Indoor Air Quality Assessment Based on Human Physiology – Part 2. Limits

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In order to evaluate indoor air quality in practice it is necessary to establish limits, or more exactly, tolerable ranges for unadapted and adapted persons. The optimal value overwhelmingly corresponds to PD = 20 %. A better value of PD = 10 % could be prescribed for asthmatics and for persons with increased requirements, i.e. those allergic to the environment and operators in airport control towers and atomic power stations. A worse value PD = 30 % could be accepted as an admissible value. These values differ for unadapted and adapted persons (as introduced by BSR/ASHRAE 62-1989 R). The long-term tolerable value is the end of SBS range (for CO_2 it is based on USSR space research, for TVOC on Molhave). The short-term tolerable value is the beginning of the toxic range (for CO_2 it is taken from British Guidance Note EH 40/90; for TVOC from Molhave).

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

1 Introduction

The increasing requirements for indoor air quality in buildings need more exact criteria in order to ascertain the real condition of the environment and to allow better optimization of its level, to remove "sick building" symptoms, i.e. to get the real comfort within a building.

Human physiology research makes evident that the Weber-Fechner law applies not only to noise perception, but also to the perception of other environmental components. Based on this fact, new decibel units for odor component representing indoor air quality in majority locations have been proposed: decicarbdiox dCd (for carbon dioxide CO_2) and decitvoc dTv (for total volatile organic compound TVOC) – see Part 1 of this paper.

Equations of these new units have been proved by application of a) experimental relationships between odor intensity (representing odor perception by the human body) and odor concentrations of CO_2 and TVOC, b) individually measured CO_2 and TVOC levels (concentrations) – from these new decibel units can be calculated and their values compared with decibel units of noise easured in the same locations.

To be able to evaluate the indoor air quality in practice, we need to establish limits or, more exactly, admissible and tolerable ranges for both unadapted and adapted persons (P).

2 Carbon dioxide

The starting points of these values are based on various studies (e.g. [23]) whose results are listed in Table 2.1 and in Fig. 2.1. See also Tables 1.2 and 1.3 (p. 24, 25) and Fig. 1.4 (p. 26) in Part 1.

The optimal value overwhelmingly corresponds PD = 20 %. A better value of PD = 10 % could be prescribed

Table 2.1: Various limits and ranges for CO_2 concentrations: *un* = unadapted persons, *asthm.* = asthmatic persons, *?* = for values of asthmatic persons there is no experimental background (analogy to TVOC is presumed)

No.	Limit			Value	Source
	[mg·m^{-3}]	[ppm]	[dCd]		
1	875	485	0	**threshold**	5.8 % dissatisfied
2	1080	600	8	USAF warning	USAF Armstrong Laboratory 1992
3	1110	615	9	**un asthm. optimal?**	10 % dissatisfied unadapted
4	1440	800	20	OSHA warning	OSHA: Federal Register 1994
5a	1800	1000	28	optimal limit	Pettenkofer 1858
5b	1800	1000	28	acceptable limit	ANSI/ASHRAE 62/1989
5c	1800	1000	28	opt. long-term	WHO/EURO:Air Quality Guidelines 1992
6a	1825	1015	29	**un optimal limit**	20 % dissatisfied unadapted
6b	1825	1015	29	**un asthm. admissible?**	
6c	2000	1110	32	concentration of no concern for non industrial buildings	WHO (Levy 1992)

Table 2.1: Various limits and ranges for CO_2 concentrations: *un* = unadapted persons, *asthm.* = asthmatic persons, *?* = for values of asthmatic persons there is no experimental background (analogy to TVOC is presumed) (continue)

No.	Limit			Value	Source
	[mg·m^{-3}]	[ppm]	[dCd]		
7a	2160	1200	35	opt. short-term	WHO/EURO:Air Quality Guidelines 1992
7b	2200	1225	36	**ad asthm. optimal ?**	10 % dissatisfied adapted
8	2830	1570	46	**un admissible**	30 % dissatisfied unadapted
9a	4350	2420	63	**ad optimal limit**	20 % dissatisfied adapted
9b	4350	2420	63	**ad asthm. admissible?**	(BSR/ASHRAE Standard 62-1989R)
10a	5035	2800	68	limit for direct gas fired air heaters	BS 5990: 1981 of British Standard Institution
10b	5035	2800	68	limit for direct gas fired air heaters	BS 6230: 1982 of British Standard Institution
11a	6300	3500	77	long-term acceptable	Env. Health Directorate, Canada 1989
11b	7000	3890	81	concentration of concern for nonindustrial buildings	WHO (Levy 1992)
11c	7360	4095	83	**ad admissible**	30 % dissatisfied adapted
12a	9000	5000	91	long-term exposure limit 8 hrs	Guidance Note EH 40/90 from HSE of GB
12b	9000	5000	91	average concentration for industrial and nonindustrial buildings	Commission de la Sante et de la Securite du Travail
12c	9000	5000	91	**long-term tolerable**	USSR space research (SBS range ends)
13a	18000	10000	118	maximum allowable concentration for ind. and nonind. buildings	Commission de la Sante et de la Securite du Travail
13b	18000	10000	118	short-term tolerable	USSR space research
14a	27000	15000	134	**short-term tolerable**	toxic range begins
14b	27000	15000	134	short-term expos. lim. 10 min	Guidance Note EH 40/90 from HSE of GB
Un A	875–1825	485–1015	0–29	Optimal range	
Un A1	875–1110	485–615	0–9	Asthm. optimal range?	
Un A2	1110–1825	616–1015	10–29	Asthm. admissible range?	
Un B	1826–2830	1016–1570	30–46	Admissible range	
Un C	2831–9000	1571–5000	47–91	Long-term tolerable (SBS) range	
Un D	9001–2700	5001–15000	92–134	Short-term tolerable range	
Un E	≥27001	≥15001	≥135	Intolerable range	
Un A	875–4350	485–2420	0–63	Optimal range	
Un A1	875–2200	485–1225	0–36	Asthm. optimal range?	
Un A2	2201–4350	1226–2420	37–63	Asthm. admissible range?	
Un B	4351–7360	2421–4095	64–83	Admissible range	
Un C	7361–9000	4096–5000	84–91	Long-term tolerable (SBS) range	
Un D	9001–27000	5001–15000	92–134	Short-term tolerable range	
Un E	≥27001	≥15001	≥135	Intolerable range	

for asthmatics and for persons with increased requirements, i.e. those allergic to the environment and operators in airport control towers and power stations (especially atomic power stations). This is analogous to the TVOC limits (see later).

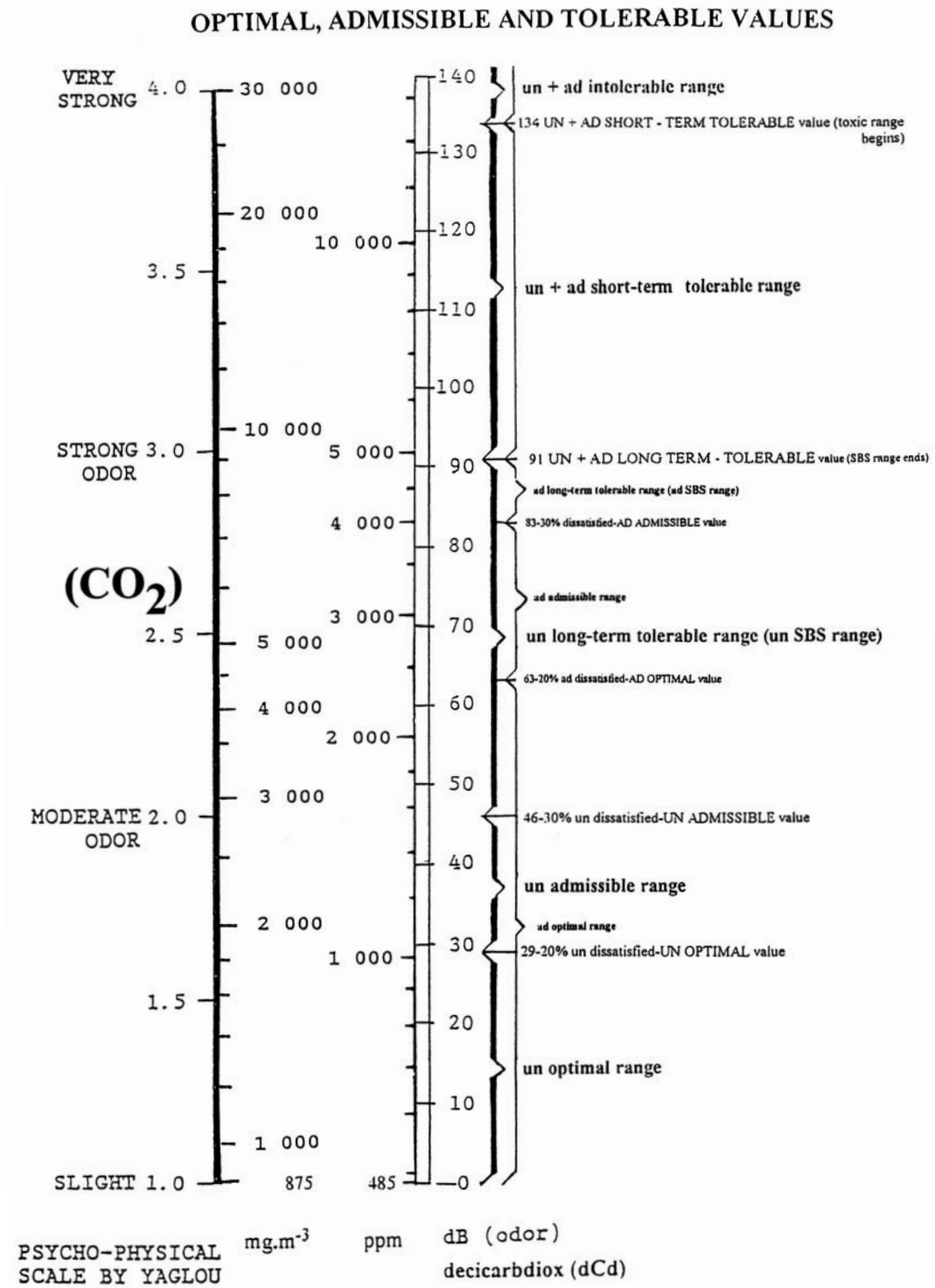

Fig. 2.1: The proposed CO_2 limits: optimal admissible and tolerable values, the psycho-physical scale slightly modified by Fanger (1988) (*ad* = adapted persons, *un* = unadapted persons)

A worse value of PD = 30 % could be accepted as an admissible value. These values differ for unadapted and adapted persons (as introduced by BSR/ASHRAE 62-1989 R).

The long-term tolerable values, which are quoted in occupational health standards and studies, are reached in buildings with sick building syndrome (SBS). Short-term tolerable values are those at the beginning of the toxic range both for unadapted and adapted persons. Also the lowest, detectable value is the same for unadapted and adapted person (P).

For unadapted persons optimal (PD = 20 %) and admissible (PD = 30 %) values are 1015 ppm and 1570 ppm (Fig. 2.2), i.e. 29 dCd and 46 dCd.

For adapted persons the curve must first be added into the diagram (Fig. 2.2) as follows:

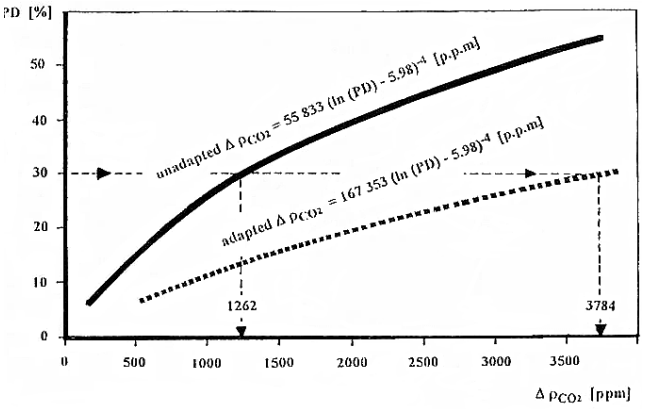

Fig. 2.2: The percentage of dissatisfied sedentary subjects as a function of the carbon dioxide concentration above outdoors

For unadapted persons the equilibrium equation is valid (1)

$$R_P = \frac{G_{PCO_2} \cdot 10^6}{3600\left(\rho_{iCO_2} - \rho_{eCO_2}\right)} = \frac{19 \cdot 1000}{3.6\left(1015 - \rho_{eCO_2}\right)} = 7.5\ [\mathrm{l \cdot s^{-1} \cdot p^{-1}}] \quad (1)$$

where $R_P = 7.5\ \mathrm{l \cdot s^{-1} \cdot p^{-1}}$, prescriptive outdoor air requirement for unadapted persons [9]; $G_{PCO_2} = 19\ \mathrm{l \cdot h^{-1} \cdot p^{-1}}$, CO_2 load caused by a sedentary person (see Table 2.2); $\rho_{iCO_2} = 1015\ \mathrm{mg \cdot m^{-3}}$, CO_2 indoor air concentration for 20 % dissatisfied unadapted persons (see Fig. 2.2); $\rho_{eCO_2} = 310$ ppm, CO_2 outdoor air concentration as a result of Eq. (1).

For adapted persons the same Eq. (1) is valid, but the prescriptive outdoor air requirements for them, according to [9], is only $2.5\ \mathrm{l \cdot s^{-1} \cdot p^{-1}}$ CO_2 load caused by a sedentary person and outdoor CO_2 concentration remain the same, i.e. $G_{\rho CO_2} = 19\ \mathrm{l \cdot h^{-1} \cdot p^{-1}}$, $\rho_{eCO_2} = 310$ ppm. So CO_2 indoor concentration ρ_{iCO_2} can be calculated:

$$R_P = \frac{19}{3600\left(\rho_{iCO_2}\right)} = 2.5\ [\mathrm{l \cdot s^{-1} \cdot p^{-1}}] \quad (2)$$

where $\rho_{iCO_2} = 2420$ ppm, i.e. for 20 % dissatisfied adapted persons, CO_2 indoor air concentration can be raised from 1015 ppm to 2420 ppm. Presuming the same character of the curve, i.e.

$$\Delta\rho_{CO_2} = k\left(\ln(PD) - 5.98\right)^{-4}\ [\mathrm{ppm}]$$
$$2420 - 310 = k\left(\ln 20 - 5.98\right)^{-4}$$

we get for adapted persons:

Table 2.2: Pollution load caused by occupants

Activity	TVOC [$\mu g \cdot h^{-1} \cdot p^{-1}$] [3)]	CO_2 [$l \cdot h^{-1} \cdot p^{-1}$]
Sedentary, 1–1.2 met [1)]		
0 % smokers	5140	19
20 % smokers [2)]	10290	19
40 % smokers [2)]	15430	19
100 % smokers [2)]	30870	19
Physical exercise		
Low level, 3 met	20580	50
Medium level, 6 met	51440	100
High level (athletes), 10 met	102890	170
Children		
Kindergarten, 3–6 years, 2.7 met	6170	18
School,14–16 years, 1–1.2 met	6690	19

[1)] 1 met is the metabolic rate of a resting sedentary person (1 met = 58 $W \cdot m^{-2}$ skin area, i.e. approx. 100 W for an average person)

[2)] average smoking rate 1.2 cigarettes/hour per smoker, emission rate 44 ml CO/cigarette

[3)] converted olf values presented in EUR 14449 EN

$$\Delta\rho_{CO_2} = 167.350\left(\ln(PD) - 5.98\right)^{-4} \quad (3)$$

For adapted persons optimal (PD = 20 %) and admissible (PD = 30 %) values are 2420 ppm and 4095 ppm, i.e. 63 dCd and 83 dCd.

Optimal (PD = 10 %) and admissible (PD = 20 %) values for asthmatics could be, for unadapted persons: 615 ppm, 9 dCd (PD = 10 %) and 1015 ppm, 29 dCd (PD = 20 %); and for adapted persons: 1225 ppm, 36 dCd (PD = 10 %) and 2420 ppm, 63 dCd (PD = 20 %). More experimental data are required.

The long-term tolerable value (5000 ppm, 91 dCd; the end of the SBS range) is based on USSR space research; the short-term tolerable value (15000 ppm, 134 dCd; the beginning of the toxic range) is taken from British Guidance Note EH 40/90 as described previously.

Table 2.3: Various limits and sranges for TVOC concentrations

No	Limit		Value	Source
	[$\mu g \cdot m^{-3}$]	[dTv]		
1	50	0	**threshold**	5.8 % dissatisfied (1.0 by Yaglou Psycho-Physical Scale)
2	85	12	**un asthm. optimal**	10 % dissatisfied unadapted (EUR 14449 EN)
3a	200	30	**un optimal limit**	20% dissatisfied unadapted (EUR 14449 EN) old dwelling houses old office buildings

Table 2.3: Various limits and ranges for TVOC concentrations (continue)

No	Limit		Value	Source
	[$\mu g \cdot m^{-3}$]	[dTv]		
3b	200	30	**un asthm. admissible**	
4	250	35	**ad asthm. optimal**	10 % dissatisfied adapted
5	300	39	target guideline	Seifert (1990)
6	360	43	**un admissible**	30 % dissatisfied unadapted (EUR 14449 EN) new dwelling houses new office buildings
7a	500	50	level of concern	National Health and Medical Research Council of Australia (Dingle, Murray 1993)
7b	580	53	**ad optimal limit**	20 % dissatisfied adapted
7c	580	53	**ad asthm.admissible**	
8	1040	66	**ad admissible**	30 % dissatisfied adapted
9a	3000	89	**long-term tolerable**	SBS range ends
9b	3000	89	multifactorial exposure range limit	Molhave (1990)
10a	25000	135	**short-term tolerable**	toxic range begins
10b	25000	135	discomfort range limit	Molhave (1990)
No	Limit			Value
	[$\mu g \cdot m^{-3}$]		[dTv]	
Un A	50–200		0–30	Optimal range
Un A1	50–85		0–12	Asthm. optimal range
Un A2	86–200		13–30	Asthm. admissible range
Un B	201–360		31–43	Admissible range
Un C	361–3000		44–89	Long-term tolerable (SBS) range
Un D	3001–25000		90–135	Short-term tolerable range
Un E	25001		136	Intolerable range
Un A	50–580		0–53	Optimal range
Un A1	50–250		0–35	Asthm. optimal range?
Un A2	251–580		36–53	Asthm. admissible range?
Un B	581–1040		54–66	Admissible range
Un C	1041–3000		67–89	Long-term tolerable (SBS) range
Un D	3001–25000		90–135	Short-term tolerable range
Un E	25000		136	Intolerable range

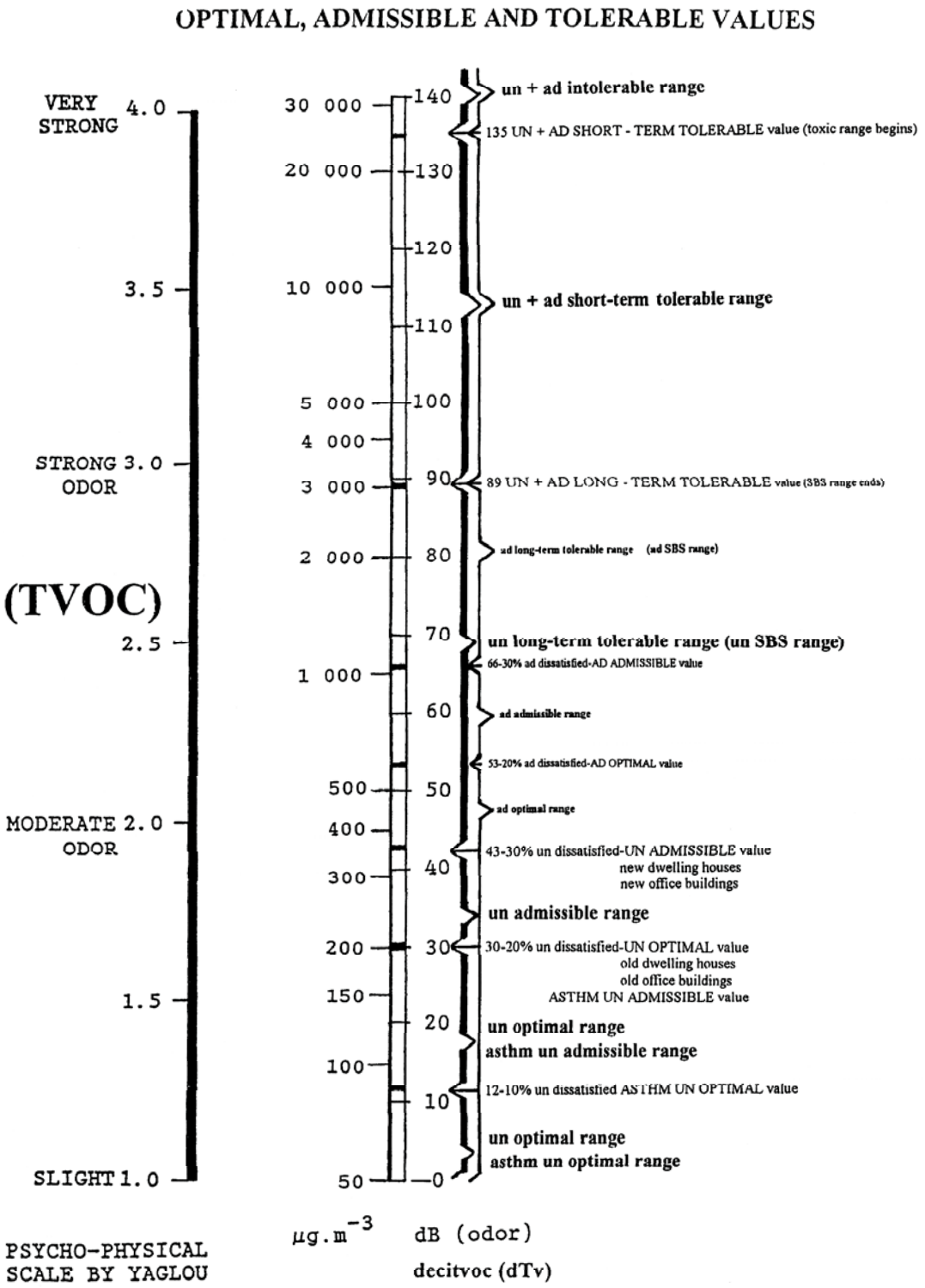

Fig. 2.3: The proposed TVOC limits: optimal, admissible and tolerable values. The psycho-physical scale slightly modified by Fanger (*ad* = adapted persons, *asthm* = asthmatic persons, *un* = unadapted persons)

3 Total volatile organic compounds

The starting points of these values are based on various studies whose results are listed in Table 2.3 and in Fig. 2.3 (see also Tables 1.3 and 1.4 (p. 25 and 28) and Fig. 1.4 (p. 26) in Part 1). The philosophy behind the various limits is the same as previously presented for CO_2. For unadapted persons optimal (PD = 20 %) and admissible (PD = 30 %) values are 200 μg·m^{-3} and 360 μg·m^{-3}, i.e. 30 dTv and 43 dTv.

For adapted persons the curve must first be added into the diagram (Fig. 2.4) as follows.

For unadapted persons the equilibrium equation (4) is valid:

$$R_B = \frac{G_{B\mathrm{TVOC}}}{3.6\left(\rho_{i\mathrm{TVOC}} - \rho_{e\mathrm{TVOC}}\right)} = \frac{5140}{3.6\left(200 - \rho_{e\mathrm{TVOC}}\right)} = 7.5\ [\mathrm{l\cdot s^{-1}\cdot p^{-1}}] \quad (4)$$

where $R_B = 7.5$ l·s^{-1}·p^{-1}, prescriptive outdoor air requirement for unadapted persons [9] $G_{B\mathrm{TVOC}} = 5140$ μg·h^{-1}·p^{-1}, TVOC load caused by sedentary person (see Table 2.2); $\rho_{i\mathrm{TVOC}} = 200$ μg·m^{-3}, TVOC indoor air concentration for 20 % dissatisfied unadapted person (see Fig. 2.4); $\rho_{e\mathrm{TVOC}} = 10$ μg·m^{-3}, TVOC outdoor air concentration, as a result of Eq. (4).

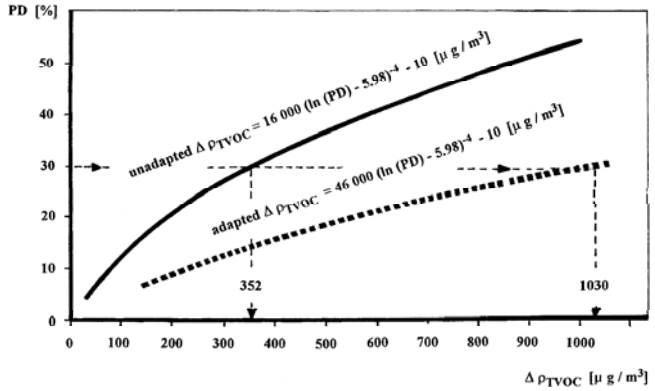

Fig. 2.4: The percentage of dissatisfied sedentary subjects as a function of total volatile organic compound concentration above outdoors

For adapted persons the same Eq. (4) is valid, but the prescriptive outdoor air requirement for them, according to BSR/ASHRAE 62-1989 R, is only 2.5 l·s^{-1}·p^{-1}; TVOC load caused by a sedentary person and outdoor air TVOC concentration remain the same, i.e., $G_{B\mathrm{TVOC}} = 5140$ μg·h^{-1}·p^{-1}, $\rho_{e\mathrm{TVOC}} = 10$ μg·m^{-3}. So TVOC indoor air concentration $\rho_{i\mathrm{TVOC}}$ can be calculated:

$$R_B = \frac{5140}{3.6\left(\rho_{i\mathrm{TVOC}} - 10\right)} = 2.5\ [\mathrm{l\cdot s^{-1}\cdot p^{-1}}] \quad (5)$$

where $\rho_{i\mathrm{TVOC}} = 580$ μg·m^{-3}, i.e. for 20 % dissatisfied adapted persons TVOC indoor air concentration can be raised from 200 μg·m^{-3} to 580 μg·m^{-3}. Presuming the same character of the curve, i.e.

$$\rho_{\mathrm{TVOC}} = k\left(\ln(\mathrm{PD}) - 5.98\right)^{-4}$$
$$580 = k\left(\ln 20 - 5.98\right)^{-4}\ [\mu\mathrm{g\cdot m^{-3}}]$$

we get for adapted persons, preferring again Δp as it was with CO_2,

$$\Delta\rho_{\mathrm{TVOC}} = 46000\left(\ln(PD) - 5.98\right)^{-4} - 10\ [\mathrm{mg\cdot m^{-3}}] \quad (6)$$

For adapted persons optimal (PD = 20 %) and admissible (PD = 30 %) values are 580 μg·m^{-3} and 1040 μg·m^{-3}, i.e. 53 dTv and 66 dTv.

Optimal (PD = 10 %) and admissible (PD = 20 %) value for asthmatics could be for unadapted persons: 85 μg·m^{-3}, 12 dTv (PD = 10 %) and 200 μg·m^{-3}, 30 dTv (PD = 20 %) and for adapted persons: 250 μg·m^{-3}, 35 dTv (PD = 10 %) and 580 μg·m^{-3}, 53 dTv (PD = 20 %). Besides asthmatics these values are also recommended for people with increased requirements: those allergic to the environment or those having responsible positions – operators in airport control towers and power stations, especially atomic power stations.

The long-term tolerable value (3000 μg·m^{-3}, 89 dTv; the end of the SBS range) and short-term tolerable value (25000 μg·m^{-3}, 135 dTv; the beginning of the toxic range) are based on [36].

4 Conclusions

1. The new units – decitvoc and decicarbdiox – can be a new basis for a constituent mutual interaction study.
2. 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.
3. The units dCd and dTv, as indoor air quality criteria, allow an optimal range definition.
4. 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.).
5. The unit allow the admissible range definition (for both healthy and allergic persons).
6. The units allow definition of the SBS range (corresponding to the long-term tolerable range).
7. The units allow the estimation of dangerous indoor air quality (corresponding to the short-term tolerable range, see Figs. 2.1 and 2.3).
8. The units allow the efficiency of air cleaners (and other indoor air-improving measures, e.g. using low polluting building materials) (see [30]) to be expressed, i.e. what is the decrease of air contamination after application?

References

See presented at the end of Part 3 (p. 44).

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