Indoor Air Quality Assessment Based on Human Physiology – Part 3. Applications

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The proposed evaluation system allows something quite new: a) the assessment of the effect of each environmental component (constituent) on the total environment level, b) accurate estimation of air volume for various locations, human occupations and sources of harmful gases. Additional benefits are listed at the conclusion of this part.

Keywords: indoor air quality, odors, air changes estimation.

1 Introduction

In the area in question there are some problems arising in practical life, which have not been solved up to now. One of these is an assessment of the effect of each environmental component (constituent) on the total condition of the environment. In addition, there are new possibilities in the area of ventilation and ascertaining acceptable indoor air quality: the great variety of air volumes corresponding to each limit for unadapted and adapted persons, so that every situation that can occur in practice may be provided with the correct quantity of outdoor air. An attempt to list the benefits of the new system is presented at the end of this paper.

2 A new prospect: the assessment of the effect of each constituent on the total environmental level

Perhaps the greatest advantage of the new decibel unit is the possibility of a new type of microenvironment evaluation: first each constituent (component) is assessed separately, and then its effect on the whole environment is assessed. Decibels can also be a new basis for a constituent mutual interaction study.

The paper by [46] can be used for this purpose. Various constituents have different effects on the resulting environment: e.g. our health is more threatened by cold than by positive aeroions.

An increase of 6 dB represents a doubling of the sound pressure level, although an increase of about 10 dB is required before the sound subjectively appears to be twice as loud. The smallest change we can hear is about 3 dB.

This is valid for the Weber-Fechner law and is also valid in a similar manner for the odor constituent. This, however, does not apply to the interaction of acoustic and odor or other constituents, as is evident from Rohles' [46] results.

The preliminary results from Rohles et al [46] are presented in Table 3.1. The hygrothermal component seems to be the most important (30 %). It is followed by illumination (24 %), acoustic (22 %), toxic (10 %), odor (8 %) and aerosol (6 %) constituents.

The influence of acoustic (AC) and odor (OD) constituents on the overall environment can be expressed as follows:

Table 3.1: The impact of some constituents and their parts on the perceived overall environment (according to Rohles et al [46])

Constituent (or part of it)	Impact [%]	Constituent factors
Hygrothermal	30.1	HT = 0.30
globe temperature	15.8	
air streaming	7.2	
air humidity	7.1	
Odor	7.5	OD = 0.08
Toxic (tobacco smoke only)	9.9	TX = 0.10
Aerosol	6.6	AE = 0.06
Acoustic	21.9	AC = 0.22
loudness	8.7	
noisy distractions	8.6	
pitch of sounds	4.6	
Lighting	24.0	LI = 0.24
brightness	11.0	
glare	7.9	
shadows	5.1	

$$L_{\text{acoustic}} = \text{AC}\, 20 \log \frac{P}{20} = \frac{22}{100} 20 \log \frac{P}{20} \quad [\text{dB}] \qquad (1)$$

$$L_{\text{odor}\,CO_2} = \text{OD}\, 90 \log \frac{\rho_{i CO_2}}{485} = \frac{8}{100} 90 \log \frac{\rho_{i CO_2}}{485}$$

[dCd], [decicarbdiox] (2)

or

$$L_{\text{odor TVOC}} = \text{OD}\, 50 \log \frac{\rho_{i \text{TVOC}}}{50} = \frac{8}{100} 50 \log \frac{\rho_{i \text{TVOC}}}{50}$$

[dTv], [decitvoc] (3)

where AC = 0.22, OD = 0.08 (22 % and 8 % from Rohles's paper [46]).

3 Accurate ventilation for acceptable indoor air quality

For this purpose BSR/ASHRAE 62-1989 R can be applied, i.e. the proposed system of dCd and dTv is compatible with this standard.

First, "Prescriptive Requirements", presented in Table 6.1 should be changed: instead of R_P and R_B air polution sources, G_P (produced by human bodies and characterized by CO_2 production) and G_B (produced by building interior surfaces and characterized by TVOC production) should be used (see Table 3.2) calculated from formulas (4) and (5).

$$G_P = \frac{2420-10}{10^6} R_P = 0.21 \cdot 10^{-2} R_P \, [\mathrm{l \cdot s^{-1} \cdot p^{-1}}] = 7.6\, R_P \, [\mathrm{l \cdot h^{-1} \cdot p^{-1}}] \quad (4)$$

$$G_B = \frac{580-10}{10^3} R_B = 0.57 R_B \quad [\mathrm{\mu g \cdot s^{-1} \cdot m^{-2}}] \quad (5)$$

where R_P $[\mathrm{l \cdot s^{-1} \cdot p^{-1}}]$ and R_B $[\mathrm{l \cdot s^{-1} \cdot m^{-2}}]$ are original values presented in BSR/ASHRAE 62-1989 R in Table 6.1a.

Values of CO_2 production from people or values of TVOC emanation within a building are prescribed for the estimation of minimum ventilation requirements or direct minimum ventilation requirements that are intended to achieve acceptable indoor air quality by dilution ventilation for various indoor spaces, when all other applicable requirements of this standard are met and the spaces are thermally comfortable. Requirements in this table are based on no smoking; refer to Appendix E when smoking or ETS is present. The prescriptive requirements for people, R_P, determined from CO_2 production from people by Equation $R_P = G_{PCO_2}/3600\,(\rho_{iCO_2} - \rho_{eCO_2})$ ($\rho_{eCO_2} = 310$ ppm, for other values see Table 3.3) are considered sufficient to satisfy adapted ($\rho_{iCO_2} = 2420$ ppm) and unadapted ($\rho_{iCO_2} = 1015$ ppm, other values see Table 2.1 – p. 31 in Part 2) (visitors to the space) persons in the space. See Appendix B. The prescriptive requirements for the building, R_B, determined from TVOC building emanation in this table by Equation $R_B = G_{BTVOC}/3.6\,(\rho_{iTVOC} - \rho_{eTVOC})$ (for adapted $\rho_{iTVOC} = 580\ \mathrm{\mu g \cdot m^{-3}}$, for unadapted $\rho_{iTVOC} = 200\ \mathrm{\mu g \cdot m^{-3}}$, for other values see Table 2.3 – p. 34, $\rho_{eTVOC} = 10\ \mathrm{\mu g \cdot m^{-3}}$, other values see Table 3.3) are for spaces that are designed, constructed, operated, and maintained according to this standard. Total rates in $\mathrm{l \cdot s^{-1}}$ in the occupied zone for each space are to be determined from Equation 6-3. See Appendix A for further discussion of rationale. Simple system requirements are based on prescriptive requirements with assumptions made for people density and diversity, ventilation system efficiency, and filtration efficiency. See Appendix A.3 for details. Ventilation rates do not apply to spaces just after completion of construction or renovation. See Section 7 for purging of spaces prior to occupancy.

Table 3.2: Minimum requirements for ventilation (Adapted from BSR/ASHRAE 62-1989R Table 6.1a)

	Prescriptive Requirements		Simple System Requirements		Notes
	People	Building	Outside Air	Supply Air	
	G_{PCO_2}	G_{BTVOC}	R_{SB}	R_{SS}	
	$[\mathrm{l \cdot h^{-1} \cdot person^{-1}}]$	$[\mathrm{\mu g \cdot s^{-1} \cdot m^{-2}}]$	$[\mathrm{l \cdot s^{-1} \cdot m^{-2}}]$	$[\mathrm{l \cdot s^{-1} \cdot m^{-2}}]$	
Miscellaneous spaces					
Private toilet/bath	–	14/fixture	25/fixture	25/fixture	D, E
Employee locker rooms	–	0.77	1.4	1.4	E
Storage rooms	–	0.34	0.60	0.60	G
Warehouses	–	0.20	0.44	0.44	G, H
Janitor's closet, trash room, recycling	–	0.48	0.85	0.85	E
Shipping/Receiving/Distribution	–	0.34	0.75	0.75	G
Public Assembly Spaces					
Churches, temples	23	0.20	4.2	15.0	
Legislative chambers	23	0.20	1.9	5.0	
Courtrooms	23	0.20	2.5	7.1	
Museums/Galleries	27	0.48	1.9	2.5	
Retail					
Sales floor (except as below)	27	0.48	1.2	1.2	
Malls	30	0.17	1.5	2.8	
Barber shop	23	0.48	1.9	2.6	E
Beauty and nails salons	38	0.77	3.3	3.3	E

Table 3.2: Minimum requirements for ventilation (Adapted from BSR/ASHRAE 62-1989R Table 6.1a)(continue)

	Prescriptive Requirements		Simple System Requirements		Notes
	People	Building	Outside Air	Supply Air	
	G_{PCO_2}	G_{BTVOC}	R_{SB}	R_{SS}	
	$[l \cdot h^{-1} \cdot person^{-1}]$	$[\mu g \cdot s^{-1} \cdot m^{-2}]$	$[l \cdot s^{-1} \cdot m^{-2}]$	$[l \cdot s^{-1} \cdot m^{-2}]$	
Furniture, carpets, fabric	27	1.34	2.5	2.5	
Pet shops	27	2.48	4.7	4.7	E
Supermarket	27	0.17	0.5	0.5	
Coin operated laundries	30	0.20	1.0	1.2	A
Food and Beverage Service					
Restaurant dining rooms	23	0.48	2.7	6.2	
Cafeteria, fast food, dining hall	23	0.34	2.3	6.1	
Bars, cocktail lounges	23	0.48	39	9.9	A
Commercial kitchens	30	1.62	3.7	3.7	A, E
Kitchenettes	23	0.77	1.5	1.5	A, D, E
Garage, Repair, Service Stations					
Enclosed parking garages	–	4.28	7.5	7.5	C, E
Auto repair rooms	–	4.28	7.5	7.5	B, E
Hotels, Motels, Resorts					
Dormitories					
Bedrooms (direct supply)	19	0.43	25/room	25/room	S
Living rooms (direct supply)	19	0.43	25/room	25/room	S
Bedrooms (indirect supply)	19	0.43	40/room	40/room	S
Living rooms (indirect supply)	19	0.43	40/room	40/room	S
Baths	–	14/room	25/room	25/room	D, E
Dormitory sleeping areas	19	0.20	0.93	2.4	
Lobbies/prefunction	27	0.20	1.4	2.9	
Meeting rooms	19	0.20	1.6	5.2	
Multi-purpose assembly	27	0.20	4.6	12	
Office Buildings					
Office space	23	0.20	0.66	0.66	
High density open office space	23	0.20	0.65	0.82	
Reception areas	27	0.20	0.88	1.3	
Telecommunication/data entry	27	0.20	2.5	5.9	
Conference rooms	19	0.20	1.6	5.2	
Main entry lobbies	27	0.17	0.59	0.59	
Public spaces					
Corridors	–	0.20	0.35	0.35	
Public restrooms	–	14/fixture	25/fixture	25/fixture	E, M
Transportation waiting	30	0.20	4.8	12	
Libraries	19	1.05	2.0	2.0	
Sports and Amusement					
Ice Arena (skating area)	–	1.34	2.4	2.4	J
Gymnasium, stadium (playing area)	76	0.11	1.7	1.7	J

Table 3.2: Minimum requirements for ventilation (Adapted from BSR/ASHRAE 62-1989R Table 6.1a)(continue)

	Prescriptive Requirements		Simple System Requirements		Notes
	People	Building	Outside Air	Supply Air	
	G_{PCO_2}	G_{BTVOC}	R_{SB}	R_{SS}	
	$[l \cdot h^{-1} \cdot person^{-1}]$	$[\mu g \cdot s^{-1} \cdot m^{-2}]$	$[l \cdot s^{-1} \cdot m^{-2}]$	$[l \cdot s^{-1} \cdot m^{-2}]$	
Locker/dressing rooms	30	0.77	2.4	2.4	E
Spectator areas	27	0.17	5.6	15	
Swimming (pool and deck area)	–	1.34	2.9	2.9	L
Disco/dance floors	57	0.20	7.9	7.9	
Health club/aerobics room	91	0.20	2.8	2.8	
Health club/weight rooms	76	0.20	1.4	1.4	
Bowling alley (seating area)	38	0.31	2.6	3.3	
Gambling casinos	27	0.48	5.1	12	
Game arcades	38	0.48	1.4	1.4	
Public restrooms	27	25/fixture	35/fixture	35/fixture	E, M
Theatres					
Auditorium seating area	19	0.20	4.1	16	
Stages, studios	38	0.20	2.1	3.0	A, K
Lobby	27	0.20	3.0	7.4	
Workrooms					
Photo studios	19	0.31	0.80	0.80	
Darkrooms	19	1.34	2.5	2.5	E
Pharmacy (preparation area)	23	0.66	1.5	1.5	
Bank vaults/safe deposit box area	19	0.20	0.48	0.48	
Photocopy, printing rooms	19	1.34	2.6	2.6	E
Computer room (exc. Printing area)	19	0.20	0.45	0.45	
Educational Facilities					
Daycare (through age 4)	27	0.40	1.9	2.6	
Classrooms Grades K to 3 (ages 5–8)	23	0.40	1.7	2.7	
General classrooms (grade 4 plus)	23	0.31	1.8	4.1	
Lecture Classroom	23	0.31	2.7	8.1	
Lecture Hall (fixed seats)	19	0.20	4.1	16	
Art classroom	38	1.05	3.6	3.6	Q
Science laboratories	27	1.62	3.7	3.7	A, Q, I
Wood/metal shop	30	1.05	2.7	2.7	A,Q
Media Center	23	0.40	1.2	1.4	R
Music/theater/dance	53	0.40	3.2	3.2	
Multi-use Assembly	23	0.31	2.7	7.0	
Health Care					
Patient rooms	–	0.77	1.7	1.7	N
Treatment and exam rooms	30	1.03	2.6	4.5	N, P
Operating and delivery rooms	30	1.03	2.6	12.5	N, P
Recovery& ICU	30	0.46	1.6	4.5	N, P
Autopsy	–	1.42	2.4	9.0	N, P

Table 3.2: Minimum requirements for ventilation (Adapted from BSR/ASHRAE 62-1989R Table 6.1a)(continue)

	Prescriptive Requirements		Simple System Requirements		Notes
	People	Building	Outside Air	Supply Air	
	G_{PCO_2}	G_{BTVOC}	R_{SB}	R_{SS}	
	$[l \cdot h^{-1} \cdot person^{-1}]$	$[\mu g \cdot s^{-1} \cdot m^{-2}]$	$[l \cdot s^{-1} \cdot m^{-2}]$	$[l \cdot s^{-1} \cdot m^{-2}]$	
Physical therapy	30	0.46	1.6	4.5	N, P
Waiting Room	30	0.28	1.1	4.5	N, P
Isolation Rooms	–	0.86	1.4	9.0	N, P
Correctional Facilities					
Cells	19	0.48	1.6	3.5	O, P
Dayroom	19	0.20	0.91	2.2	
Guard stations	19	0.20	0.73	1.4	
Booking/waiting	38	0.20	2.9	5.0	P

Notes for Table 3.2

A Make-up for exhaust systems not included in rates listed. Provide listed rates or rate sufficient for make-up, whichever is larger.

B Stands where engines are run shall include systems for positive engine exhaust (direct exhaust pipe connection to exhaust system discharping to outdoors).

C A garage is unenclosed if open on two or more sides with those sides at least 50 % open to outdoor. No more than 50 % of make-up air shall be drawn from garage exit for garages more than 2 stories.

D Listed rate is for installed capacity controlled by occupant. For continuous ventilation system operation, reduce rate listed by 50 %.

E Rate listed shall be exhausted from the space. Exhausted air may be recirculated as allowed by section 5.4. Make-up air shall be any combination if directly supplied outdoor air, or air transferred from adjacent occupied and ventilated spaces.

F Ventilation required to optimize plant growth not included in listed values.

G Listed values may not be sufficient when stored materials include those having high VOC or other potentially harmful emissions. Use the analytical procedure in this case. (See section 6.4 and Appendix B).

H Listed rates do not account for combustion driven vehicles driven in space. Use the Analytical Procedure in this case. (See section 6.4 and Appendix B).

I Ventilation systems shall comply with NFPA 45-1991 and ANSI/AIHA Z9.5-1992.

J When internal combustion equipment is intended to be used on the playing surface for more than 10 minutes at a time (e.g., bike racing, truck shows), the listed rate shall be provided as exhaust from no more than 3 m from (both vertically and horizontally) the play area. Temporary use of internal combustion equipment, such as ice-surfacing machines, is acceptable provided a 5-minute waiting period is allowed before occupants return to the field.

K Rate listed does not include special exhaust for stage effects, e.g., dry ice vapors, smoke.

L Rate listed is not intended to be sufficient for humidity control. Provide additional ventilation of mechanical system to remove moisture.

M Fixtures include both water closets and urinals.

N See “Guidelines for Control of Tuberculosis” (CDC, 1994) for other requirements.

O Allows for double occupancy per cell.

P The MSR for these spaces shall determined in accordance with the simple systems procedure (section 6.2.1) even if the prescriptive procedure is used to determine outdoor air rates.

Q Ventilation to these spaces may be broken into two components. Minimum rates determined using the category “General Classroom (grade 4 plus)” shall be provided at all times the room is expected to be occupied. This rate may be supplemented by exhaust air to provide the rates listed in the table for this category. The exhaust may be locally controlled so that it can be operated by occupants as required by the activity in the space. Air from these spaces may be recirculated only as allowed by section 5.4. Make-up air shall be any combination of directly supplied outdoor air, recirculated air, or air transferred from adjacent occupied and ventilated spaces.

R For high school and college libraries, use values shown for Public Spaces-Library.

S Direct supply means the room is supplied with outdoor air via a supply grille (either directly or after being mixed with return air) or outdoor air is induced into the room by an exhaust system and the make-up outdoor air source is on the opposite side of the room from the point exhaust. All other designs are considered indirect supply systems. Systems for which the only source of make-up air is infiltration shall be considered indirect supply systems. [Examples of indirect systems include exhaust from an interior toilet room with make-up air drawn from the adjacent corridor.]

Table 3.3: Outdoor TVOC and CO_2 concentration

Location	TVOC [$\mu g \cdot m^{-3}$]	CO_2 [ppm]	Source	Note
At sea		300–340	ICAO 1964	
	0		EUR 14449EN	
In towns, good air quality	14	350	EUR 14449 EN	TVOC converted decipol value
	15–18	–	Ekberg 1993	
In towns, bad air quality	71	350–400	EUR 14449 EN	TVOC converted decipol value
	23–98	–	Brown and Crump 1993	

The introduction of G_P and G_B allows a) various levels of indoor air quality as presented in Table 2.1 (p. 31), Table 3.3, Fig. 2.1 (p. 33) and Fig. 2.3 (p. 36), and b) various levels of outdoor air quality as presented in Table 3.3 using the formulas (6), and (7) to be taken into account.

$$R_P = \frac{G_P[1 \cdot h^{-1} \cdot p^{-1}]}{\left(\rho_{iCO_2} - \rho_{eCO_2}\right) 3.6} \quad [1 \cdot s^{-1} \cdot p^{-1}] \qquad (6)$$

$$R_B = \frac{1000 G_B [g \cdot s^{-1} \cdot m^{-2}]}{\left(\rho_{iTVOC} - \rho_{eTVOC}\right)} \quad [1 \cdot s^{-1} \cdot m^{-2}] \qquad (7)$$

where

G_P and G_B are listed in Table 3.2 and Table 3.4,

ρ_{iCO_2} = indoor CO_2 concentration [ppm], see Table 2.1 (p. 31) and Fig. 2.1 (p. 33),

ρ_{iTVOC} = indoor TVOC concentration [$\mu g \cdot m^{-3}$], see Tab. 2.3 (p. 34) and Fig. 2.3 (p. 36),

ρ_{eCO_2} = outdoor CO_2 concentration [ppm], see Table 3.3,

ρ_{eTVOC} = outdoor TVOC concentration [$\mu g \cdot m^{-3}$], see Table 3.3.

With new values of R_P, R_B, calculated from formulas (6), (7) we can follow the way prescribed in BSR/ASHRAE 62-1989 R.

Table 3.4: TVOC emission rate according to various authors

Location	TVOC [$\mu g \cdot h^{-1} \cdot m^{-2}$ floor]		Author	Note
	Mean	Range		
Existing buildings offices	1550	100–4890	EUR 1444 EN	Converted olf value
working hours (9–11)	360	132–691	Ekberg 1993	
night-time (5–7)	–	90–467	Ekberg 1993	
Schools (class rooms)	1550	620–2780	EUR 14449 EN	Converted olf value
Kindergartens	2060	1030–3810	EUR 14449 EN	Converted olf value
Assembly halls	2570	670–6790	EUR 14449 EN	Converted olf value
Dwellings	720	360–1080	EUR 14449 EN	
New PVC floor tiles	795	450–1400	Brown et al 1993	
Low-polluting buildings (target values)	–	260–510	EUR 14449 EN	Converted olf value
Solid flooring materials (vinyl, carpet, chipboard)	typically below 55		Crump et al 1997	Emission rates constant
Wall and ceiling materials			Crump et al 1997	Emission rates constant
plasterboard	max 6			
6-mm plywood	max 10			
15-mm plywood	max 12			
bituminised fibre board asphalt	max 30		Crump et al 1997	Emission rates constant

Table 3.4: TVOC emission rate according to various authors

Location	TVOC [$\mu g \cdot h^{-1} \cdot m^{-2}$ floor]	Author	Note
PVC skirting board	below the detection limit	Crump et al 1997	
polythene spacer	4 when heated to 40 °C		
rockwool (cavity wall)	below 15	Crump et al 1997	Emission rates declined slowly
mineral wool (loft)			

4 Conclusions – the benefits of using the decibel scale

The advantages of the new proposed evaluation system can be summed up in the following items:

1. The undoubted benefit of using the decibel scale is that it gives a much better approximation to human preception of odor intensity compared to the CO_2 and TVOC concentration scales. This is because the human olfactory organ (see [27]) reacts to a logarithmic change in level which corresponds to the decibel scale, where a change of 1 dB is approximately the same relative change everywhere on the scale.
2. The new decicarbdiox and decitvoc values also fit very well with the dB values for sound, e.g. the optimal odor value of 30 dB corresponds to the ISO Noise rating acceptable value NR 30 for libraries and private offices. They can therefore be compared to each other.
3. It is possible, by comparing dCd and dTv values, to estimate, which component – CO_2 or TVOC – plays a more important role and hence which sources of contamination are more serious.
4. The new units – decitvoc and decicarbdiox – can be a new basis for a constituent mutual interaction study (see earlier section).
5. The units dCd and dTv can be estimated by the direct measurement of TVOC and CO_2 concentrations – instruments can be calibrated directly in the new units.
6. The units dCd and dTv, as indoor air quality criteria, allow an optimal range definition and corresponding optimal ventilation rate estimations for unadapted and adapted persons by applying optimal limits to formulas (6) and (7).
7. The units allow an optimal range definition (so-called asthmatics optimal range) for persons with increased requirements (e.g. those allergic to indoor air quality, operators in airport control towers, power stations etc.) and corresponding asthmatic optimal ventilation rate estimations for unadapted and adapted persons by applying asthmatics optimal limits to formulas (6) and (7).
8. The unit allow the admissible range definition (for both healthy and allergic persons) and corresponding admissible ventilation rate estimations for unadapted and adapted persons by applying admissible limits to formulas (6) and (7).
9. The units allow definition of the SBS range (corresponding to the long-term tolerable range) and corresponding long-term tolerable ventilation rate estimations, by applying long-term tolerable limits to formulas (6) and (7).
10. The units allow the estimation of dangerous indoor air quality (corresponding to the short-term tolerable range, see Figs. 2.1 and 2.3, p. 40 and 43) and corresponding short term tolerable ventilation rate estimations by applying short-term tolerable limits to formulas (6) and (7).
11. The units allow the efficiency of air cleaners (and other indoor air-improving measures, e.g. using low polluting building materials) to be expressed, i.e. what is the decrease of air contamination after application.
12. The units allow the determination of the required ventilation rates depending on the various levels of outdoor air quality (see before).
13. The method developed is universal, it can also be applied to other environmental constituents (see Introduction of Part 1, p. 22).

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