CODE REVIEW ON SMOKE TOXICITY AND SELECTED TESTS

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ABSTRACT

Toxicity of smoke is a key factor in fire safety. Smoke toxicity in the codes will be reviewed in this paper. Key terms associated are explained. Selected fire tests on assessing smoke toxicity are briefly reviewed. Some terms are clarified. Points to note for including smoke in the codes are highlighted.

1. INTRODUCTION

Smoke is believed to be main threat to life safety in an accidental building fire. However, very little information on toxicity of smoke appears in the building codes and regulations for fire safety provisions in many countries. A main reason is because toxicity depends on not only on the materials that burn, but also on how the materials are burnt. Burning carbon-containing materials would give much higher concentration of carbon monoxide if the combustion is incomplete; say due to inadequate air or cooling of burning objects. Although it is difficult to study the toxicity of smoke, this part should be reviewed and investigated on how to put into the fire codes.

There are many new architectural features such as those for green or sustainable buildings, new materials with polymer-based composites and new style of living such as staying a long time indoor. All these bring problems on fire safety and there had been arguments in approving those green or sustainable building designs with extensive use of glass construction systems. In addition to the big accidental fires such as the two big old high-rise building fires, tunnel fires and bus fires in Hong Kong, the number of non-accidental fires appeared to be increasing in the past few years. These included the arson bank fire and karaoke fire in Hong Kong; World Trade Centre terrorist attack fires; and the South Korean underground railway arson fire. All these suggested the hidden threat on fire safety must be dealt with urgently.

Of all the complex fire phenomena, smoke toxicity is a key element.

2. KEY TERMS

In fire hazards, harm may be caused by falls, heat, suffocation or smoke inhalation. But people believe that smoke is the major cause of harm. Fire deaths in Maryland, USA was analyzed by Berl and Halpin in 1970s [1]. Over 48% of victims were found to have lethal carbonhemoglobin levels, 26% of victims had carbonhemoglobin level of 30-50% and other conditions like cyanide exposure or preexisting heart disease which deemed sufficient in combination with the sub-lethal carbonhemoglobin levels to cause death. Smoke inhalation accounted for roughly three-quarters of all fire deaths. The effects on human included incapacitating the victims, i.e. it leads to the inability of the victims to escape and reduces the egress spread, or the choice of a longer egress path due to eye and lung irritation, visual obscuration and decreased mental acuity. These effects were brought by the toxicants inside the smoke. In the past 30 years, different test methods were developed to determine the toxic potency of smoke that different materials released during combustion.

Toxic potency was measured in EC_{50}, LC_{50}, IC_{50} or sometimes LT_{50} and IT_{50} defined as follows:

- EC_{50} is the effect concentration which is used for any observed response of the animal,
- LC_{50} is used to denote the concentration of materials or fire effluent that produces death in 50% of the animals for a specified exposure time,
- IC_{50} is the concentration necessary to incapacitate 50% of the animals for a specified exposure time,
- LT_{50} is the mean time-to-death, and
- IT_{50} is the time-to-incapacitation, where concentration is fixed [2].

3. TOXIC POTENCY DATA

Many terms can be used to characterize the toxic potency data. Most of them are related both to the concentration of the toxicants C and to the length of exposure time t. The product of concentration and time Ct is a quantitative expression to which a subject is exposed. The exposure-dose is assumed to be proportional to the actual dose retained by the subjects. The exposure-dose Ct required to produce a biological effect is, to a first approximation, reasonably constant over the range of concentrations of toxicants of interest in fire.

The fractional effective dose (FED) at time t_0 to time t under a chemical species at concentration C_i is calculated by using the equation below.

$$FED = \sum_{i=1}^{n} \int_{t_0}^{t} \frac{C_i}{(Ct)_i} dt$$

Statistical methods [2] are employed to determine the concentration required to produce a specified effect. The concentration which will produce a response of effect in 50% of the animals within the specified time can be obtained by interpolation. The effective concentration is commonly termed EC_{50}. EC_{50} is a general term which may be used for any observed response of the animals. When lethality is the observed response, the term LC_{50} is used to denote the concentration of materials or fire effluent that produces death in 50% of animals for a specified exposure time. IC_{50} designates the concentration necessary to incapacitate 50% of animals also for a specified exposure time. Apart from the above, some test methods measure the rapidity of action of the effluent in causing either lethality or incapacitation. In these methods, concentration is held constant and the times at which animals die or incapacitated are recorded. From these data, a mean time-to-death LT_{50} and IT_{50} time-to-incapacitation can characterize the smoke toxic potency of smoke.

4. REVIEW OF TEST METHODS

The study of combustion toxicity in 1970s and early 1980s involved a number of bench-scale apparatus designed to obtain quantitative data on the toxic potency of the smoke and the chemicals that might be the source of harm. Those testing materials were focused commercial products but the interactive effects of multiple products involved in a single fire were not addressed [1]. The study in this field by that time also focused on issues such as the probability of “super toxicants” whether or not to assess incapacitation, the validity of data obtained from tests using rodents in assessing toxicity to humans, the precision and accuracy of smoke toxicity data, the relevance of laboratory-scale tests to real fires and how much data should be used [3]. Super toxicants means the formation of a neurotoxin from the thermal decomposition of noncommercial rigid polyurethane foam and the unusual toxic potency exhibited by polytetrafluoroethylene in some laboratory tests which would appear to be largely an aircraft of the test method. Research at that time also indicated that mass lost rate or other measures of the quantity of toxic gas released per unit time, which would be a factor in the dose received by any exposed people and flame spread rate, time to ignition or other measures of how quickly a product becomes involved in a fire which would also be a factor in the quantity of toxic gas released are the elements potentially important in the overall fire hazard.

In 1980s and 1990s, several standardized test methods were developed [2,3] including the DIN method, the US-National Bureau of Standards (NBS) test, the U-PITT methodology (US-University of Pittsburgh) (1983), ASTM E1678/NFPA 269 (1991) and ISO 13344 (1995).

DIN method was fully developed in the Federal Republic of Germany in 1981. It is used to assess the relative toxicities of combustion products of a material under different temperatures or to compare the relative toxicities of combustion atmosphere produced by different materials. Toxicity is expressed in terms of mortality as the ratio of the number of dead animals to the number of animals exposed. The mortality values were related to the total air flow and to either the volume of the specimen heated or to the mass of mass lose of the specimen. Dose-response relationship and LC_{50} was determined for each material by varying the volume of diluting air in order to vary the concentration of the combustion mixture to which the animals are exposed.

The US-National Bureau of Standards (NBS) test was fully developed in 1982 and mainly used in 1980s. It is a static system using a cup-type furnace as the combustion device and the concentration-response relationships are determined using rats. The concentration of gas sample is done by controlling the sample mass. The toxic potency data obtained is in LC_{50}.

The U-PITT methodology (US-University of Pittsburgh) was established in 1983. The testing procedure is to expose mice to fire effluents produced in a dynamic system from programmed heating of a specimen in a box or muffle fur with 30 mins exposure and 10 mins post-exposure period. Then, the concentration-response and time-to-death for lethality and the LC_{50} data in this test method only refer to the weight.

ASTM E1678/NFPA 269 test method was originally developed by the National Institute of Standards and Technology (NIST) and Southwest Research Institute and standardized in 1991. This test involved specimen exposed for 15 mins to a radiant heat flux of 50 kWm^{-2}. Then, smoke will be collected for 30 mins within a 200 L chamber and the concentration of CO, CO_2, O_2, HCN, HCl, and HBr are monitored over this 30 mins period. After that, the fractional effective exposure dose (FED) and LC_{50} can be calculated. Finally, the estimated FED is then tested by using rats.

ISO 13344 was standardized in 1995. This standard subjects a test specimen to the combustion conditions of a specific laboratory combustion device, chosen to have demonstrated relevance to one or more of the specific classes or stages of fires. The concentration of the major gaseous toxicants in the smoke atmosphere is monitored over 30 mins. Then, the concentration-time products were determined from integration of the areas under the respective concentration-time plots. The concentration-time products data with either the mass charge or mass lose of the test specimen during the test are used in FED calculation to predict the 30 mins LC_{50}.

In May 2000, the FPRF and NIST began a major private/public fire research entitled "International Study of the Sublethal Effects of Fire Smoke on Survival and Health (SEFS)". The project is composed of research tasks including Toxicological Data, Smoke Transport Data, Behavioral Data, Fire Data, Risk Calculations, Product Characterization, Social Analysis, and Dissemination [7].

Literature results indicated that most of the test methods are small-scale laboratory tests. But all laboratory test methods suffer from several types of limitations. Due to rapidly changing conditions in a real fire involving the dynamics of fuel, heat and air interactions, it is not realistic unless a single laboratory test will be relevant to all stages of all fires. All the test methods might be relatable to at least some stage of actual fires. Each laboratory combustion rig would give some physical limitations with regard to specimen size, shape or assembly. A large gap between the experimental results and the real fire statistic still exists.

In the last three decades, more than 20 laboratory test methods of smoke toxicity were developed by different institutes and laboratories around the world. But the fire scenarios and test materials of those methods were not the same and not comparable. All those methods cannot fully illustrate the case of real fires. Therefore, a new standard test method shall be developed for building materials assessment to improve the fire safety of buildings.

5. FIRE CODES IN HONG KONG

The design of the active fire safety systems and passive building construction related to fire safety in Hong Kong shall follow the four fire codes [9-11]. They are:

- Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment
- Code of Practice for Fire Resisting Construction
- Code of practice for the Provision of Means of Escape in Case of Fire
- Code of Practice for the Provision of Means of Access for Firefighting and Rescue Purposes

But the objectives of the local fire codes related to life safety mainly concern how to egress the occupants inside the building as fast as possible and never consider the health effects or post-exposure effects of the smoke products to the occupants. As from the last fire statistics, most of the fire victims were not harmed by the fire but by the smoke toxicants. Thus, the measure of smoke toxicity must be added to local fire codes.

6. THE BUILDING REGULATIONS APPROVED DOCUMENT B, UK

The fire safety code currently used in the United Kingdom is the Building Regulations Approved Document B [12]. The Building Regulations Approved Document B consists of five parts B1-B5.

They are:

- **B1 Means of warning and escape.** The aim of B1 is to ensure satisfactory provision of means of giving an alarm of fire and a satisfactory standard of means of escape for persons in the event of fire in a building
- **B2 Internal fire spread (linings).** B2 guarantees that fire spread over the internal linings of buildings is inhibited.
- **B3 Internal fire spread (structure)**. To ensure the stability of buildings in the event of fire; to ensure that there is sufficient degree of fire separation within buildings; and to inhibit the unseen spread of fire and smoke in concealed spaces in buildings.
- **B4 External fire spread.** To assure the external walls and roofs have adequate resistance to the spread of fire over the external envelope, and that spread of fire from one building to another is restricted.
- **B5 Access and facilities for the fire service.** To guarantee satisfactory access for fire appliances to buildings and the provision of facilities in buildings to assist fire-fighters in the life-saving of people in and around buildings.

The Approved Document B also concerns the burning performance of building materials. But the main concerns are to limit combustibility, flame spread of internal lining and restrict the ignitability of the materials.

According to part B1 of Approved Document B, "the primary danger associated with a fire in its early stages is not flame but the smoke and noxious gases produced by the fire. They cause most of the casualties and may also obscure the way to escape routes and exits. Measures designed to provide safe means of escape must therefore provide appropriate arrangement to limit the rapid spread of smoke and fumes". So, the objective of the document is to design appropriate facilities to either limit the ingress of smoke to the escape routes or to restrict the fire and remove smoke. However, only concerns for preventing occupants 'direct contact' with smoke were mentioned in B1 and no information on the tolerance of occupants when exposed to smoke or on the adverse health effects of smoke is provided.

Part B2, B3 and B3 set out some restrictions of building material selection. But the restrictions only concern the flame spread rate and heat release rate of internal lining and the fire resistance of building construction materials. No smoke generation rate or smoke toxicity measurement is mentioned in the document.

7. BUILDING CONSTRUCTION AND SAFETY CODE NFPA 5000, USA

The purpose of NFPA 5000 is "to provide minimum design regulations to safeguard life, health, property, and public welfare and to minimize injuries by regulating and controlling the permitting, design, construction, quality of materials, use and occupancy, location, and maintenance of all buildings and structures within the jurisdiction and certain equipment specifically regulated herein" [13].

Fire protection focuses on the use of fire resistive materials and construction. The code addresses fire protection features intended to restrict or resist the spread of fire and smoke beyond the compartment of fire origin. Also, buildings shall be divided into compartments to limit the spread of fire and restrict or resist the movement of fire by using devices like smoke barrier. To measure the fire resistive of a building material, a flame spread or a smoke developed index is specified following NFPA 255 or ASTM E84. Besides that, no other concern is related to the burning performance of building materials.

8. CONCLUSION

Although smoke toxicity is a key factor in fire safety, very little information appears in the codes surveyed. A possible reason is because toxicity of the building materials, or toxicity of smoke has to be assessed. There are not yet any clear guidelines on how to carry out standard tests, even at bench-scale level.

REFERENCES

1. R.G. Gann, V. Babrauskas, R.D. Peacock and J.R. Hall Jr., "Fire conditions for smoke toxicity measurement", Fire and Materials, Vol. 18, No. 3, pp. 193-199 (1994).
2. British Standard, PD 6503: Part 1:1990 ISO/TR 9122-1:1989, Toxicity of combustion products - Part 1: General, British Standards Institution, UK.
3. G.E. Hartzell, "Combustion products and their effects on life safety", Section 4, Chapter 2, The SFPE Handbook of Fire Protection Engineering, 2nd ed., National Fire Protection Engineers, Quincy, MA, USA, pp. 4-10 – 4-21 (1995).
4. H.L. Kaplan, A.G. Grand and G.E. Hartzell, Combustion toxicity: Principles and test methods, Technomic Publishing, Lancaster, PA (1983).
5. NFPA 269, Standard test method for developing toxic potency data for use in fire hazard modelling, National Fire Protection Engineers, Quincy, MA, USA (2000).
6. ASTM E 1678, Standard test method for measuring toxicity for use in fire hazard analysis, American Society for Testing and Materials, USA (1997).
7. R.G. Gann, J.D. Averill, K.M. Butler, W.W. Jones, G.W. Mulholland, J.L. Neviaser, T.J. Ohlemiller, R.D. Peacock, P.A. Reneke and J.R. Hall Jr., "Sublethal effects of smoke on survival and health", Proceedings of the 2nd International Symposium on Human Behavior in Fire: Understanding Human Behavior for Better Fire Safety Design, 26-28 March 2001, Boston, MA, Interscience Communications Ltd., London, England, pp. 285-296 (2001).
8. Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment, Fire Services Department, Hong Kong (1998).
9. Code of Practice for Fire Resisting Construction, Fire Services Department, Hong Kong (1996).
10. Code of Practice for the Provision of Means of Escape in Case of Fire, Fire Services Department, Hong Kong (1996).
11. Code of Practice for the Provision of Means of Access for Firefighting and Rescue Purposes, Fire Services Department, Hong Kong (1995).
12. The Building Regulations 1991: Approved Document B: Fire Safety (2000).
13. NFPA 2000, Building Construction and Safety Code (2003).