SUBLETHAL EFFECTS OF FIRE SMOKE: FINDING HOW TO INCLUDE THEM IN FIRE SAFETY DECISIONS

by

Richard G. Gann
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

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SUBLETHAL EFFECTS OF FIRE SMOKE: Finding How to Include Them in Fire Safety Decisions*

ABSTRACT

It has long been realized that the sublethal effects of smoke can affect survival in fires, but only sparse data were available on which to base fire safety decisions. A recent draft standard under consideration in the International Standards Organization Committee on Fire Safety has prompted an industry/government consortium to conduct research on the role of sublethal effects of smoke in evaluating building and/or product fire safety. This paper outlines the components of this high visibility and high potential impact study with the intent of informing FRCA members and soliciting their input into the formulation of the project.

BACKGROUND

Smoke from all fires presents a potential for harm, and smoke inhalation is the largest single factor in fire fatalities. The danger from smoke is a function of:

- the toxic potency of the smoke (often expressed as an EC_{50}, the concentration needed to cause the effect on half of the exposed population) and
- the integrated *exposure* a person experiences to the (changing) smoke concentration and/or thermal stress over some time interval: $\int C(t)\,dt$.

Some of the effects of smoke increase with continued exposure, others occur instantaneously. A person's survival depends on such factors as the exposure, the type of effect, the person's will to escape the fire, intervention by others, etc. Unfortunately, the only representative real-world data we have on smoke effects in real fires are for death or hospitalization that occurs proximate to the fire event.

Past studies have shown that about 3/4 of all U.S. fire deaths are due to inhalation of smoke[1]. About 2/3 of these occur outside the room of fire origin from fires that have proceeded beyond the room of fire origin. Fire modeling shows that it is difficult to produce lethal levels of smoke within the room of fire origin and that heat is the first threat for all but extremely toxic smoke (Figure 1).

Not all countries will have the same profile of fire deaths as in the U.S. For example, in the United Kingdom, where the national fire statistics are comparable in quality to those in the U.S., the experience appears to be quite different. Most people die within the room of fire origin, still from smoke inhalation. This suggests that smoldering fires, with the person in close proximity to the combustion, are relatively more prevalent there.

*Richard G. Gann, Building and Fire Research Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Mail Stop 8650, Gaithersburg, MD 20899-8650

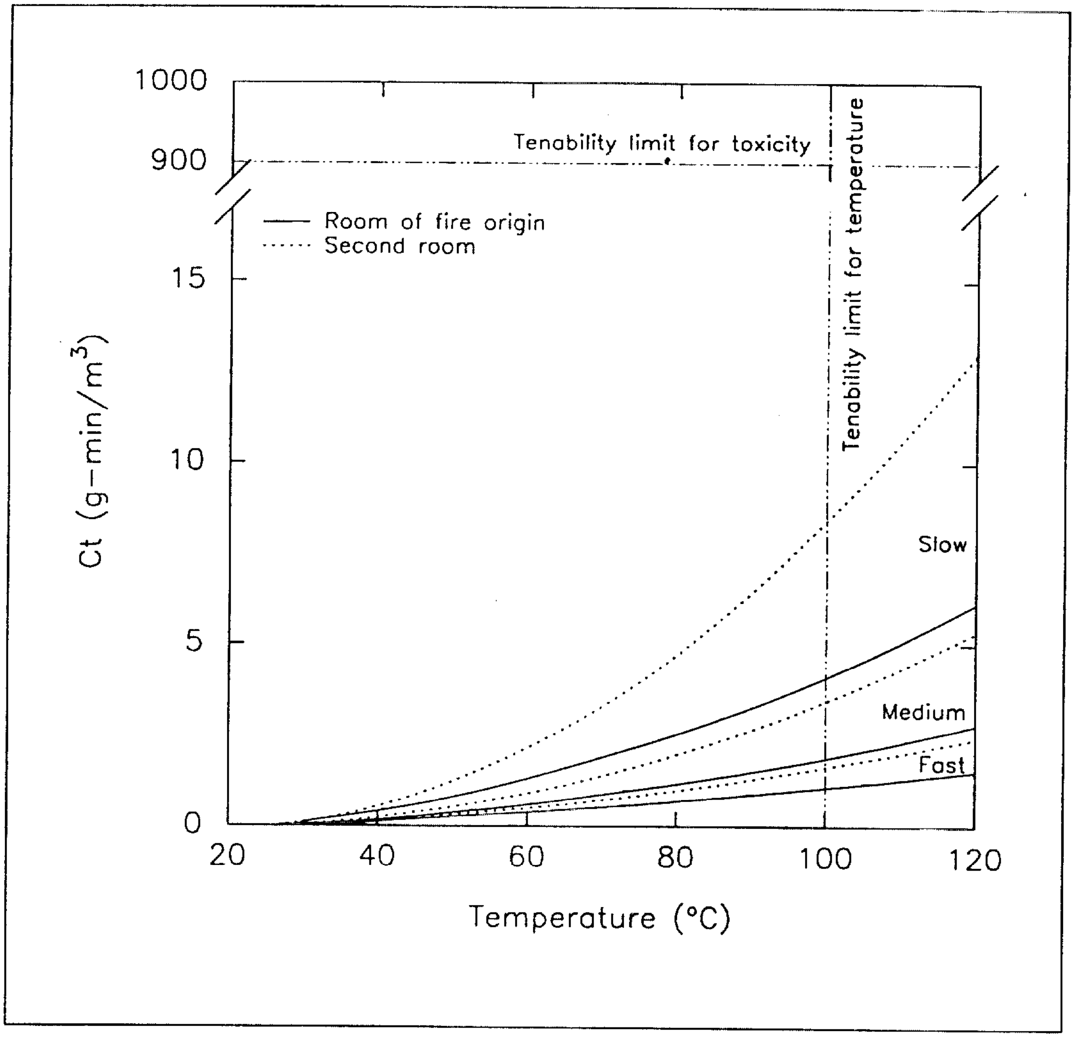

FIGURE 1. RELATIVE IMPACT OF TOXIC AND THERMAL EFFECTS IN THE ROOM OF FIRE ORIGIN AND A SECOND, CONNECTED ROOM FOR A RANGE OF FIRE GROWTHS

SMOKE LETHALITY

At the dawn of modern fire research in the 1970s, numerous lab-scale apparatus were developed for measuring the lethality of combustion smoke [2]. Examples include the NBS cup furnace, the DIN (German) tube furnace, and the UPITT method (adopted by New York State). None of these reflected relevant fire conditions and none were tested against real-scale fire tests to determine the accuracy of the smoke they produced.

In the late 1980s, a lab-scale test method for smoke lethality was developed at NIST, based on an apparatus developed at the Southwest Research Institute [3]. The method exposes a product specimen to fire-like radiant energy. An algebraic equation (the N-gas Equation) is used to predict lethal toxic potency from the concentrations of a small number of gases (CO, CO_2, HCN, HCl, HBr, reduced oxygen) that are emitted during the combustion. This equation is based on data from exposure of rats to these gases, individually and in combination. [The CO data have been linked to lethal human exposures.] The prediction is then verified by repeat experiments using the same apparatus, now exposing rats to the smoke.

The results from this apparatus have been verified against animal tests of the smoke from post-flashover room fires of wood, PVC, and a rigid urethane foam [4]. For post-flashover fires, the N-Gas Equation is corrected for the high CO resulting from underventilation in the fire room. The accuracy level is adequate for use in hazard analysis. This method has been adopted as NFPA 269 and ASTM E1678.

SUBLETHAL EFFECTS OF SMOKE

There are a wide range of impacts that smoke can have on people, short of causing death during their exposure:

- physical collapse (incapacitation)
- reduced egress speed due to, *e.g.*:
    - sensory (eye, lung) irritation
    - visual obscuration
    - heat or radiation injury
- reduced motor capability
- decreased mental acuity

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

Comparison of data from bench-scale incapacitation and lethality experiments indicates that the latter results from exposures 2-3 times those that cause incapacitation [5]. There is a paucity of data on other sublethal effects, and no such ratios with lethality have been derived for them. It is presumed that the exposure ratios that will cause the more subtle effects, such as a decrease in mental acuity, will be larger than the incapacitation ratio.

ISO DIS 13571

This draft international standard (DIS) was prepared in subcommittee SC3 on Toxic Hazards in Fire (now Fire Threat to People and the Environment) of the ISO TC92 Committee on Fire Safety. It provides generic equations for assessing smoke hazards - inhalation of narcotic gases, exposure to irritant gases, visual obscuration, and heat. DIS 13571 formalizes the inclusion of sublethal effects, including the variation of the effects of smoke on more susceptible segments of the population.

The balloting on the earlier versions of this document was highly positive. However, there has been an increased awareness of the constraints these concerns impose on product design, resources, and building functionality. An important ballot for this DIS to become an international standard has just been concluded, but at the time of this writing, the results have not been compiled.

There are a variety of shortcomings with DIS 13571.

1. DIS 13571 bounds the smoke effects issue describes above by establishing a "no harm" level based on 1-hour occupational exposures that have been deemed safe. These levels are a factor of 10 below the "serious harm" exposures. Table 1 lists some of these numbers.

TABLE 1. EXPOSURE LIMITS FOR SELECTED GASES

Safe Exposure for All		Potential for Serious Harm
3,500 ppm-min	CO	35,000 ppm-min
100 ppm	HCl	1,000 ppm
3 ppm	acrolein	30 ppm

Simple calculations show that for a room 30 m^3 (1500 ft^3), a 1-minute exposure to the smoke from 50 g of a typical halogenated FR product or from 150 g of smoldering wood would be intolerable. Further, it has been estimated that these CO levels would produce blood carboxyhemoglobin levels lower than those of a moderate smoker.

These results, then, do not make sense. In the U.S., we experience about 2 million reported fires per year, certainly all larger than the above fire sizes. Only about 1 percent of these fires result in reported injury or death. The minimal fires mentioned above are below detectable limits. They should rarely result in harm to people.

Thus, it appears that the suggested "band width" between lethality and safety is too broad. A prime scientific question is: how do we determine this ratio correctly within today's state-of-the-art?

2. The presumption that the effects of irritant fire gases is instantaneous remains to be verified.
3. The equations for the combination of fire gases to produce sublethal effects are generic and have not been validated.

THE FIRE PROTECTION RESEARCH FOUNDATION PROJECT

In light of the potential impact of DIS 13571 on product markets, a number of companies and trade associations have combined to support a project under the NFPA Fire Protection Research Foundation. The objective of the project is to ascertain whether there is a role for the sublethal effects of smoke in evaluating building and/or product fire safety, and if so, then:

- determine the fire scenarios in which the role is substantial,
- develop a protocol for obtaining data on or best estimates for sublethal effects of smoke on people and their ability to escape and survive, and
- develop guidance for policy makers for using these data in fire risk and hazard analysis.

This is a serious public safety and potential product regulation issue that needs to be addressed. The formulation of the project reflects that it is highly unlikely that new data on controlled human exposures will be possible; no human or animal exposure studies are currently planned in this project. However, there is a need for carefully documented, quantitative analysis of the existent data and of the principles for their use, e.g., what is the accuracy of extrapolating from animal tests to human response. There is a current timeliness for these results, as prescriptive codes are being revised and performance-based codes are emerging.

The following are the planned components of the project:

Task 1: Toxicological Data

- Review the existing data on lethal and sublethal physiological effects of heat, smoke, fire gases/aerosols and their combinations on animal species and humans
- Identify the best such data (including from non-fire literature) and determine uncertainty bars
- Review the literature on the relative penetration into the lungs of gases and aerosols of differing dimension
- Review the data on people's susceptibility as a function of age, physical condition, etc.
- Examine the methods for extrapolation of the animal data to people and determine the associated uncertainty levels
- Determine how to obtain more/better data without using human subjects

Task 2: Smoke Transport Data

- Review the literature on the dimensions of aerosols produced in fires
- Review the literature on the losses and agglomeration of gases and aerosols as the smoke moves from the fire
- Review the literature on models of the solubility in and evaporation from aqueous aerosols of toxic gases in the humid fire effluent

Task 3: Behavioral Data

- Review the relationships between physiological effects (especially from irritant gases) and impairment of human escape
- Appraise methods for extrapolating such effects in animals to people and estimate the uncertainty levels
- Determine how to obtain more/better data without using human subjects

Task 4: Fire Data

- Review data from reports on fires, on chemical exposures, from hospitals, etc. to characterize our ability to determine the importance of sublethal exposures on escape, survival, and health
- Estimate the magnitude of the importance (relative to lethality) of sublethal effects, with uncertainty bars
- Identify ways to improve future gathering of case and epidemiological data

Task 5: Risk Calculations

- Based on past fire risk analyses, identify fire scenarios for which significant incidence data exist
- Compile list of primary factors that would mitigate the incidence of fire and accompanying casualties

- Perform calculations to estimate the decreased chance of escape and survival in these fire scenarios when people are exposed to sublethal levels of smoke
- Verify, to the extent possible, with the data from Task 4 or from specific fires where the exposure information can be inferred

Task 6: Fire Characterization

- Determine analytically and/or experimentally the fire types and sizes (e.g., single burning object, spread to successive objects) that can produce atmospheres to which sublethal exposure would result in significant decrease in survival likelihood
- Develop accurate reduced-scale measurement methodology for obtaining smoke (component) yield data for commercial products

Task 7: Societal Analysis

- Develop a method and case studies for projecting the enhancements of public safety and the costs to society that would accrue from the inclusion of exposure to sublethal levels of smoke in design specifications

Task 8: Dissemination

- Compile a reference document for the subject
- Archive the research findings
- Prepare practical guidance sheets for decision makers
    - based on the existing literature and the Project outcome
    - delineating the relative importance of lethal and varying levels of debilitating smoke exposures

Project Output

- Identification of fire scenarios for which sublethal smoke exposures would reduce survival significantly
- Compilation of best knowledge of effects on people of sublethal exposures to fire smoke
- Validated method for obtaining product smoke data for inclusion in appropriate fire hazard and risk analyses
- Benefit/cost analysis of including consideration of exposure to sublethal levels of smoke in design specifications

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