	1-Octen-3-ol	3391-86-4	0.2	0.3	1
	4	2-Ethylhexanol (2-Ethyl-1-hexanol)	104-76-7	2.4	12.8	12
	5	2-Propanol (Isopropyl alcohol)	67-63-0	15	74.2	75
	6	Benzyl alcohol	100-51-6	0.5	4.2	4
	7	Ethanol*	64-17-5	713 / 1169 *	-	-
	8	Isoamyl alcohol (3-Methylbutan-1-ol)	123-51-3	0.3	0.7	1
	9	Isobutyl alcohol (2-Methyl-1-propanol)	78-83-1	3	21.7	20
	10	n-Pentanol (1-Pentyl alcohol)	71-41-0	1.8	6.6	7
Aldehydes	11	2-Furaldehyde (Furfural)	1998-01-01	1	2	2
	12	Acetaldehyde	75-07-0	23	72.2	70
	13	Acrolein *	107-02-8	1.29 / 5.02 *	-	-
	14	Benzaldehyde	100-52-7	3.5	10	10
	15	Butyraldehyde (Butanal)	123-72-8	3	11	9
	16	Formaldehyde	50-00-0	32.5	84.5	30
	17	n-Decanal (Caprinic aldehyde)	112-31-2	2	7.5	2
	18	n-Heptanal (Heptanal)	111-71-7	2	7.8	8
	19	n-Hexanal (Capronaldehyde)	66-25-1	14	67	19
	20	n-Nonanal (Pelargonic aldehyde)	124-19-6	7	21	4
	21	n-Octanal (Caprylic aldehyde	124-13-0	3	9	2
	22	Pentanal (Valeraldehyde)	110-62-3	5	24.2	7
	23	Propionaldehyde (Propanal)	123-38-6	4	17.7	18
Ketones	24	1-Methyl-2-pyrrolidinone (N-Methylpyrrolidone)	872-50-4	1	5	5
	25	2-Butanone (Methylethyl ketone MEK))	78-93-3	5	42.2	40
	26	2-Heptanone (Methyl pentyl ketone)	110-43-0	0.5	1.9	2
	27	2-Hexanone (Methyl butyl ketone MBK)	591-78-6	0.2	1.4	1
	28	3-Heptanone (Ethyl-n-butyl ketone)	106-35-4	0.4	1.5	2
	29	3-Octanone (Ethyl pentyl ketone	106-68-3	0.2	0.2	1
	30	4-Methyl-2-pentanone (Methyl isobutyl ketone MIBK)	108-10-1	1	7.7	8
	31	Acetone **	67-64-1	28.5	76.4	-
	32	Acetophenone (Methyl phenyl ketone)	98-86-2	1.6	4	4
	33	Cyclohexanone	108-94-1	1	4	4
Esters of monohydric & dihydric Alcohols	34	1-Butanol, 3-methoxy-,1-acetate (3-Methoxybutyl acetate)	4435-53-4	0.5	0.9	1
	35	2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB)	6846-50-0	0.9	4	4
	36	Acrylic acid, butyl ester (n-Butyl acrylate)	141-32-2	0.5	0.5	1
	37	Acrylic acid, ethyl ester (Ethyl acrylate)	140-88-5	0.5	0.5	1
	38	Acrylic acid, methyl ester (Methyl acrylate)	96-33-3	0.5	0.5	1
	39	Benzoic acid, methyl ester (Methyl benzoate)	93-58-3	0.5	2.5	3

Table A. 1 (continued)

		Compound (Synonyms)	CAS	Normal-Value 50th Percentile [µg/m³] 1	Attention-Value 90th Percentile [µg/m³] 2	Guidance-Value [µg/m³] 3
Esters of monohydric & dihydric Alcohols (continued)	40	Bornyl acetate	76-49-3	0.7	1	2
	41	Dibutyl maleate	105-76-0	0.5	1	1
	42	Dibutyl phthalate	84-74-2	0.5	3	3
	43	Diethyl Phthalate	84-66-2	1	3	3
	44	Diethyleneglycol monobutyl ether acetate (Butyl carbitol acetate)	124-17-4	0.5	2	2
	45	Diisobutyl phthalate	84-69-5	1	4	4
	46	Dimethyl adipate (Hexanedioic acid, dimethyl ester)	627-93-0	0.5	1.8	2
	47	Dimethyl glutarate	1119-40-0	0.5	1.1	2
	48	Dimethyl phthalate	131-11-3	0.5	2	2
	49	Dimethyl succinate	106-65-0	0.5	1.8	2
	50	Ethyl acetate	141-78-6	4	38	40
	51	Ethylene glycol monobutyl ether acetate (EGBEA, 2-Butoxyethyl acetate)	112-07-2	0.5	0.7	1
	52	Ethylene glycol monoethyl ether acetate (EGEEA, 2-Ethoxyethyl acetate)	111-15-9	0.7	1	2
	53	Ethylenglykole mono methyl ether acetate (EGMEA, 2-Methoxyethanol acetate)	110-49-6	0.5	0.9	1
	54	Formic acid, butyl ester (n-Butyl formate)	592-84-7	0.5	2	2
	55	Isobutyl acetate	110-19-0	0.5	4	4
	56	Isopropyl acetate	108-21-4	0.9	1.3	2
	57	Methacrylic acid, methyl ester (Methyl methacrylate)	80-62-6	0.5	2	2
	58	n-Butyl acetate	123-86-4	3.1	49.8	10
	59	n-Propyl acetate	109-60-4	1	1.3	2
	60	Propanol, (2-methoxymethylethoxy)-, acetate (Propanol, 1(or 2)-(2-methoxymethylethoxy)-, acetate)	88917-22-0	0.5	0.5	1
	61	Propylene glycol mono methyl ether acetate (PGMEA, 1-Methoxy-2-propanol acetate)	108-65-6	1	12	12
	62	Texanol	25265-77-4	0.7	4	4
Polyhydric Alcohols & Their Ethers (Glycols and Glycol Ethers)	63	1-Butoxy-2-propanol (1,2-Propylene glycol monobutyl ether)	5131-66-8	1.3	3	3
	64	1-Methoxy-2-hydroxypropane (PGME, 1-Methoxy-2-propanol)	107-98-2	3	23	25
	65	1-Phenoxypropan-2-ol (Propylene phenoxetol)	770-35-4	0.6	2	2
	66	Diethylene glycol monoethyl ether (2-(2-Ethoxyethoxy)ethanol, Ethoxydiglycol)	111-90-0	2.5	8.5	9
	67	Diethylene glycol monomethyl ether (2-(2-Methoxyethoxy)ethanol, Methoxydiglycol)	111-77-3	3	8.5	8
	68	Diethylene glycol mono-n-butyl ether (2-(2-Butoxyethoxy)ethanol, Butyl diglycol)	112-34-5	1.5	13.9	14
	69	Dipropylene glycol monobutyl ether (2-Propanol, 1-(2-butoxy-1-methylethoxy)-)	29911-28-2	1	4.7	5
	70	Dipropylene glycol monomethyl ether	34590-94-8	0.5	7	7
	71	Ethylene glycol monobutyl ether (n-Butoxyethanol)	111-76-2	2.3	18.1	18
	72	Ethylene glycol monoethyl ether (2-Ethoxyethanol)	110-80-5	0.5	2.5	3
	73	Ethylene glycol monomethyl ether (2-Methoxyethanol, Methyl cellosolve)	109-86-4	2.5	3	4
	74	Ethylene glycol monophenyl ether (2-Phenoxyethanol)	122-99-6	1	9.2	9
	75	Propylene glycol (1,2-Propylene glycol)	57-55-6	2.5	17	18
	76	Tripropylene glycol n-butyl ether (Propanol, (2-(2-butoxymethylethoxy) methylethoxy)-)	55934-93-5	1	6	6

Table A. 1 (continued)

		Compound (Synonyms)	CAS	Normal-Value 50th Percentile [µg/m³] 1	Attention-Value 90th Percentile [µg/m³] 2	Guidance-Value [µg/m³] 3
Alkane	77	2,2,4,4,6,8,8-Heptamethylnonane	4390-04-09	0.5	2	2
	78	2,2,4,6,6-Pentamethylheptane	13475-82-6	0.7	6.4	6
	79	2,2,4-Trimethylpentane (Isooctane)	540-84-1	0.5	1	1
	80	2-Methylpentane	107-83-5	1.7	6.1	6
	81	3-Methylhexane	589-34-4	1	8.9	9
	82	3-Methylpentane	96-14-0	0.7	5	5
	83	n-Decane	124-18-5	2	20.1	20
	84	n-Dodecane	112-40-3	2	16	16
	85	n-Eicosane	112-95-8	0.5	0.5	1
	86	n-Heptadecane	629-78-7	1	2	2
	87	n-Heptane	142-82-5	3	13	14
	88	n-Hexadecane	544-76-3	1	3	3
	89	n-Hexane	110-54-3	2	11	10
	90	n-Nonadecane	629-92-5	0.5	1	1
	91	n-Nonane	111-84-2	1	7.6	8
	92	n-Octadecane	593-45-3	0.5	2	2
	93	n-Octane	111-65-9	1	7.1	7
	94	n-Pentadecane	629-62-9	1	3.4	3
	95	n-Tetradecane	629-59-4	1.1	5	5
	96	n-Tridecane	629-50-5	1	5	5
	97	n-Undecane	1120-21-4	3	29	30
Cycloalkanes	98	Cyclohexane	110-82-7	2	13	13
	99	Methylcyclohexane	108-87-2	1	9	9
	100	Methylcyclopentane	96-37-7	0.9	4.1	4
Alkenes	101	1,3-butadiene **	106-99-0	0.2	1.6	
	102	1-Decene	872-05-9	0.9	1	2
	103	1-Nonene	124-11-8	0.7	1	2
	104	1-Octene	111-66-0	0.7	1	2
	105	1-Propene, 2-methyl-, trimer (Triisobutylene)	7756-94-7	0.5	1	1
	106	1-Undecene	821-95-4	0.7	1	2
	107	4-Phenylcyclohexene	4994-16-5	0.5	0.5	1
	108	4-Vinylcyclohexene	100-40-3	0.5	0.5	1
Aromatic Hydrocarbons	109	1,2,3-Trimethylbenzene (Hemimellitene)	526-73-8	0.5	4.2	4
	110	1,2,4,5-Tetramethylbenzene (Durene)	95-93-2	0.5	1.1	1
	111	1,2,4-Trimethylbenzene (Pseudocumene)	95-63-6	2	16	16
	112	1,3,5-Trimethylbenzene (Mesitylene)	108-67-8	1	5	5
	113	1,3-Diisopropylbenzene	99-62-7	0.7	0.9	1
	114	1,4-Diisopropylbenzene	100-18-5	0.7	0.9	1
	115	1-Methylethylbenzene (Cumene)	98-82-8	0.5	2	2
	116	2,6-Di-tert.-butyl-4-methylphenol (Butylated hydroxytoluene BHT)	128-37-0	0.5	0.5	1
	117	o-Xylene	95-47-6	2	14	14
	118	m & p-Xylene	108-38-3/ 106-42-3	5	38.4	40
	119	Benzene	71-43-2	1.7	4	4

Table A. 1 (continued)

		Compound (Synonym)	CAS	Normal-Value 50th Percentile [µg/m³] 1	Attention-Value 90th Percentile [µg/m³] 2	Guidance-Value [µg/m³] 3
Aromatic Hydrocarbons (continued)	120	Benzene, 1-ethyl-2-methyl-(2-Ethyltoluene)	611-14-3	0.5	4	4
	121	Benzene, 1-ethyl-3-methyl-(3-Ethyltoluene)	620-14-4	1.4	10	10
	122	Benzene, 1-ethyl-4-methyl-(4-Ethyltoluene)	622-96-8	0.9	5.7	6
	123	Benzene-1-methyl-4-(1-methylethyl) (4-Cymene)	99-87-6	0.5	3.6	4
	124	Benzothiazole	95-16-9	0.5	1	2
	125	Ethylbenzene	100-41-4	2	13	4
	126	Indan	496-11-7	0.5	2	2
	127	Naphthalene	91-20-3	1	2	2
	128	n-Butylbenzene	104-51-8	0.5	2	2
	129	n-Propylbenzene	103-65-1	0.5	3	3
	130	Phenol	108-95-2	0.5	3	3
	131	Styrene	100-42-5	2	12.1	12
	132	Toluene	108-88-3	12	49	50
Halocarbons	133	1,1,1-Trichloroethane (Methylchloroform)	71-55-6	0.5	2	2
	134	1,1,2,2-Tetrachloroethane **	79-34-5	0.01	0.01	
	135	1,1-Dichloroethylene **	75-35-4	0.005	0.83	
	136	1,2-Dichlorobenzene	95-50-1	0.9	0.9	1
	137	1,2-Dichloroethane **	107-06-2	0.01	0.01	
	138	1,2-Dichloropropane **	78-87-5	0.02	0.02	
	139	1,4-Dichlorobenzene	106-46-7	0.5	0.9	1
	140	Carbon tetrachloride	56-23-5	0.5	1	1
	141	Chlorobenzene **	108-90-7	0.005	0.005	
	142	Chloroform **	67-66-3	4.5	15.1	
	143	Dichloromethane **	75-09-2	1.9	43.2	
	144	Ethylene dibromide **	106-93-4	0.01	0.01	
	145	Tetrachloroethylene	127-18-4	0.5	1	1
	146	Trichloroethylene	1979-01-06	0.5	1	1
Terpenes	147	(1(1alpha,3Abeta,4alpha,8abeta))-decahydro-4,8,8-trimethyl-9-methylene-1,4-methanoazulene (Longifolene)	475-20-7	0.9	2	2
	148	2H-2,4a-Methanonaphthalene, 1,3,4,5,6,7-hexahydro-1,1,5,5-tetramethyl- (Isolongifolene)	1135-66-6	0.9	0.9	2
	149	3-Carene ((+-)-delta3-Carene)	13466-78-9	2.5	34	35
	150	alpha-Pinene	80-56-8	8	93	95
	151	alpha-Terpinene	99-86-5	0.5	0.5	1
	152	beta-Pinene	127-91-3	1	12	12
	153	Bicyclo(3.1.1)hept-3-en-2-one, 4,6,6-trimethyl-, (1S,5S)-(Verbenone)	1196-01-6	0.5	1	1
	154	Borneol	507-70-0	0.5	2	2
	155	Camphene	79-92-5	0.7	3	3
	156	Camphor	76-22-2	0.9	1.3	2
	157	Caryophyllene (beta-Caryophyllen	87-44-5	0.9	1.1	2
	158	Citronellol	106-22-9	0.5	0.5	1
	159	Eucalyptol	470-82-6	1	2.3	2
	160	gamma-Terpinene	99-85-4	0.7	0.9	1

Table A. 1 (continued)

		Compound (Synonym)	CAS	Normal-Value 50th Percentile [µg/m³]	Attention-Value 90th Percentile [µg/m³]	Guidance-Value [µg/m³]
Terpenes (continued)	161	Limonene	138-86-3	6	33.3	35
	162	Linalool (beta-Linalool)	78-70-6	0.5	1	1
	163	Racementhol (Menthol)	89-78-1	0.5	1	1
Siloxanes	164	Decamethylcyclopentasiloxane	541-02-6	4.3	30.4	30
	165	Hexamethylcyclotrisiloxane	541-05-9	1	9	9
	166	Octamethylcyclotetrasiloxane	556-67-2	1.5	9.8	10
Others	167	1,4-Dioxane	123-91-1	1	5	5
	168	2-pentyl Furan	3777-69-3	0.5	2	2
	169	3,5-dimethylaniline	108-69-0	0.6	0.6	
	170	Methyl tert-butyl ether (MTBE)	1634-04-4	1.7	2.5	3
	171	Tetrahydrofuran (THF)	109-99-9	0.5	2.5	3
Sum Total Values	172	∑ Bicyclic terpenes		12	150	150
	173	∑ C1 − C4 Alkyl aromatic hydrocarbons		30	168	170
	174	∑ C3 − C6 Alkanals		21	96	95
	175	∑ Monocyclic terpenes		6	34	35
	176	TVOC (total volatile organic compounds)		380	1,636	1,000

Note:

- 1: The 50^{th} percentile level is considered as a typical concentration indoors
- 2: The 90^{th} percentile level is chosen as the concentration threshold whereby any value exceeding the level indicates is considered as an unusual exposure.
- 3: The guidance level indicates the threshold, above which the indoor air concentration of a compound must be considered a problem based on statistical significance, or toxicological or olfactory knowledge (AGÖF, 2008).

References:

- Reference for ethanol (*) and acrolein (*), summer/winter: Stocco, C., Macneill, M., Wang, D., Xu, X., Guay, M., Brook, J. and Wheeler, A.J. (2008) "Predicting personal exposure of Windsor, Ontario residents to volatile organic compounds using indoor measurements and survey data: Selected Papers from the First International Conference on Atmospheric Chemical Mechanisms", *Atmospheric Environment*, **42**, 5905-5912.
- Reference for acetone (**), 1,3-butadiene,1,1,2,2-tetrachloroethane, 1,1-dichloroethylene, 1,2-dichloroethane, 1,2-dichloropropane, Chlorobenzene, Chloroform, ethylene dibromide: Zhu, J., Newhook, R., Marro, L. and Chan, C.C. (2005) "Selected Volatile Organic Compounds in Residential Air in the City of Ottawa, Canada", *Environ. Sci. Technol.*, **39**, 3964-3971
- Reference for other compounds: AGÖF (2008) “AGÖF Guidance Values for Volatile Organic Compounds in Indoor Air (10 October 2008 Edition)”, http://agoef.de/agoef/oewerte/orientierungswerte_englisch.html