Toxic Hazard of Building Products and Furnishings*

ABSTRACT

Since it was recognized nearly 30 years ago that most fire victims succumb to smoke, there has been a broad effort to include consideration of smoke toxicity in fire standards and code provisions. Research has made great advances in this area, progressing from **a** focus on identifying "supertoxicants" to providing accurate input data for fire safety analyses. Building on efforts from NBS/NIST and FRCA, it is now becoming recognized that reducing the burning rate of products is the most efficient way of curtailing the life safety threat from fire smoke. Efforts in the international standards arena now need to be channeled to embody this knowledge.

BACKGROUND

The National Institute of Standards and Technology (NIST) and its preceding manifestation, the National Bureau of Standards (NBS), have been performing fire safety research for almost the entire century of their existence. From metrics for fire resistance of walls to smoke detectors to flame-resistant clothing, the metrology of NIST/NBS is seen throughout the fire codes and standards in the United States and abroad. As new needs for measurements of fire arise and old ones recur (as they often do), NIST applies its expertise in fire science and measurement technology to improve safety and enable equity in the marketplace.

Fire smoke toxicity has been a recurring theme for fire safety professionals for over four decades. This is because:

- all combustible construction and furnishing products can produce harmful smoke in a fire;
- about 70 % to 75 % of the U.S. fire victims succumb to smoke inhalation, which fraction has been generally increasing for at least two decades [1]; and

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- the problem of how to address smoke toxicity in standards and codes has not yet been "solved."

The rise of quantitative research in fire toxicology occurred in the 1970s. The governing principle was that the toxicity of smoke was a property of the burning material or product, and thus the focus was on measuring the potency of smoke from various materials and commercial products. There were some attempts at toxicity indexes, again under the presumption that the fuel determined the threat. The detection of a small number of "supertoxicants," materials whose smoke was orders of magnitude more harmful to laboratory animals than most smoke, further sparked the development of over 20 laboratory test apparatus. Few of these "supertoxicants" were identified in the laboratory, not all correctly, and no commercial products were found to behave thus.

By the 1980s, the concept had begun to emerge that the toxic hazard from smoke is a function of both:

- the toxic potency of the smoke (often expressed as an EC_{50}, the Concentration needed to cause an Effect on half (50 %) of the exposed population), itself a function of the combustion environment, and
- the integrated exposure a person experiences to the (changing) smoke concentration over some time interval: IC(t) dt. Some of the effects of smoke increase with continued exposure, others occur almost instantaneously.

The former was being measured by the laboratory-scale tests. The concentration and distribution of smoke in a burning home, public building or vehicle depends on such factors as the chemical composition and burning rates of the products (interior finish, furnishings, etc), the rate and direction of ventilation, and actuation of a suppression system. The time of exposure is a function of, *e.g.*, the time of detection and alarm, the design of the building, the motor capability of the people, and the presence of rescuers. The severity of the outcome depends on all these plus the sensitivity of the occupants to the chemical components of the smoke.

Smoke is, of course, not the only output of a fire. The fire also generates heat in the form of radiation from flames and hot surfaces, convection from the hot smoke, and conduction from hot surfaces. The effects on people are a result of any or all of these. The critical hazard is the one that caused harm first.

In 1988, NIST published the first version of HAZARD I, a method that combined expert judgment and calculations for estimating the consequences of a fire [2]. This enabled integrating knowledge of all the factors contributing to the growth of threats to life safety and began the modem era of fire safety engineering.

SMOKE LETHALITY

HAZARD I focused on the most immediate effect that smoke could have on occupants or on fire service personnel responding to the fire: loss of life. This focus also has driven the development and adoption of a standard laboratory-scale device (NFPA 269 [3], ASTM E1678 [4]) for measuring the lethal toxic potency of smoke form burning products for use in hazard and risk analyses. In developing this method, NIST scientists did a limited validation of the results against the toxic potency of the same materials in room-scale fires and derived an estimate of the accuracy of the method [5].

The capability of fire safety professionals to estimate potentially lethal smoke exposures has developed extensively since then. The EXITT routine in HAZARD I, EXIT 89 [6] and EXODUS [7] offer the ability to simulate people movement through a burning facility. The Fire Protection Research Foundation (FPRF) has developed a method for calculating fire risk by combining scenario analysis with hazard analysis [8].

Numerous hazard calculations have been performed in which the survival of occupants is the predicted outcome. In many of these cases, the predictions are sufficiently in line with the actual occurrence and are sufficiently consistent with established fire physics that the community can have some degree of confidence in this predictive capability.

Perhaps the seminal document in the early era of toxic hazard analysis resulted from a collaboration between the Fire Retardant Chemicals Association (FRCA) and NIST, at the time the National Bureau of Standards [9]. At issue was whether fire retardant additives effect a trade-off between decreased burning rate and increased emission of toxic gases and whether there was a net safety benefit from the use of fire retardants. This project demonstrated the interaction between toxic potency and ultimate fire hazard, expressed as the time available for escape, and showed that reductions in burning rate far outweighed minor changes in toxic potency in providing this time. Subsequent work at NBS/NIST established the importance of rate of heat release as the controlling variable in fire hazard [10].

SUBLETHAL EFFECTS OF SMOKE

There also have been frequent reports from fire survivors telling how smoke and heat impeded their progress toward exits, caused them lingering health problems, or impaired fellow occupants' escape so that they did not survive. These are the consequences of a wide range of sublethal effects that smoke can have on people, short of causing death during their exposure:

- incapacitation (inability to effect one's own escape)
- reduced egress speed or choice of a longer egress path due to, *e.g.* :
  - sensory (eye, lung) irritation
  - heat or radiation injury
  - reduced motor capability
  - visual obscuration
  - decreased mental acuity

Each can limit the ability to escape, to survive, and to continue in good health after the fire.

There continue to be difficulty and controversy in assessing and addressing the contribution of these sublethal effects of smoke in hazard and risk analyses. This results fiom:

- the unknown number of affected people, the fire conditions under which they are affected, and the severity of their afflictions;
- the confounding of assigning causation of any lingering effects because of, *e.g.*, inhalation of dust and other irritants encountered in normal activities;
- the tendency to ascribe toxicity to each product potentially involved in a fire, even though other factors in the fire often affect toxic smoke yield more than inherent product characteristics do (*e.g.*, ref.11, and even though there are many factors,

unrelated to products, that affect the conversion of toxic smoke yield at the burning product into toxic smoke exposure at a potential victim;

- inadequate measurement methods for and inadequate or inaccessible data on the sublethal effects of smoke and inconsistent interpretation of the existing data;
- lack of consensus on a method for measuring the yields of the smoke components that contribute to sublethal effects and lack of accepted, quantitative relationships between exposures based on these yields and the deleterious effects on escape and survival;
- companies seeking an edge in the competition among products; and
- differing objectives for fire safety and the cost, both public and commercial, of providing a given degree of fire safety.

As a result, product manufacturers and specifiers, building and vehicle designers, regulatory officials, and consumers are faced with persistence of this issue with little momentum toward closure, inconsistent or inaccurate representation in the marketplace, and continuing liability concerns.

ISO DOCUMENT 13571

Indicative of this overall uncertainty regarding sublethal effects of fire smoke has been the response to draft document 13571 that emerged from ISO TC92 SC3 (Fire Threat to People and the Environment). This one-time draft international standard formalized consideration of the first of these sublethal consequences of smoke: incapacitation, or the inability to effect one's own escape. Although there is relatively little information quantifying the effects of smoke on an occupant's ability to escape, this document incorporated estimates of human tolerance thresholds of the toxicants, along with estimates of the impact on the more susceptible segments of the population. These conservative figures led to implied limitations on product flammability that would be impossible to meet. When this became broadly recognized, the document was voted down and redrafting as a candidate ISO Technical specification began. The current draft of ISO 13571 [12] has moderated the constraints on smoke toxic potency, while retaining the basic concept of toxic effects resulting fiom accumulated fractional effective dose (FED) or concentration (FEC). It is almost certain that this document will become an ISO Technical Specification within the next year or so. Three years later, it will automatically be considered for progression to an ISO Standard. [A similar document was introduced into ASTM E5 and is currently on hold pending final development of the ISO version.]

An aggressive European presence continues to drive ISO TC92 SC3 toward very tight toxicity requirements aimed at preserving the lives and health of all building occupants under all fire conditions, a worthy goal that nevertheless goes far beyond the stated goals of most, if not all, national fire codes. There is clear intent on the part of some ISO participants to follow 13571 with a document that addresses other sublethal effects of smoke. ISO TC92 SC3 WG4 is in the process of drafting a guidance document whose scope currently includes this.

NEED FOR RESOLUTION

There is little doubt that some sublethal effects of fire smoke continue to affect life safety and that the professional community does not yet have the knowledge to develop technically sound tools to include these effects in hazard and risk analysis. This inability has severe consequences for all parties. Underestimating smoke effects could result in not providing the intended degree of safety. Erring on the conservative side could inappropriately bias the marketing of construction and furnishing materials, constrain and distort building design options, and increase construction costs. Meanwhile, competition'in the marketplace is already being affected by poorly substantiated or misleading claims regarding smoke toxicity. Above all is the need to ensure that smoke toxicity is always considered in the context of the burning rates of the combustibles and in the overall context of the facility use and properties.

THE SEFS PROJECT

In May 2000, the FPRF and NIST began a major private/public fire research initiative to provide this scientific information for public policy makers. Entitled the "International Study of the Sublethal Effects of Fire smoke on Survival and Health" (SEFS), the project objectives are to:

1. Identify fire scenarios where sublethal exposures to smoke lead to significant harm;
2. Compile the best available toxicological data on heat and smoke, and their effects on escape and survival of people of differing age and physical condition, identifying where existing data are insufficient for use in fire hazard analysis;
3. Develop a validated method to generate product smoke data for fire hazard and risk analysis; and
4. Generate practical guidance for using these data correctly in fire safety decisions.

The project is composed of a number of research tasks under the headings of: Toxicological Data, Smoke Transport Data, Behavioral Data, Fire Data, Risk Calculations, Product Characterization, Societal Analysis, and Dissemination. The initial focus is on incapacitation (inability to effect one's own escape), since it was the most serious sublethal effect and since there was more quantitative information on this effect than the other sublethal effects. The first phase of the research began with 5 tasks:

- provide decision-makers with the best available lethal and incapacitating toxic potency values for the smoke from commercial products for use in quantifying the effects of smoke on people's survival in fires.
- provide state-of-the-art information on the production of the condensed components of smoke from fires and their evolutionary changes that could affect their transport and their toxicological effect on people.
- assess the potential for using available data sets (a) to bound the magnitude of the U.S. population who are harmed by sublethal exposures to fire smoke and (b) to estimate the link between exposure dose and resulting health effects.
- provide a candidate scenario and intervention strategy structure for future calculations of the survivability and health risk from sublethal exposures to smoke from building fires.
- determine the potential for various types of fires to produce smoke yields from ½ to 1/100 of those that result in lethal exposures in selected scenarios.

It had previously been known that for post-flashover fires, lethal or incapacitating exposures could precede untenable thermal conditions in rooms remote from the fire room. From this project we now know [13]:

- **Far** more people are exposed to fire smoke **than** are suffering consequences, either immediate to the fire incident or afterward. Thus nearly all of the smoke exposures are inconsequential. The likely reason is the remoteness of the people from the fire, and thus their exposure is to dilute smoke.
- For pre-flashover fires in buildings with large rooms, smoke is diluted rapidly, and the exposure threshold for significant smoke inhalation effects occurs well after incapacitation from heat.
- For pre-flashover flaming fires in residential buildings, incapacitation **from** smoke inhalation rarely occurs before incapacitation from heat and thermal radiation or escape or rescue. These occurrences of incapacitation fiom smoke take place remote from the room of fire origin at times long after ignition. In remote rooms, the exposure threshold for significant sublethal effects ***is*** exceeded from fires that stay below flashover.
- Roughly half of the fire deaths and two-thirds of the injuries could be prevented if the time to incapacitation were significantly lengthened.

[In performing the analyses that led to the second and third bullets, we found that there was insufficient real-scale fire test data on the yields of irritant gases. Including their effects, *e.g.*, in stairwells **and** other egress paths, could change the above and following statements.]

This knowledge suggests the following guidance regarding occupancies where sublethal effects of smoke are not of prime concern because incapacitation from thermal effects, escape or rescue are likely to occur at earlier times [13]:

- Single- or two-compartment occupancies (*e.g.*, small apartments and transportation vehicles)
- Buildings with high ceilings and large rooms (*e.g.*, warehouses, mercantile)
- Occupancies in which fires will be detected promptly and from which escape or rescue will occur within a few minutes

This leaves larger residences, offices, medical facilities, schools, **and** correctional facilities **as** sites where sublethal effects could affect escape and survival.

The following summarizes new guidance for calculating toxic hazard:

- The toxic potency of smoke from a given material of product, as measured in bench-scale apparatus, is not a strong function of the combustion conditions.
- A generic value of the smoke concentration that will incapacitate smoke-sensitive people in 15 min (IC_{sens}) is 15 g/m^3, with an uncertainty of about a factor of three. Simulations using this IC value should test to see if variation within this uncertainty range changes the consequences of the fire being modeled. For exposure times other than 15 min, a reasonable scaling function is $(IC)^2 t$ = constant.
- For the large fires of most consequence, there is little change in the nature of the smoke as one moves further from the fire room: changes in respirability (from changes in aerosol dimension) **and** losses of toxicants from the breathable atmosphere are relatively modest.

These findings strongly suggest that the largest uncertainties in performing toxic fire hazard and risk calculations are:

- the source term for the combustibles, including rate of heat release, mass burning rate, and yields of toxic species (especially irritant gases and aerosols) and
- the relationships between smoke exposure and escape behavior.

THE FUTURE

In some sense, the title of this paper is itself a product of our misleading times. Toxic hazard fiom a fire in a facility is not solely a product of the combustibles. It involves many aspects of the facility, the contents and the occupants. We have core engineering tools for integrating these many components. To bring order **to** the unfettered toxicity information, we need to define the input to these tools and adopt standardized methods for generating that information. "Definition" includes identifying the facts at our disposal, the characterizations we can make from those facts, and designating those areas where our knowledge is insufficient to make any supportable statements at all. Then, we need to ensure that manufacturers, standards developers, regulators, even lawyers are using the same dictionary.

The dawning of the era of performance-based fire **and** building codes provides both a stimulus and a demand to address and complete this task. The technical community **has** the expertise to bring this about. The task requires aggregating the science and the resources of those who will benefit. In the 1980s, FRCA and NBS/NIST showed how this could be started. This decade, the SEFS Project is the vehicle to complete the task.

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