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Toxicity Data for Fire Hazard Analysis

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Abstract

A comprehensive methodology has been developed for obtaining and using smoke toxicity data for fire hazard analysis. The methodology comprises: determination that the post-flashover fire is the proper focus of smoke inhalation deaths; criteria for a useful bench-scale toxic potency (LC_{50}) measurement method; a method which meets these criteria, especially validation against real-scale fires; a computational procedure for correcting the results for the CO levels observed in real-scale post-flashover fires; procedures for reducing the usage of animals and broadening the applicability of data by interpreting gas measurement data using the N-Gas Model; and a procedure for identifying whether a product produces smoke within the ordinary range of toxic potency for post-flashover fires. The method is currently being developed for standardization by the National Fire Protection Association and the American Society for Testing and Materials.

I. Introduction

It has long been realized that most fire victims in the United States die from smoke inhalation rather than from burns. However, there has also been long-term controversy over how to characterize the potential for harm from fire-generated smoke and on an apparatus from which to obtain accurate data.

The importance of toxic fire hazard[b] (relative to heat, burns, generalized trauma from falling debris or leaping from a window, etc.) in the overall threat to life safety in fires varies with the type of fire, the location of the people relative to the fire, and the time they are exposed to the fire and its products. It is thus inappropriate to make materials selection decisions based solely on a single characterization (e.g., toxic potency[c]) of the smoke or even a simple index containing

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[b] Toxic fire hazard: a sub-set of 'fire hazard,' where the threat is inhalation of toxic combustion products.

[c] *Toxic potency*: toxicity of the smoke from a specimen of material or product, taken on a per-unit-specimen-mass basis. At present, for fire research, the dominant biological end point adopted is death; and the measured quantity is the LC_{50}, which is the concentration ($g{\cdot}m^{-3}$) of smoke which is lethal to 50% of the exposed specified test animals in a specified time period. The LC_{50} notation must include the exposure time, generally 30 minutes (along with a 14-day post-exposure observation period). **Toxic potency is not an inherent property of a material.**

toxic potency and other fire variables.

Fortunately, it is now possible to perform computations of fire hazard leading to assessments of the degree of threat to life safety.[1] These calculations require valid toxic potency input data. Since death during or immediately following the fire is the outcome most to be avoided, the LC_{50} is the most appropriate term by which to describe the toxic potency of fire smoke.

This paper describes the first technically sound methodology for obtaining and using LC_{50} data for hazard analysis.[2] The method consists of:

(a) a bench-scale measurement which represents the important combustion conditions of real fires; and

(b) a design and analysis framework which will allow the toxic potency data to be used in a rational, consistent, appropriate, and adequate way.

Post-flashover fires are the ones in which smoke toxicity is most important, and the ones on which this method is focussed. In the United States, 69% of all fire deaths are associated with post-flashover fires, with the preponderance of deaths due to smoke inhalation and occurring outside the room of fire origin.[3,4] These fires are characterized by primarily radiant heating, many items simultaneously on fire, and vitiated combustion air for some, but not all, burning items.

The method is also applicable to pre-flashover fires. However, deaths from these fires generally occur within the room of fire origin; and analysis of real fires, computer modeling, and room-scale fire tests show that these deaths are far more likely to be due to heat and burns than smoke toxicity.

II. Apparatus

The device is a descendant of the NIST cup furnace and the Weyerhaeuser radiant apparatus, and is an advanced version of the apparatus developed by the Southwest Research Institute for the National Institute of Building Sciences. Figure 1 is a schematic, showing the combustion cell, the animal exposure box, and a chimney system for the transport of smoke between them.

Simulating post-flashover fires, a product is exposed to radiant heat under likely end-use conditions. For uniformity, a constant 50 kW/m^2 radiance is used. The sample surface area may be as large as 7.6 cm (3") x 12.7 cm (5"), with a maximum thickness of 5.1 cm (2"). Six rats can be exposed to the smoke collected in an approximately 200 liter rectangular box located above the furnace. Changes in the concentration of smoke are achieved by variation of the surface area of the sample.

III. Determination of the LC_{50}

The intent is to obtain a value of the LC_{50} using a minimal number of tests and test animals. This is accomplished by first estimating the toxic potency of the smoke based on established toxicological interactions of the smoke components. Thus, a small fraction of the chamber atmosphere is removed for chemical analysis of CO, CO_2, O_2, HCN, HCl, HBr, and NO_x. An N-Gas Model has been developed to enable the use of these data to obtain approximate LC_{50}

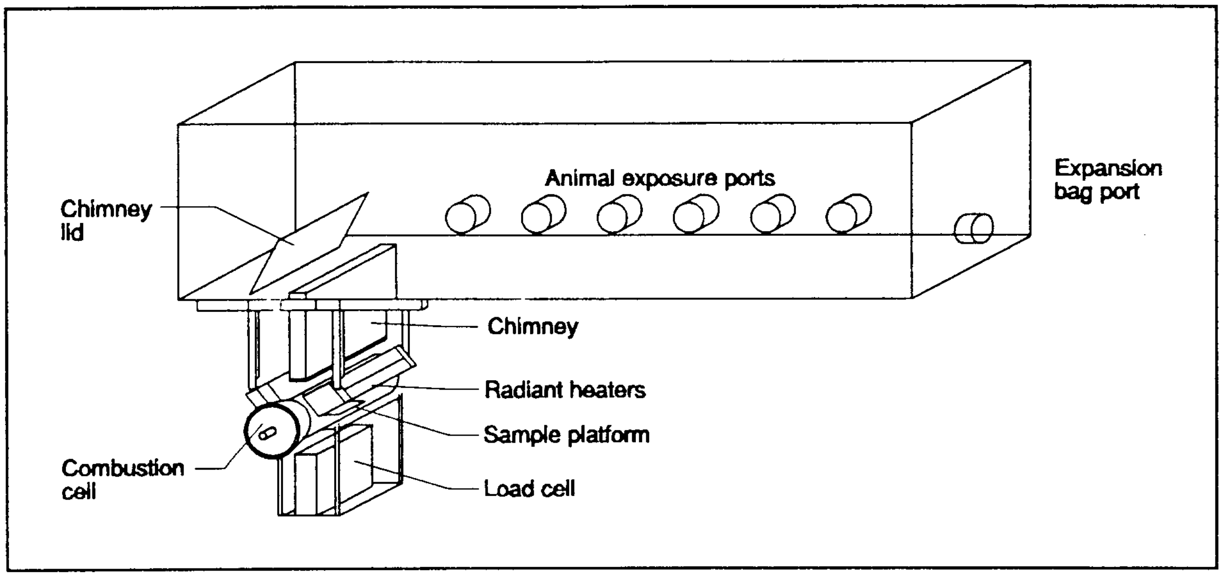

Figure 1 General view of radiant toxicity apparatus.

values, based on the calculation of a Fractional Effective Exposure Dose (FED) of mixtures of these gases.[5] The FED value is approximately 1.1 at the LC_{50}.

The samples are exposed to the radiant source for 15 minutes, sufficient to combust most products fully. The animals are exposed to the smoke for 30 minutes. Lethality is noted both during this time and for 14 days afterwards, thus including those animals who received a mortal insult with a delayed effect.

The determination of the approximate LC_{50} is a 2- or 3-step process:

1. **Determine an estimated LC_{50} (30 minute exposure plus 14 day post-exposure observation period) using the N-Gas Model.** This entails two experiments, neither involving animals. The specimen size for the first is obtained using existing data from similar products. The consumed sample mass and the concentrations of gases in the N-Gas Model are measured, and an FED is calculated. Based on this result, a similar second experiment is performed for a specimen that should produce an FED of about 1.1. The LC_{50} for a test is estimated by dividing the volatilized sample mass by the product of the FED for that test and the apparatus volume.

2. **Check the estimated LC_{50} (30 minute exposure plus 14 day post-exposure observation period) using animals.** Again two experiments are needed: one where the specimen surface area (and mass) is chosen to produce an FED of about 0.8, and one to produce an FED of about 1.4. In each, 6 rats are exposed to the smoke for 30 minutes, and the mass loss and standard gas concentrations are measured. The measurements are to assure that the sample decomposition indeed provided the desired FED. If the LC_{50} estimate is accurate, the exposure at FED = 0.8 should result in 0 or 1 animal death and the exposure at FED =

1.4 should result in 5 or 6 animal deaths. If the animal deaths are as predicted, then the chemical data from the 4 experiments are used to calculate an approximate LC_{50}, and no further measurement is needed. The calculation includes a correction for the generation of less-than-post-flashover amounts of CO in bench-scale devices. Post-flashover fires produce CO yields higher than any bench-scale device (or pre-flashover fires).

3. **If such results are not seen, then determine a more precise value for the LC_{50}.** For a proper statistical determination, 3 experiments are needed in which some, but not all, of the rats die. The selection of sample sizes is guided by the prior 4 tests. After determining the LC_{50}, it should be reported to 1 significant figure.

The one aspect in which this apparatus does not mirror post-flashover fires is in the CO yield. A recent compilation of real-scale data shows a near-uniform yield of 0.2 g of CO per gram of fuel consumed.[6] This values is then substituted into the N-gas equation, modifying the LC_{50} value.

For hazard analysis of pre-flashover fires, the combustion conditions in the radiant apparatus are directly applicable. One would determine the LC_{50} as above, but not correct it for post-flashover CO. The irradiance of 50 kW/m^2 for a pre-flashover test is somewhat high, but should have little effect on the LC_{50}. Lower fluxes can be accommodated if necessary.

IV. Validation of the Data

This is the first bench-scale device for obtaining smoke toxicity data to have been validated against real-scale fires. Five quantitative, plausible validation hypotheses were established both for this procedure and by which future bench-scale toxicity tests could be tested. They entail agreement between the bench-scale apparatus and real-scale room fire tests, within a reasonable uncertainty, of:

- LC_{50} values,
- identity of primary toxic gases,
- yields of the toxic gases (with a post-correction method used for CO values from bench-scale tests),
- N-Gas Model lethality predictions, and
- type of death (within- or post-exposure).

The study showed that a factor of 3 agreement expected between the bench-scale and the real-scale results was useful and achievable.

In the real-scale tests, rooms lined with each of 6 diverse products were burned.[7] The products were: Douglas fir, a rigid polyurethane foam, rigid PVC, wall cork, particle board, and a laminated melamine/vermiculite composite. While a set of only 6 products is limited, they were chosen with significant care. They comprise products that are natural and man-made, high and low density, uniform and irregular physically, and relatively pure and complex chemically. For some, CO (along with CO_2 and low O_2) is the only toxicant, while others produced significant amounts of HCl and HCN.

The results showed that the 5 hypotheses were proved to within the chosen limits. Thus, even with the small number of products used to challenge the method, a successful demonstration of validity has been made.

V. Use of the Data in Hazard Analyses

A post-flashover fire, being oxygen-starved, produces a large amount of CO and CO_2. This means that, independent of the fuel, the smoke toxicity will most often be determined by the fire ventilation, rather than the specific products burning. The LC_{50} of CO in the presence of CO_2 is about 5 g/m^3, and one-fifth of the smoke in post-flashover fires is CO. Therefore, the LC_{50} of post-flashover smoke (based only on CO_2 and CO) is about 25 g/m^3. The validation of this bench-scale apparatus showed that the results could be used to predict real-scale toxic potency to about a factor of 3.[d] Therefore, post-flashover smokes with LC_{50} values greater than 8 g/m^3 [(25 g/m^3)/3] are indistinguishable from each other.[8]

A measured LC_{50} value greater than 8 g/m^3 should thus be recorded only as 'greater than 8 g/m^3.' A hazard analysis would then use this value for the toxic potency of the smoke. A measured LC_{50} value less than 8 g/m^3 would be recorded to one significant figure. These products could well be grouped, reflecting the factor-of-3 accuracy of the bench-scale test. A hazard analysis would then use values of 8 g/m^3, 3 g/m^3, 1 g/m^3, 0.3 g/m^3, etc.

When the fire community has sufficient experience with LC_{50} measurements using this approach, some groupings of products could be exempted from further determinations **by inspection** and placed in the 'greater than 8 g/m^3' category. Some possible examples are:

- wood and other cellulosics, since all species would be expected to show similar LC_{50} values;
- synthetic materials containing only C, H, and O;
- polymer/additive mixtures that have been shown to follow the N-Gas Equation (i.e., produce no additional toxicants) and have LC_{50} values greater than 8 g/m^3;
- products that are only used in small quantities (for this case, a procedure is presented in this report for determining the fractional contributions of concurrently-burning combustibles to the total toxic potency of the smoke); and
- products that would not be expected to become fuel for a flashed-over fire, such as those items only installed behind a sufficiently-protective barrier.

Most common building and furnishing materials will lie in one of these groupings. Thus, this

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[d] A prior risk analysis had demonstrated that this level of uncertainty would not affect the prediction of loss from the most common fire loss scenario: furniture fires in residences.

method could result in an extremely small fraction of commercial products needing to be measured. Note that this statement applies to post-flashover scenarios only.

People are likely to inhale smoke from real fires for a range of times. It is therefore useful to obtain appropriate LC_{50} values for other exposure times without having to perform additional measurements. Experimental data for CO/CO_2 exposures ranging from 5 to 60 minutes indicate that a reasonable approximation for the toxic potency of post-flashover smoke[9] is:

$$LC_{50} \approx 45 \cdot g \cdot m^{-3} \cdot min^{1/2} t^{-1/2}$$

This is a useful scaling rule for those cases where CO and CO_2 dominate the N-Gas equation.

VI. Status

This method is currently being considered by the National Fire Protection Association's Fire Test Committee and the American Society for Testing and Materials' E-5 Committee on Fire Standards. The City of New York is also contemplating citing the method in its building code.

VII. Acknowledgements

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8. Reference 2, p.50.

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