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Introduction

The aim of this white paper is to cover the basics of total volatile organic compounds (TVOC) and indoor air quality (IAQ). Volatile organic compounds are the main source for poor indoor air quality, which can affect a person's daily life. Recommendations from various institutions and agencies regarding TVOC levels that are deemed hazardous to human health are given in the "Hazardous Condition Limits and Standards for TVOC" section. Monitoring objects that outgas in indoor areas is recommended, especially in critical places, such as schools and public buildings as well as in homes. Hence, sensitive and robust instrumentation is needed. IDT provides TVOC gas sensors in two gas sensor families, ZMOD and SGAS, which are small and easy to implement and therefore offer a unique capability to monitor the TVOC in various places over a long product lifetime.

Gases of Interest for Indoor Air Quality

Definition of TVOC

There are different classifications of Total Volatile Organic Compounds (TVOC). Most commonly used is the World Health Organization (WHO) definition[1], which differentiates the volatility (or boiling point) of organic compounds to define Very Volatile Organic Compounds (VVOCs), Volatile Organic Compounds (VOC) and Semi-volatile Organic Compounds (SVOCs) as defined in Table 1. This usually involves the molecular length of the carbon structure; i.e., the number of carbon atoms in the chemical formula. The summation of all VOCs is called the Total Volatile Organic Compounds (TVOC). The volume of gas per classification and the sum of all gases (TVOC) are important reflections of the relevant organic compounds found in indoor air.

Table 1. Classifications of Volatile Organic Compounds

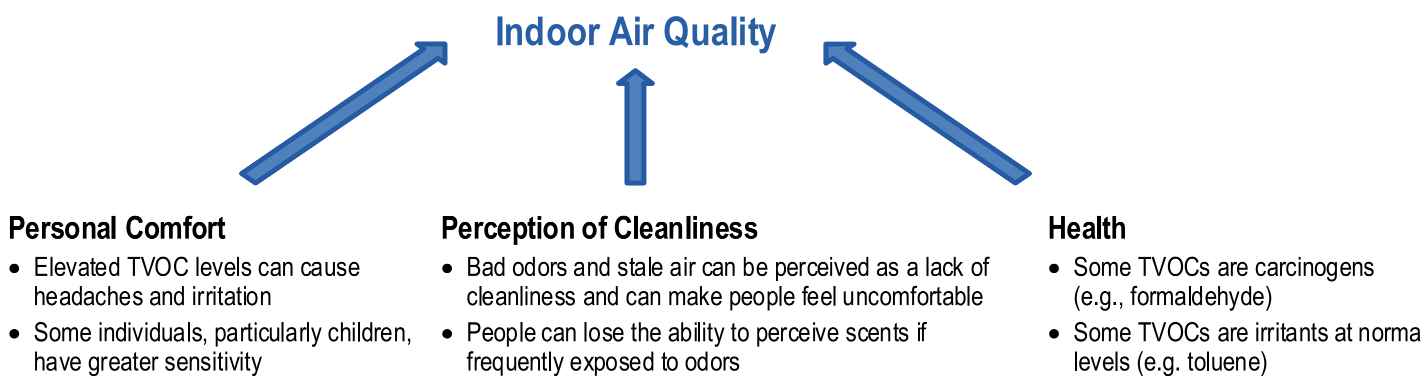
Class	Name	Typical Boiling Point [°C]	Typical Number of Carbon Molecules	Example
VVOC	Very Volatile Organic Compound	< 0 to (50 – 100)	$< C_6$	Formaldehyde
VOC	Volatile Organic Compound	(50 – 100) to (240 – 260)	C_6 to C_{16}	Benzene
SVOC	Semi Volatile Organic Compound	(240 – 260) to (380 – 400)	$> C_{16}$	Diisononyl phthalate
TVOC	Total Volatile Organic Compounds	Sum of all compounds listed above		

[1] World Health Organization, *Indoor Air Quality: Organic Pollutants, EURO Reports and Studies 111* (Copenhagen: WHO Regional Office for Europe, 1989).

TVOC as an Indicator for Indoor Air Quality

Figure 1 shows some of the reasons for concern about the TVOC inside buildings. The TVOC is considered an important indicator for indoor hygiene and indoor air quality (IAQ). In addition to serious health concerns, there is the psychological aspect: homes, offices, and other environments that smell clean typically seem more welcoming than areas with foul odors caused by organic compounds.

Figure 1. Effects of the TVOC



Common Volatile Organic Compounds in Indoor Spaces and their Sources

Volatile organic compounds are pervasive both outdoors and indoors. Depending on the interior decoration and usage, a room might be polluted with different organic compounds at the same time. Figure 2 shows typical sources of volatile organic compounds inside a home, and Table 2 gives potential examples and sources for the TVOC. Many volatile organic compounds have a chemical similar structure, which makes it difficult or sometimes impossible to distinguish between these in a VOC gas mixture. More information on detection of the TVOC can be found in IDT's *Application Note – TVOC Sensing.*

Figure 2. Typical Sources of the TVOC inside a Home

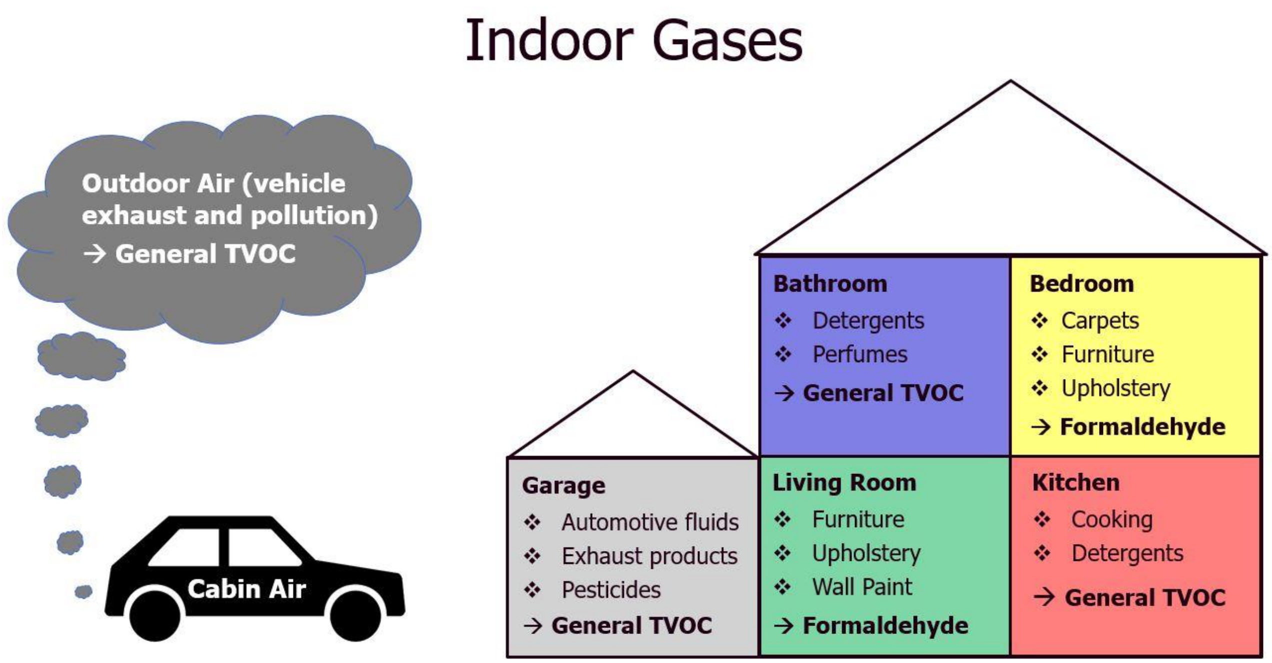


Table 2. VOCs that Contribute to Poor Air Quality and their Sources

Chemical TVOC Class	Chemical Examples	Source Examples
Alkanes	n-Butane, n-Pentane, n-Hexane, n-Heptane, n-Octane, Cyclohexane	Aerosol spray products for some paints, cosmetics, automotive exhaust products, leather treatments, paint thinner, oil based paints, spot removers, aerosol/liquid insect pest products, mineral spirits, furniture polishes
Alkenes	Isobutylene, Ethylene	Solvents, fruit ripening, pest control, rubber production
Aromatics	BTEX (Benzene, Toluene, Ethylbenzene, Xylene), Dichlorobenzene, Naphthalene, Styrene	Tobacco smoke, moth balls, moth flakes, deodorizers, air fresheners, automotive exhaust products, paint thinner, oil based paints, aerosol/liquid insect pest products, mineral spirits, furniture polishes, rigid foam products, contact cement, model cement, tar board, plasticizer
Halocarbons	Methylene Chloride, PERC, TCE, 1,1,1-Trichloroethane, Carbon Tetrachloride, Dichlorodifluoromethane (R12), Difluoromethane (R32), Pentafluorethane (R125), R-410A	Dry cleaned clothes, spot removers, fabric/ leather cleaners, degreasers, aerosol penetrating oils, brake cleaner, carburetor cleaner, commercial solvents, electronics cleaners, spray lubricants, refrigerant from air conditioners, freezers, refrigerators, dehumidifiers, urinal deodorizer block
Alcohols	Ethyl Alcohol (Ethanol), Methyl Alcohol (Methanol), 2-Propanol (Isopropyl Alcohol)	Cleaning agent, personal care products: nail polish, nail polish remover, colognes, perfumes, rubbing alcohol, hair spray
Terpene	α-Pinene (pine odor), D-Limonene (citrus odor)	Cosmetics, citrus (orange) oil, pine oil cleaners, fragrance additive, wood
Aldehyde	Formaldehyde, Hexanal	Disinfectants, upholstered furniture, carpets, plywood, pressed wood products, linoleum decomposition, oil-based paint
Ketones	Acetone, Methyl Ethyl Ketone (MEK), Methyl Isobutyl Ketone (MIBK)	PVC cement and primer, various adhesives, contact cement, model cement, UV processed varnishes
Ether	Methyl Tert-Butyl Ether (MTBE)	Automotive additive, medical solvent, plasticizer
Siloxane	Octamethylcyclotetrasiloxane (D4), Decamethylcyclopentasiloxane (D5)	Cosmetics, soaps, defoamer, silicone oil, detergent, antiperspirants

Implications of TVOC Exposure

There are significant health hazards associated with exposure to indoor air contaminants in residential and office spaces. The US Environmental Protection Agency (EPA) estimates that poor indoor air quality (IAQ) affects 33% to 50% of commercial buildings in the USA and is responsible for over 125 million lost school days and 10 million lost work days each year. Problems with indoor air quality, such as the so-called sick building syndrome, have significant health and financial impacts on the community. For example, recent studies have found that increased indoor pollutant concentrations and lower ventilation rates are associated with a statistically significant reduction in perceived mental performance among students and that controlling pollutant concentrations improved the measured performance of office workers[2]. Reports also show that building and indoor air quality significantly affects the prevalence of respiratory disease, allergies, asthma symptoms, and poor worker performance. The financial impact of improvements in IAQ are estimated at 6 to 14 billion US dollars in savings from reduced respiratory disease, 2 to 4 billion in savings from reduced allergies and asthma, 15 to 38 billion in savings from reduced symptoms of sick building syndrome, and 20 to 200 billion in savings from improvements in productivity unrelated to health[3]. The effect of indoor air quality on health is dramatic. It has been reported that the median level of the TVOC in office buildings might increase to 5 times greater than outdoor levels. Taking into consideration the greater amount of time most people spend indoors, indoor exposures are 10 to 50 times greater than outdoor exposures.

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2 U.S. Environmental Protection Agency, *Indoor Air Quality Tools for Schools Program*, https://www.epa.gov/iaq-schools.

3 W.J. Fisk, "Estimates of Potential Nationwide Productivity and Health Benefits from Better Indoor Environments: An Update," in J. Spengler (ed.) *Indoor Air Quality Handbook* (New York: McGraw-Hill, 2001).

Hazardous Condition Limits and Standards for TVOC

There are several sources of recommendations regarding the TVOC levels that are hazardous to human health. Table 3 presents a summary that compares levels from the varying sources for a range of chemicals. All levels are expressed in milligrams per cubic meter (mg/m^3) with a usual exposure time of 8 hours daily, except where a different period is mentioned. Although the concentrations vary from agency to agency there is a general agreement to keep the TVOC concentrations to a minimum.

US Environmental Protection Agency (EPA)[4]

Acute Exposure Guideline Levels (AEGLs) provided by the Environmental Protection Agency of the United States of America describe the human health effects from exposures to airborne chemicals. AEGLs, which are used by emergency responders when dealing with chemical spills or other catastrophic exposures, are set through a collaborative effort of the public and private sectors. AEGLs are classified into levels by the toxic effects caused by the exposure, with Level 1 being the least and Level 3 being the most severe, and these are divided into sublevels for the time of exposure. A Level 1 effect means a notable discomfort and irritation occurs but these effects are not disabling, are transient, and are reversible after exposure. Table 3 gives the AEGLs for a Level 1 exposure period of 8 hours.

Commission for the Investigation of Health Hazards of Chemical Compounds (Germany)[5, 6]

Maximum Workplace Concentrations (MAK and AGW values) are derived by the DFG Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, which is part of the German Research Foundation (DFG). The commission aims to determine the latest state of research related to health risks caused by materials and chemical substances in workplaces and to advise public authorities accordingly. MAK and AGW values for Time Weighted Average (TWA) are usually given for an 8-hour working day and are based on an average 40-hour working week. The values are published every year by the commission itself and are provided by other institutions; e.g., the statutory accident insurance.

World Health Organization (WHO)[7, 8]

The World Health Organization (WHO) presents guidelines for the protection of public health from risks due to a number of chemicals commonly present in indoor air. The substances under consideration have indoor sources; their hazardousness to health is known; and they are often found indoors in concentrations of health concern. The guidelines target public health professionals who are involved in preventing health risks due to environmental exposures, as well as specialists and authorities involved in the design and use of buildings, indoor materials, and products. They provide a scientific basis for legally enforceable standards.

Table 3. TVOC Values Reported as "Actionable" by Different Agencies

Chemical Substance	EPA, USA (8 hours daily)	DFG, Germany (8 hours daily)	WHO (exposure time)
Benzene	29 mg/m^3	0.2 mg/m^3	No safe level
Formaldehyde	1.12 mg/m^3	0.37 mg/m^3	0.1 mg/m^3 (30 min)
Napthalene		0.5 mg/m^3	0.01 mg/m^3 (1 year)
Styrene	86 mg/m^3	86 mg/m^3	0.26 mg/m^3 (1week)
Trichloroethylene	420 mg/m^3	33 mg/m^3	230 mg/m^3 (lifetime risk of 1/10.000)
Tetrachloroethylene	241 mg/m^3	138 mg/m^3	0.25 mg/m^3 (1 year)
Toluene	257 mg/m^3	190 mg/m^3	0.26 mg/m^3 (1 week)

4 Environmental Protection Agency, *Acute Exposure Guideline Levels for Airborne Chemicals,* 2017.

5 Deutsche Forschungsgemeinschaft, *MAK- und BAT-Werte-Liste 2016*, (Weinheim; Wiley-VCH, 2016).

6 Deutsche Gesetzliche Unfallversicherung, *Grenzwerteliste 2017 - Sicherheit und Gesundheitsschutz am Arbeitsplatz*, (Berlin: IFA Report, 2017).

7 World Health Organization, *Air Quality Guidelines for Europe, European Series, No. 91, 2nd Edition*, (Copenhagen: WHO Regional Publications, 2000).

8 World Health Organization, *WHO guidelines for indoor air quality: selected pollutants*, (Bonn: WHO European Centre for Environment and Health, 2010).

Standards for IAQ

At present, there is no global standard that defines indoor air quality (IAQ). Some countries have local approaches and have published studies that give indicators of clean ambient air and its implications. These have in common that there is a direct link between the TVOC and poor IAQ. This section gives a short overview of the most relevant studies, research results, and certifications. These publications also include non-VOC-related IAQ parameters such as radon, mercury, bacteria, and others, which are only relevant for the particular standard's mission.

Study by the German Federal Environmental Agency[9]

The "Umweltbundesamt" (UBA) is the Federal Environmental Agency in Germany, which carried out investigations and studies on indoor air and the TVOC for several years. A study from the year 2007 became very well-known. It is a compendium of 48 other research papers and reports that seeks to understand and summarize the best knowledge on indoor air quality. In particular, the TVOC references for indoor air quality are useful because not only does it identify levels of potential hazards, but it also provides guidance on which actions are recommended based on these TVOC levels. This 5-step TVOC indication for IAQ is used by IDT's gas sensor ZMOD4410 and is described in more detail in the "IAQ Classification" section.

IAQ itself is defined by 11 gases, of which 8 belong to the TVOC classification (see Table 4). The Guideline Values GV I describe concentrations below which no adverse health effects are to be expected at life-long exposure. Guideline Values GV II concentrations are likely to present a threat to health, especially for sensitive people, when exceeded and immediate action should take place, e.g. restriction of the time spent in the room.

Table 4. Gases to be Evaluated for IAQ by the German Federal Environmental Agency

Chemical Substance	GV I	GV II
Aliphatic Hydrocarbons	0.2 mg/m^3	2 mg/m^3
Bicyclic Terpenes	0.2 mg/m^3	2 mg/m^3
Carbon Monoxide	6 mg/m^3	60 mg/m^3
Dichloromethane	0.2 mg/m^3	2 mg/m^3
Mercury	0.035 $\mu g/m^3$	0.35 $\mu g/m^3$
Naphthalene	2 $\mu g/m^3$	20 $\mu g/m^3$
Nitrogen Dioxide	–	0.35 mg/m^3
Pentachlorophenol	0.1 $\mu g/m^3$	1 $\mu g/m^3$
Styrene	0.03 mg/m^3	0.3 mg/m^3
Toluene	0.3 mg/m^3	3 mg/m^3
Tris(2-Chloroethyl) Phosphate	5 $\mu g/m^3$	50 $\mu g/m^3$

9 Umweltbundesamt, *Beurteilung von Innenraumluftkontaminationen mittels Referenz- und Richtwerten*, (Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 2007).

Guide by the Indoor Air Quality Management Group of Hong Kong[10]

The document *A Guide on Indoor Air Quality Certification Scheme for Offices and Public Places* (the Guide) sets out the procedures for participating in the Indoor Air Quality Certification. It was published by the Indoor Air Quality Management Group of the Hong Kong Special Administrative Region Government. It gives details for a voluntary IAQ certification scheme with a differentiation into two classes (good and excellent) for offices and public places, such as theaters, cinemas, hotels, shopping malls, hotels, etc. A competent examiner, such as a registered professional engineer or appointed public officer, will execute the certification scheme and conduct a walkthrough inspection, identify any IAQ problems, and conduct an IAQ measurement. This IAQ measurement consists of 12 parameters, which are recorded over a period of 8 hours and include 3 physical parameters; 8 chemical parameters and 1 biological parameter (see Table 5). As an alternative, the measurements of 10 more commonly found individual volatile organic compounds can determine compliance with a Good Class TVOC objective (see Table 6).

The guide describes in detail the procedure for sample collection. After completion, if the environment is in compliance with the certification scheme, the certificate is issued and is valid for 12 months.

Table 5. Parameters for IAQ as Reported by the IAQ Management Group in Hong Kong

Parameter	Unit	8-Hour Average	
		Good Class	Excellent Class
Room Temperature	°C	< 25.5	20 to < 25.5
Relative Humidity	%	< 70	40 to < 70
Air Movement	m/s	< 0.3	< 0.2
Carbon Dioxide (CO_2)	ppm	< 1000	< 800
Carbon Monoxide (CO)	µg/m^3	< 10000	< 2000
Particulates (PM_{10})	µg/m^3	< 180	< 20
Nitrogen Dioxide (NO_2)	µg/m^3	< 150	< 40
Ozone (O_3)	µg/m^3	< 120	< 50
Formaldehyde (HCHO)	µg/m^3	< 100	< 30
Total Volatile Organic Compounds (TVOC)	µg/m^3	< 600	< 200
Radon (Rn)	Bq/m^3	< 200	< 150
Airborne Bacteria	cfu/m^3	< 1000	< 500

[10] Indoor Air Quality Management Group, Hong Kong SAR Government, *A Guide on Indoor Air Quality Certification Scheme for Offices and Public Places*, 2003.

Table 6. Maximum VOC Levels for Compliance with the Good Class per the IAQ Management Group

Volatile Organic Compound	Good Class [µg/m³]
Benzene	16.1
Carbon Tetrachloride	103
Chloroform	163
1,2-Dichlorobenzene	500
1,4-Dichlorobenzene	200
Ethylbenzene	1447
Tetrachloroethylene	250
Toluene	1092
Trichloroethylene	770
Xylene	1447

WELL Building Standard[11]

The WELL Building Standard was first launched in 2014 with an addendum in 2017 by the International WELL Building Institute (IWBI), which is a public benefit corporation. It promotes health and well-being in buildings, focusing on the people's needs because of the increasing staff incapacities due to unsatisfactory working conditions. The IWBI also cooperates with the Green Business Certification Institute, which is a commonly used green building rating system, and certifies the LEED (Leadership in Energy and Environmental Design). The goal of the WELL Building Standard certification is to raise awareness of human health and comfort needs in the planning and design of buildings and in the development of best building practices. Parameters such as air, water, nourishment, light, fitness, comfort, and mind are measured by an assessor, rated, and classified in the categories "Applicable" and "Achieved." The result is a total score value in the range of 1 to 10, and it is listed in the WELL Scorecard for the individual parameters. Depending on the total score, IWBI grants a Silver, Gold, or Platinum Certificate, which in most cases is valid for 3 years.

To identify relevant air contaminants, the WELL Building Standard adopts the National Ambient Air Quality Standards (NAAQS) by the Environmental Protection Agency (EPA) and expands these requirements by taking additional standards, such as the World Health Organization (WHO), and best practices from industry, such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), into consideration. Also, the LEED program sets standards for air filtration and building material selection to improve air quality. The parameter "Air" considers 29 criteria, such as air quality standards, smoking prohibition, ventilation effectiveness, VOC reduction, air filtration, and others. The Air Quality Standards criteria itself gives detailed information regarding single gases (see Table 7).

Table 7. Gases Evaluated for the WELL Building Standard

Chemical Substance	Limit for Passing Test
Formaldehyde	< 27 ppb
Total Volatile Organic Compounds	< 500 µ/m³
Carbon Monoxide	< 9 ppm
PM2.5	< 15 µ/m³
PM10	< 50 µ/m³
Ozone	< 51 ppb
Radon	< 50.148 Bq/L

[11] International WELL Building Institute: The WELL Building Standard with Q3 2017 addenda, International WELL Building Institute pbc and Delos Living LLC, New York, 2017.

IAQ Classification

The TVOC covers a large range of different organic gases that may be chemically similar and difficult to distinguish. Therefore, a single gas is not representative for an IAQ rating. Hence, IDT has investigated different TVOC and IAQ standards as discussed above. To cover a wide range of standards and gases, two internationally well accepted TVOC representatives were used: a combination of the Environmental Protection Agency (see the "US Environmental Protection Agency (EPA)" section) standards and the volatile organic components of the study by the German Federal Environmental Agency (UBA; see the "Study by the German Federal Environmental Agency" section).

The TVOC representative mixture *EPA TO-15/17 Calibration Mix* by the Environmental Protection Agency consists of 25 individual volatile organic compounds and complies with all US EPA and state-mandated methods. The VOC representative mixture of the UBA study gives the 8 listed volatile organic compound gases (see Table 4). Tested with both blends, IDT's gas sensors were tested with the most relevant volatile organic compounds in a large concentration range.

As a result, the UBA levels for the TVOC are applied as a reference for all of IDT's IAQ ratings (see Table 8). Integrating a gas sensor in home applications not only provides information about the current TVOC level to an end-user, but also allows the user to determine which actions should be taken and over what time period. Given the UBA levels as a reference, for an end-user who has conditions with temporarily elevated TVOC levels (cooking, cleaning, painting, new carpet), gas sensing helps to reduce concerns about air quality and to monitor the levels as they decrease over time.

Table 8. IAQ Rating by IDT

IDT IAQ Rating	Reference Level [12]	Air Information	Action	TVOC (mg/m^3)[13]	Air Quality
≤ 1.99	Level 1	Clean Hygienic Air (Target value)	No action required.	< 0.3	Very Good
2.00 – 2.99	Level 2	Good Air Quality (If no threshold value is exceeded)	Ventilation recommended.	0.3 – 1.0	Good
3.00 – 3.99	Level 3	Noticeable Comfort Concerns (Not recommended for exposure > 12 months)	Ventilation required. Identify sources.	1.0 – 3.0	Medium
4.00 – 4.99	Level 4	Significant Comfort Issues (Not recommended for exposure > 1 month)	Refresh air when possible. Increase ventilation. A search for sources is required.	3.0 – 10.0	Poor
≥ 5.00	Level 5	Unacceptable Conditions (Not recommended)	Use only if unavoidable and only for short periods.	> 10.0	Bad

For more information on TVOC detection in general and IDT's gas sensors, the *Application Note – TVOC Sensing* is recommended.

A certificate by the research institute KSI for an independent investigation of IDT gas sensors confirms their functionality, and it is available on the IDT website at www.IDT.com/gas.

[12] Umweltbundesamt, *Beurteilung von Innenraumluftkontaminationen mittels Referenz- und Richtwerten*, (Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 2007).

[13] Conversion from mg/m^3 to ppm for most common TVOC is by the factor ca. 0.5; for example, $10mg/m^3$ equals ca. 5ppm. Conversion from ppm to ppb is by the factor 1000; for example, 0.1ppm equals 100ppb.

Revision History

Revision Date	Description of Change
May 24, 2018	Initial release.

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