Measurement of Toxic Potency for Fire Hazard Analysis

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This study is the principal product of a research program to provide a technically sound methodology for obtaining and using smoke toxicity data for hazard analysis. It establishes:

(a) an improved bench-scale toxic potency measurement, one 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.

This establishment of proper bench-scale test conditions, validation of the output against real-scale fire measurements, and development of a consistent framework for fire hazard analysis is unique and represents a successful, usable implementation of the state of the art.

A method for including toxicity in fire hazard assessment should focus on post-flashover fires. The U.S. fire statistics show that 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. These fires are characterized by:

- primarily radiant heating, with heat fluxes from about 20 to 150 $kW \cdot m^{-2}$ throughout the room;
- many items simultaneously on fire; and
- vitiated combustion air for some, but not all, burning items.

By contrast, deaths from pre-flashover fires generally occur within the room of fire origin. Both computer modeling and full-scale simulation of these fires show that these deaths are far more likely to be due to heat and burns than smoke toxicity.

The importance of toxic fire hazard (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 both with the type of fire and the time and location of the people relative to the fire. There is thus an inherent error in making materials selection decisions based solely on a single characterization (e.g., toxic potency) of the smoke or even a simple index containing toxic potency and other fire variables.

It is now possible to perform computations of fire hazard leading to assessments of the degree of threat to life safety. These range from:

- simple, closed-form equations ("hand calculations") generally not requiring a computer for solving, to
- computer simulations of a fire where a large number of differential equations are being solved simultaneously.

Either mode of calculation requires valid toxic potency (LC_{50}) input data.

This study recommends that this data be obtained using a radiant apparatus. This device is the first to be validated against data from real-scale fires. It is a descendant of the 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.
In this radiant apparatus, materials, products, composites, and assemblies are exposed to 50 $kW \cdot m^{-2}$ radiant heat under likely end-use conditions. 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 are exposed to the smoke collected in an approximately 200 L rectangular box located above the furnace. Changes in the concentration of smoke are achieved by variation of the surface area of the sample.

The number of animal tests is minimized by 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 had been previously developed to enable the use of these data to estimate LC_{50} values, based on the calculation of a Fractional effective Exposure Dose (FED) of mixtures of these gases. The FED value is approximately 1 at the LC_{50}.

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. The LC_{50} is then estimated by dividing the volatilized sample

mass by 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 0.7, and one to produce an FED of about 1.3. 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 = 0.7 should result in 0 or 1 animal death and the exposure at FED = 1.3 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-postflashover amounts of CO in bench-scale devices. Post-flashover fires produce CO yields for 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 LC_{50} of CO_2-potentiated CO is about 5 $g{\cdot}m^{-3}$, and one-fifth of the smoke in post-flashover fires is CO. Therefore, the LC_{50} of post-flashover smoke (based only in CO_2 and CO) is about 25 $g{\cdot}m^{-3}$. The previous work on 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. Therefore, post-flashover smokes with LC_{50} values greater than 8 $g{\cdot}m^{-3}$ are indistinguishable from each other.

A measured LC_{50} value greater than 8 $g{\cdot}m^{-3}$ should be recorded only as 'greater than 8 $g{\cdot}m^{-3}$.' A hazard analysis would then use this value for the toxic potency of the smoke. A measured LC_{50} value less than 8 $g{\cdot}m^{-3}$ 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 $g{\cdot}m^{-3}$, 3 $g{\cdot}m^{-3}$, 1 $g{\cdot}m^{-3}$, 0.3 $g{\cdot}m^{-3}$, etc.

Most common building and furnishing materials have LC_{50} values substantially higher than 8 $g{\cdot}m^{-3}$ prior to the CO correction. Thus, the toxicity of the smoke will most often be determined by the fire ventilation, rather than the specific products burning.

Further simplification of step 2 is possible. One could perform a single animal test at an FED that corresponds to an LC_{50} of 8 $g{\cdot}m^{-3}$. An observation of no deaths would confirm the suggestion. If any animals were to die, then step 3 would be performed.

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 "LC_{50} value greater than 8 $g{\cdot}m^{-3}$" 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 $g{\cdot}m^{-3}$;
- 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.

Based on an overview of reported toxic potency values, this process could result in an extremely small fraction of commercial products needing to be measured. Note that this statement applies to post-flashover scenarios only.

There will be some cases where it is important to have toxic potency data useful for analysis of pre-flashover fires. For these, 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 $kW{\cdot}m^{-2}$ for a pre-flashover test is somewhat high, but should have little effect on the LC_{50}. Lower fluxes can be accommodated if necessary.

The computations in a hazard analysis must account for the fact that the oxygen concentation in post-flashover smoke is significantly depleted, the amount of depletion depending on the entrainment (outside the fire room) of fresh air into the smoke. This effect could not be simulated in a bench-scale apparatus. By contrast, the pre-flashover fire, such shortage of oxygen is small.