

A POINT TO NOTE IN THE DRAFT CODE OF PRACTICE FOR FIRE SAFETY IN BUILDINGS 2011: SMOKE TOXICITY ASSESSMENT OF BURNING MATERIALS

C.L. Chow¹ and W.K. Chow²

¹ Hong Kong Fire Engineers Ltd., Hong Kong, China

² Research Centre for Fire Engineering, Department of Building Services Engineering
The Hong Kong Polytechnic University, Hong Kong, China

(Received 14 October 2011; Accepted 16 December 2011)

ABSTRACT

A draft updated code of building fire safety in Hong Kong was just released in end September 2011. Effect of smoke toxicity on tenability limits was not yet specified clearly. Only temperature of smoke layer, visibility and carbon monoxide concentration were mentioned on specifying smoke effect on tenability limits. The necessity of specifying smoke toxicity on tenability limits properly is pointed out in this short note. Earlier experimental data reported on studying smoke toxicity of burning video compact disc boxes in a cone calorimeter were taken as an example. The effects to human beings are proposed to be assessed based on the fractional exposure dose with carbon dioxide and carbon monoxide measured at least. Empirical correlation expressions including other toxic gases should be derived from cone calorimeter tests under high heat fluxes; and real-scale tests under post-flashover fires.

1. INTRODUCTION

Many big accidental post-flashover building fires have occurred all over the world since 1996 in Hong Kong [1] and other places in Far East. Consequently, fire codes were revised in many of these places. There are mandatory requirements on upgrading fire safety provisions in existing buildings. However, several firemen have been even killed while fighting against such big fire [2-4]. Another big killing fire [5] just occurred on 30 November 2011. This raised public awareness on building fire safety. A draft code on building fire safety was just released recently for public consultation [6], after spending over ten years of effort. However, it is not clear whether the specified requirements are justified strongly by in-depth research. Data used elsewhere are specified without demonstration with strong justifications. There are no full-scale burning tests carried out to support the prescriptive data as in other countries developing new fire codes like Mainland China. Even the reference citations of those data are not clearly spelled out. Some arguments or data coming from analysis not appropriate to Hong Kong should be justified and will be pointed out one by one later. Those points to watch will be reported as a series of publications and lectures.

The first part is on smoke which is believed to be the main threat to life safety in an accidental building fire [e.g. 7]. However, smoke toxicity is

difficult to put in building codes and regulations on fire safety provisions [7]. One of the main reasons is that toxicity depends not only on the materials that burn, but also on how the materials are burnt. It is very difficult to know the burning conditions of burning carbon-containing materials. A much higher concentration of carbon monoxide CO would be generated if the combustion is incomplete due to inadequate air or cooling of the burning objects, say by water mist.

Effect of smoke on tenability limits was specified in the new building fire safety code released recently [8] as summarized in Appendix A. There are two points to watch on estimating tenable conditions due to smoke toxicity:

- A stable smoke layer assumed to be formed with all toxic gases in there. This assumption should be watched for tall and large halls over 10 m high with a small design fires. In this case, the fire source cannot emit sufficient thermal power to give high buoyancy to form a stable stratified hot layer.
- Only CO concentration was specified with value less than 1,000 ppm. Toxicity of smoke [8,9] due to other gases generated while burning plastic materials was not even mentioned.

The importance of specifying smoke toxicity is pointed out in this note. Published experimental data on studying smoke toxicity of burning video compact discs (VCD) [10-12] are referred to. Smoke toxicity of burning VCDs was studied with a cone calorimeter [e.g. 13-16]. Similar results compiled on both heat and smoke for burning common combustible materials should be applied for fire hazard assessment.

2. FRACTIONAL EFFECTIVE EXPOSURE DOSE (FED)

An approach assessing smoke toxic potency is the N-Gas Model developed by the National Institute of Standards and Technology (NIST). This was compiled as NFPA 269 ‘Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling’ [17] and ASTM E 1678 ‘Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis’ [18].

Fractional effective exposure dose (FED) is defined [18] as “the ratio of the concentration and time product for a gaseous toxicant produced in a given test to that product of the toxicant that has been statistically determined from independent experimental data to produce lethality in 50% of test animals within a specified exposure and post-exposure period” which can be expressed mathematically in terms of the concentration c_i of the i^{th} toxic component; and the specific exposure dose (concentration-time product) $(ct)_i$ as:

$$FED = \sum_{i=1}^n \int_{t_0}^t \frac{c_i}{(ct)_i} dt \quad (1)$$

When FED is equal to 1, the mixture of the gaseous toxicants would be lethal to 50% of the exposed animals.

The toxic potency parameter LC_{50} [19-21], that is the concentration of the material or fire effluent that produces death in 50% of the animals for a specified exposure time, is suggested to be considered. LC_{50} means the concentration of a sample causing 50% mortality in a standard toxicity test on the specified species over a specific period of time. Typical values of 30-min LC_{50} for CO, hydrogen cyanide HCN, hydrogen chloride HCl and hydrogen bromide HBr (denoted by LC_{50CO} , LC_{50HCN} , LC_{50HCl} and LC_{50HBr}) as quoted in NFPA 269 [17] are 5700 ppm, 150 ppm, 3700 ppm and 3000 ppm respectively.

Using the transient concentrations of O_2 , CO_2 , CO, HCl, HCN and HBr denoted by $[O_2]$, $[CO_2]$, $[CO]$, $[HCl]$, $[HCN]$ and $[HBr]$ of the smoke generated

from a sample in the chamber, the concentration-time (in ppm/min) product can then be deduced by integrating the area under the measured concentration-time curves to give FED as:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{21-[O_2]}{21-LC_{50O_2}} + \frac{[HCN]}{LC_{50HCN}} + \frac{[HCl]}{LC_{50HCl}} + \frac{[HBr]}{LC_{50HBr}} \quad (2)$$

where b and m are reviewed [8,10]:

As LC_{50} is time-dependent, the values for each chemical specie (such as 5000 ppm for CO) used are the average LC_{50} over 30 minutes.

This can be further simplified by assuming that the toxic effects are linearly additive as in ISO 13344 [22]:

$$FED = \frac{[CO]}{5000} + \frac{[HCN]}{150} + \frac{[HCl]}{3800} + \frac{[HBr]}{3000} + \frac{[NO]}{1000} + \frac{[NO_2]}{200} \quad (3)$$

LC_{50} of the product specimen can be estimated experimentally [e.g. 21] by the specimen mass loss Δm_s and chamber volume V_c .

$$LC_{50} = \frac{\Delta m_s}{FED * V_c} \quad (4)$$

3. EARLY EXPERIMENTS ON VCD BOXES WITH A CONE CALORIMETER

Samples of VCD boxes made of polyethylene (PE) were tested with a cone calorimeter [23] under different radiation fluxes R_f (in kWm^{-2}). Using the measured curves of the transient heat release rate per unit area $Q(t)$ (in kWm^{-2}), thermal parameters studied [13-16] for assessing the materials are time to ignition, TTI (in s); peak heat release rate, pk RHR (in kWm^{-2}); time to pk RHR after ignition, t_{fp} (in s); average heat release rate in 60 s after ignition, \bar{Q}_{60} (in kWm^{-2}); average heat release rate in 180 s after ignition, \bar{Q}_{180} (in kWm^{-2}); total heat released, THR (in MJm^{-2}); mass loss percentage of sample, m_L (in %); and average effective heat of combustion, ΔH_c^{av} (in $MJkg^{-1}$).

Two key smoke parameters, total smoke released TSR (a non-dimensional quantity) and the peak fractional effective dose FED, can be deduced [20] by the measured transient curves on CO concentration denoted by $[CO]$ (in ppm), CO_2 concentration denoted by $[CO_2]$ (in %), smoke release rate S_R (in s^{-1}), mass loss of the samples, and smoke extinction area SEA (in m^2). TSR at the

end of the test calculated by integrating the S_R curve over the burning time t_B :

$$TSR = \int_0^{t_B} S_R dt \quad (5)$$

Since only CO and CO₂ were measured in this cone calorimeter and toxic potency LC₅₀ for CO₂ is much greater than that for CO (i.e. 5000 ppm) [24], FED_c was calculated from the peak concentration of CO denoted by pk[CO] in the cone calorimeter by:

$$FED_c = \frac{pk[CO]}{5000} \quad (6)$$

A correlation curve should be measured on common building materials to correlate FED given by equation (3) on FED_c with only pk[CO] by equation (6).

Two arrangements were cut from on the VCD sample boxes for carrying out the cone calorimeter tests [10,11]:

- A: One sheet of VCD box
- B: Smaller VCD box

The VCD boxes were cut into size of 10 cm × 10 cm as shown in Fig. 1.



(a) Test A



(b) Test B

Fig. 1: The two testing arrangements

Eight tests were carried out on the two arrangements with different heat fluxes [10,11]. Values of TSR, pk[CO] and FED for testing the

VCD box samples had been reported [10,11]. The materials will burn more vigorously under higher heat fluxes, pk[CO] and FED will increase significantly.

Note that in a flashover room fire, radiation heat fluxes are 20 kWm⁻² at the floor, 35 kWm⁻² on the wall, and 50 kWm⁻² at the ceiling. The burning environment of the samples is difficult to estimate. Materials, both the fixed and movable fire load, must be tested under higher heat fluxes of at least 50 kWm⁻² in a cone calorimeter.

4. HAZARD ASSESSMENT

Three parameters are recommended by the author years ago [e.g. 11,12,25] to assess fire safety of the material. Two parameters were for studying the thermal contribution of the materials, and one parameter on assessing the smoke hazard. The first parameter is the flashover propensity x (in kWm⁻²s⁻¹):

$$x = \frac{pkHRR}{TTI} \quad (7)$$

The second parameter is the THR (in MJm⁻²):

$$y = THR \quad (8)$$

The third parameter z [25] is the LC₅₀.

Parameters x , y were originally proposed by Petrella [14] with values for the six ignited arrangements at heat flux on the VCD boxes taken are shown in Table 1. The values of z or LC₅₀ on the VCD boxes tested by the cone calorimeter were calculated by using Δm_s , measured in the cone and taking V_c as 0.01 m³, with a correction factor of 4000 [e.g. 9] as shown in Table 1.

Arbitrary scales suggested [11] for x are:

- Low risk to flashover (LRF) : 0.1 to 1.0
- Intermediate risk to flashover (IRF) : 1.0 to 10
- High risk to flashover (HRF) : 10 to 100

Similarly, arbitrary scales [11] for y are:

- Very low risk to thermal effect (VLRT) : 0.1 to 1.0
- Low risk to thermal effect (LRT) : 1.0 to 10
- Intermediate risk to thermal effect (IRT) : 10 to 100
- High risk to thermal effect (HRT) : 100 to 1000

Arbitrary scale for z should be matched with in-depth studies on smoke toxicity still in progress.

Table 1: Testing results

Hazard parameter	Parameters	Test A: One sheet of VCD box				Test B: Smaller VCD box			
	R_f / kW^{-2}	70	50	20	10	70	50	20	10
Thermal behavior	$x / kWm^{-2}s^{-1}$	162	147	87	0	221	175	89	0
	Classification	HRF	HRF	HRF	LRF	HRF	HRF	HRF	LRF
	y / MJm^{-2}	31.5	32.0	32.0	-	75.3	75.0	81.8	-
	Classification	IRT	IRT	IRT	VLRT	IRT	IRT	IRT	VLRT
Smoke emission	FED	0.071	0.054	0.025	0	0.098	0.061	0.019	0
	z	2.95	8.34	8.20	-	4.94	7.84	25.1	-

5. SMOKE TOXICITY ASSESSMENT

As discussed by Babrauskas [21], LC_{50} is commonly used in assessing smoke toxicity of products. LC_{50} can be used as a ‘toxic potency’ parameter to account for the combustion product toxicity. It can be viewed as ‘per-gram toxicity’ (in gm^{-3}), not affected by the burning rate of the product or by the amount of product present. The scale is an ‘inverse’ one as this is the amount of substance dispersed to a unit square volume to cause a 50% probability of lethality. Bench-scale LC_{50} is commonly used. The recent standard ISO 13344 [22] is the first normative international standard on smoke toxicity.

Toxic effect might be calculated from two factors on burning real products:

- Real-scale mass loss rate
- Real-scale LC_{50}

It was found from a developed database that LC_{50} in actual fires would not be deviated much from LC_{50} determined by bench-scale tests. However, the mass loss rates in a real fire and in a bench-scale test varied significantly. Therefore, the burning rate should be reduced, rather than making the effluent less toxic. Anyway, another point of concern is how the materials are burnt, as incomplete combustion of polymer will give higher levels of carbon monoxide.

As proposed by Babrauskas [21], taking full-scale value for FED in terms of the burning mass loss Δm_{f-s} full-scale space, volume V_{f-s} (something unknown) and $LC_{50(f-s)}$ for real-scale fires as:

$$FED_{f-s} = \frac{\Delta m_{f-s}}{V_{f-s} \cdot LC_{50(f-s)}} \quad (9)$$

The mass loss Δm_{f-s} can be predicted by a fire model. Assuming that the bench-scale measured LC_{50} is correlated with $LC_{50(f-s)}$, though a constant K:

$$LC_{50(f-s)} = K \cdot LC_{50} \quad (10)$$

This gives

$$FED_{f-s} = \frac{\Delta m_{f-s}}{V_{f-s} \cdot K \cdot LC_{50}} \quad (11)$$

In this way, the real-scale toxic fire hazard in a building is then inversely proportional to the bench-scale determined LC_{50} :

$$\text{i.e. } FED_{f-s} \propto \frac{1}{LC_{50}} \quad (12)$$

On cone test data with [CO] only, FED_c estimated from equation (6) is lower than the actual FED as from equation (4) [12] with other toxic gases:

$$FED = FED_c + \alpha \quad (13)$$

Value of α should be fitted by additional cone tests with other toxic gases measured.

6. CONCLUSION

A new building fire safety code [6] was released in September 2011 in Hong Kong, which is a right move. However, the approach of study, methodology adopted, level of investigation and effort paid on fundamental research in the entire study are not clearly reported. For example, effect of smoke toxicity on tenability limits was not yet specified. Only temperature of smoke layer, visibility and carbon monoxide concentration were mentioned on specifying smoke effect on tenability limits. The necessity of specifying effect of smoke toxicity on tenability limits properly was pointed out in this short note. Experimental data [10,11] compiled from VCD boxes in a cone calorimeter under high radiant heat fluxes were taken as example.

The toxic potency parameter LC_{50} is proposed to quantify the toxicity of smoke resulted from

chemical species CO, CO₂ and HCN on narcosis-producing toxicants, and HCl and HBr on irritants. The values of LC₅₀ are very useful in assessing materials while setting up design guides or regulations on selecting materials, and implementing engineering performance-based fire codes. Value of FED can then be estimated. Consequently, both FED and LC₅₀ in real-scale fires can be worked out together with fire models through equation (11) for studying the consequences of fire scenarios on burning different combustibles.

Results of the early study [10,11] confirmed that very different tenable conditions will be resulted from smoke toxicity of burning different scenarios. The effects to human beings are proposed to be assessed based on the FED with identified key toxic species. At least, FED should be measured by carbon dioxide and carbon monoxide in a cone calorimeter. Smoke toxicity effects due to other toxic gases for common building materials in real-scale fires can then be estimated by deriving correlation expressions through cone calorimeter tests under high heat fluxes encountered in post-flashover fires.

Apart from smoke toxicity, there are other points to note in the new draft building fire safety code. A series of papers will appear in the near future on pointing out these points. As proposed in New Zealand [26], it is good to include some prescriptive data even on performance-based design. However, such information must be justified by strong research under Hong Kong environment.

ACKNOWLEDGEMENT

The work described in this paper was partially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China for the project "Smoke Emission in Burning Fire Resisting Glass with Higher Rating" (PolyU 514507) with account number B-Q05q.

REFERENCES

1. W.K. Chow, "Numerical studies on recent large high-rise building fire", *ASCE Journal of Architectural Engineering*, Vol. 4, No. 2, pp. 65-74 (1998).
2. The Standard, "One fireman killed, 6 hurt in firestorm", *Hong Kong*, 23 May (2007).
3. The Standard, "Inferno heroes mourned", *Hong Kong*, 11 August (2008).
4. The Standard, "Fire veteran dies and 3 hurt in factory hell", *Hong Kong*, 9 March (2010).

5. South China Morning Post, "An accident just waiting to happen", 1 December (2011).
6. Code of Practice for Fire Safety in Buildings 2011, Draft released for public consultation, Buildings Department, The Hong Kong Special Administrative Region, September (2011).
7. G.E. Hartzell, "Engineering analysis of hazards to life safety in fires: the fire effluent toxicity component", *Safety Science*, Vol. 38, pp. 147-155 (2001).
8. C.L. Chow, MSc Dissertation, Smoke toxicity of materials in a building fire, Department of Building Services Engineering, The Hong Kong Polytechnic University (2004).
9. C.L. Chow, W.K. Chow and Z.A. Lu, "Assessment of smoke toxicity of building materials", *Proceedings of the 6th Asia-Oceania Symposium on Fire Science & Technology*, Daegu, Korea, 17-20 March 2004, pp. 132-142 (2004).
10. C.L. Chow, S.S. Han and W.K. Chow, "Smoke toxicity assessment of burning video compact disc boxes by a cone calorimeter", *Journal of Applied Fire Science*, Vol. 11, No. 4, pp. 349-366 (2002-2003).
11. W.K. Chow and S.S. Han, "Studies on fire behaviour of video compact disc (VCD) materials with a cone calorimeter", *Polymer Testing*, Vol. 23, No. 6, pp. 685-694 (2004).
12. S.S. Han and W.K. Chow, "Calculating FED and LC₅₀ for testing toxicity of materials in bench-scale tests with a cone calorimeter", *Polymer Testing*, Vol. 24, No. 7, pp. 920-924 (2005).
13. V. Babrauskas and S.J. Grayson, *Heat release in fires*, Elsevier Applied Science, London and New York (1992).
14. R.V. Petrella, "The assessment of full-scale fire hazards from cone calorimeter data", *Journal of Fire Sciences*, Vol. 12, No. 1, pp. 14-43 (1994).
15. V. Babrauskas, "Sandwich panel performance in full-scale and bench-scale fire tests", *Fire and Materials*, Vol. 21, No. 1, pp. 53-65 (1997).
16. W.K. Chow, "Assessment on heat release rate of furniture foam arrangement by a cone calorimeter", *Journal of Fire Sciences*, Vol. 20, No. 4, pp. 319-328 (2002).
17. NFPA 269, Standard test method for developing toxic potency data for use in fire hazard modeling, National Fire Protection Association, Quincy, Mass., USA (2000).
18. ASTM E 1678, Standard test method for measuring toxicity for use in fire hazard modeling, ASTM International (1997).
19. V. Babrauskas, R.H. Harris, E Braun Jr., B.C. Levin, M. Paabo and R.G. Gann, The role of bench-scale tests data in assessing real-scale fire toxicity, NIST Technical Note 1284, Center for Fire Research, National Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland, USA (1991).

20. R.G. Gann, V. Babrauskas, R.D. Peacock, B.C. Levin, M. Paabo and R.H. Harris, "A methodology for obtaining and using toxic potency data for fire hazard analysis", *Fire Safety Journal*, Vol. 31, pp. 345-358 (1998).
21. V. Babrauskas, "Fire safety improvements in the combustion toxicity area: is there a role for LC50 tests?", *Fire and Materials*, Vol. 24, pp. 113-119 (2000).
22. ISO 13344, Determination of the lethal toxic potency of fire effluents, International Organization for Standardization (1996).
23. ISO 5660-1, Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method), 2nd edition, International Organization for Standardization (2002).
24. V. Babrauskas, "Sandwich panel performance in full-scale and bench-scale fire tests", *Fire and Materials*, Vol. 21, pp. 53-65 (1997).
25. S.S. Han and W.K. Chow, "Cone calorimeter studies on fire behaviour of polycarbonate glazing sheets", *Journal of Applied Fire Science*, Vol. 12, No. 3, pp. 245-261 (2003-2004).
26. C. Fleischmann, "Is prescribing the design fire the way forward for performance-base design?", *Fire Safety Asia Conference (FiSAC) 2011*, 12-14 October 2011, Suntec, Singapore (2011).

Appendix A: Code of Practice for Fire Safety in Buildings 2011, Buildings Department, The Hong Kong Special Administrative Region, September 2011

p. 213

Radiated Heat Transfer

Radiated heat transfer occurs when the smoke layer is above occupants' heads, and is a function of the smoke layer depth, smoke layer emissivity, and distance from the smoke layer to occupants. Radiated heat transfer can also impact on occupants who are in the hot smoke layer. A value of 2.5 kW/m^2 (in the order of 200°C) is acceptable to occupants for a short period of exposure.

Convected Heat Transfer

Convected heat transfer only occurs once occupants are in contact with the smoke layer, and is therefore a function of the occupant height and the smoke temperature.

Toxicity

Toxicity becomes an issue when occupants are in contact with the smoke layer. The relative conservativeness of the layer height limits should be an indication of the confidence in the modelling being conducted, and the other levels of redundancy and contingency in the design. It is very specific to the Use Classifications and the occupants. If toxicity becomes an issue when occupants are in contact with the smoke layer, the authorized persons should consider this factor for special cases. It is recommended that the CO concentration should not exceed 1,000ppm.

Visibility

Visibility can delay evacuation until such time as the other three factors above cause untenability but it is only an issue if the smoke has descended to a height where it impacts on evacuating occupants. The optical density should not exceed 0.1 m^{-1} (i.e. 10m visibility).

Smoke Temperature

If the smoke layer falls below the acceptable smoke layer height, it is recommended that the temperature should not exceed 60°C .

References for Use

The following references are useful for determining acceptance criteria:

- PD 7974-6, *The Application of Fire Safety Engineering Principles to the Design of Buildings – Part 6: Human Factors: Life Safety Strategies – Occupant Evacuation Behaviour and Conditions (Sub-System 6)*, British Standards Institution, London, 2004.
- CIBSE Guide E Fire Safety Engineering, Chartered Institution of Building Services Engineers, London, 3rd Edition, 2010.
- ISO/TR 13387-8, *Fire Safety Engineering – Part 8: Life Safety - Occupant Behavior, Location and Condition*, British Standards Institution, London, 1999.
- *SFPE Engineering Guide to Human Behavior in Fire*, Society of Fire Protection Engineers, Bethesda, MD, 2003.
- Purser, D.A., "Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat," in *SFPE Handbook of Fire Protection Engineering*, 4th ed., Section 2, Chapter 6, P.J. DiNenno et al. (Eds.), National Fire Protection Association, Quincy, MA, 2008.
- *SFPE Engineering Guide to Predicting 1st and 2nd Degree Skin Burns*, Society of Fire Protection Engineers, Bethesda, MD, 2000.