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Fire Conditions for Smoke Toxicity Measurement

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

and John R. Hall, Jr
Fire Analysis & Research Division, National Fire Protection Association, Quincy, MA 02269-9101, USA

This paper identifies those fire conditions most often present when smoke toxicity is the cause of death. It begins with a review of the evidence that smoke-inhalation deaths are in the majority in fire fatalities in the United States. Next, there is an analysis of the evidence from the national fire experience showing the connection between post-flashover fires and smoke-inhalation deaths. Third is a presentation of real-scale fire test results demonstrating that post-flashover conditions are necessary to produce enough smoke to cause smoke-inhalation deaths in the cases where they actually occur. The fourth component is a sampling of results from computer simulations of fires, affirming and broadening the results from the fire tests. It is concluded that smoke-inhalation deaths occur predominantly after fires have progressed beyond flashover. This conclusion then provides a focus for smoke toxicity measurement in particular and fire hazard mitigation in general.

INTRODUCTION AND PURPOSE

For decades, students of the United States fire problem have known that most fire deaths are due not to burns but to toxic gas effects, oxygen deprivation, and other effects of what has been loosely referred to as 'smoke inhalation'.[1-4] What has been less well understood is the fire circumstances under which smoke-inhalation effects are most important in causing these deaths. This information has considerable potential relevance to an understanding of the relative roles of different products in contributing to lethal conditions in fires. This in turn underlies fire performance evaluation, whether by laboratory testing of products, computer-based calculation or, most likely, a combination of the two.

The purpose of this paper is to identify, through analysis of national fire incidence data and the results of fire tests and computer models of fires, those fire conditions most often associated with deaths due to one-time inhalation of fire smoke. (The paper does not address deaths resulting from chronic exposure to smoke.) These diverse sources of information all clearly indicate that in the United States deaths occur predominantly after fires have progressed to or beyond flashover and usually involve victims located in a room other than the room or area where the fire originated. This finding has implications for the fire conditions most relevant to fire toxicity assessment in general and smoke toxicity measurement in particular.

BACKGROUND

Since the 1970s there have been numerous toxicological studies of the potential harm from the smoke produced by a diversity of burning fuels. These studies have 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 the harm.[5] The early focus was on being able to evaluate commercial products by the toxic potency of their smoke produced when forced to pyrolyze or burn. Inherent in this era was a realization that while the smoke from all burning products was toxic, some products produced smoke appreciably more toxic than others. Unusual and severe symptoms beyond carbon monoxide poisoning could also be observed in laboratory animals.[6]

Realizing that the potency of the smoke was but one of several factors affecting the noxiousness of the fire atmosphere, fire scientists began merging these factors into simple fire hazard calculations.[7-10] These equations combined measures of the toxic potency of smoke with measures of other elements potentially important in overall fire hazard or at least fire hazard due to toxic effects. Examples include:

- Mass loss 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 fire, which would also be a factor in the quantity of toxic gas released.

Both the toxic potency tests and the calculations were intended to enable comparison of different candidate products for a particular use in a given compartment; *i.e.* assessment of their *relative* contribution to harm. They were limited in predicting *absolute* hazard, in that they omitted transport of the gases from the burning product to victims in other rooms. Thus, it was not possible to assess whether a pair of differently ranked products were *both* threatening, *both* of minor concern, or truly different in contribution to life threat. Moreover, the interactive effects of multiple products involved in a single fire were not addressed.

In 1989, the first (prototype) methodology for quantifying the hazards to occupants involved in a building fire was published. Called HAZARD I, it involves defining a fire scenario of interest, including information about the building, contents and people. This enables a more comprehensive, truer assessment of the threat of a fire to people and property. HAZARD I uses a set of computer

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programs to calculate the time-varying environment within a building resulting from a specified fire; the locations and actions of occupants; and the impact of the exposure of each of the occupants to the fire products in terms of whether the occupants successfully escape, are incapacitated or are killed.[11]

FAST, the program that calculates the environment, is a *zone* model. It includes the assumption that the heat evolved from a fire will result in a well-stratified, heated, smokey upper layer (zone) in the fire room, in accordance with visual observations of fire tests. The smoke is instantaneously and evenly distributed within this layer. Depending on the rate of heat flow into adjacent rooms, they too may show layering. Provision is included for contamination of the lower layer (or zone), although the inter-layer mixing is small. As will be seen later, the accuracy of this type of model is limited to cases where enough heat has been generated to drive formation of the layers.

In the course of developing a fire hazard assessment method, it was noted that there are several possible causes of harm, such as falls, heat, suffocation, smoke inhalation. The one (or more) of these that is important to a person in a given fire is typically the one (or more) that affects him or her first. This can be referred to as the *limiting hazard* concept. For example, in those cases where the temperature is untenable before the smoke level becomes too high to incapacitate or kill, heat is the limiting hazard, and the toxic potency of the smoke is secondary. Alternatively, there will be cases where heat and smoke reach lethal levels within seconds of each other. In these cases, taking measures to delay either hazard is not productive, since the available escape time would not change significantly. This leads to the premise that fires in which the potency of smoke is potentially important are those in which smoke inhalation is the first threat to survival. These are the cases which need to be identified for proper use of smoke toxicity information.

The paper begins with a review of the evidence that smoke inhalation accounts for most fire deaths. Next, there is an analysis of the evidence from the US national fire data showing the connection between post-flashover fires and smoke-inhalation deaths. Third is a presentation of real-scale fire test results demonstrating that post-flashover conditions are necessary to produce enough smoke to cause smoke-inhalation deaths in most cases where they actually occur. The fourth component is a sampling of results from computer simulations of fires, affirming and broadening the results from the fire tests.

It is the conclusion of this paper that the post-flashover stage of a fire is responsible for most deaths due to smoke inhalation, which in turn accounts for most fire deaths. The number of deaths from smaller, pre-flashover fires is far smaller. Nonetheless, we develop a basis for determining when toxicity is the limiting hazard for this type of fire as well.

THE PREVALENCE OF FIRE DEATHS FROM SMOKE INHALATION

There is no single database in the United States that routinely and uniquely categorizes all fire deaths in terms of the nature of fatal injury (e.g. burns, smoke inhalation, fall). However, there are several databases and special studies that come close and that tend to agree on some overall characteristics of the toxic hazard problem in fire.

The classic study in this area was by Berl and Halpin and involved analysis of 463 Maryland fire deaths occurring during 1972–1977.[12] That study did not have the benefit of any data representing judgment of the cause of death as smoke inhalation or burn related by either fire service or medical personnel, but did have data from a number of autopsy measurements. The analysis focused on carboxyhemoglobin as an indicator of death due to carbon monoxide inhalation and found the following:

- 48% of the victims had lethal carboxyhemoglobin levels (based on a 50% threshold).
- 26% had carboxyhemoglobin levels of 30–50% and had other conditions (cyanide exposure and/or pre-existing heart disease) deemed sufficient in combination with the sub-lethal carboxyhemoglobin levels to cause death.
- 18% had apparently lethal thermal injuries and had carboxyhemoglobin levels too low ($<30\%$) to be considered a contributing factor.
- 8% were assigned to miscellaneous and unknown causes, including causes such as falls, not associated with fire effects.

Combining the first two groups provided Berl and Halpin with an initial estimate that smoke inhalation accounted for roughly three-quarters of all fire deaths. Note that their approach was tantamount to assuming that carbon monoxide poisoning was the most likely cause of death, and that any other cause would be considered only after the possibility of carbon monoxide poisoning had proven insufficient to explain the death. Such an approach might overstate the relative importance of smoke inhalation in general and of carbon monoxide in particular.

In 1979, the coding of US death certificates was revised to provide for the coding of burns versus smoke inhalation for most fire deaths. This was done through the addition of a fourth digit to the so-called E-code, which describes the 'environmental events, circumstances, and conditions' which caused fatal injury. The deaths so coded were those coded as 'conflagrations' in the database, a term used in this system to mean structure fires and not the multi-building incidents for which that term is reserved in most branches of fire analysis. Roughly 15–20% of fire deaths are not coded as conflagrations and so are not coded as to burns versus smoke inhalation. These divide primarily into two groups:

- Those where it is very likely that the cause was burns (e. g. clothing ignition, ignition of some highly flammable material).
- Those where it is likely that the medical cause of death would have been undetermined (e.g. unclassified or unknown-type fire).

Harwood and Hall analyzed these data for 1979–1985 US fire deaths and developed a best estimate that fire deaths due to smoke inhalation outnumbered those due to burns by roughly two-to-one in 1985.[13] This was, at most, a slightly lower share than that estimated in the Maryland study, and still a large majority of all fire deaths.

The third major source of information on this subject is the database of fire department reports on reported fire incidents. The two principal limitations of this database are:

- The classification of nature of fatal injury (the name for the coding element that identifies burns versus smoke inhalation versus other as the medial cause of death) is typically done by fire officer judgment without the benefit of medical testing.
- The most frequently coded condition is that the victim died of burns *and* smoke inhalation, with the relative contribution of each left undetermined.

Table 1. Civilians killed by smoke inhalation in structure fires, by final extent of flame damage and victim location, annual average of 1986–1990 fires reported to fire departments

	Final extent of flame damage		
Victim location	Confined to room of origin	Extended beyond room of origin	Total
Intimate with ignition of fire	12 (1.6%)	29 (3.7%)	42 (5.2%)
In room of fire origin but not intimate with ignition of fire	46 (5.8%)	69 (8.8%)	115 (14.5%)
Outside room of fire origin	114 (14.3%)	522 (65.8)	636 (80.1%)
Unclassfied	0 (0.0%)	1 (0.1%)	1 (0.1%)
Total	172 (21.7%)	621 (78.3%)	793 (100.0%)

Source: 1986–90 NFIRS and NFPA survey.
Note:
Here and in Tables 2 and 3, statistics are calculated separately for residential and non-residential structures, then combined. In calculations, incidents with unknown final extent of flame are proportionally allocated over incidents with known final extent of flame. Then, incidents with unknown victim location are proportionally allocated over incidents with known victim location.

Table 2. Civilians killed by burns in structure fires, by final extent of flame damage and victim location, annual average of 1986–1990 fires reported to fire departments

	Final extent of flame damage		
Victim location	Confined to room of origin	Extended beyond room of origin	Total
Intimate with ignition of fire	65 (30.3%)	36 (16.7%)	101 (47.0%)
In room of fire origin but not intimate with ignition of fire	20 (9.1%)	36 (16.9%)	56 (26.0%)
Outside room of fire origin	4 (2.1%)	52 (24.1%)	56 (26.2%)
Unclassified	1 (0.4%)	1 (0.4%)	2 (0.9%)
Total	90 (41.9%)	125 (58.1%)	216 (100.0%)

Source: 1986–90 NFIRS and NFPA survey.

Table 3. Civilians killed by smoke inhalation and burns in structure fires, by final extent of flame damage and victim location, annual average of 1986–1990 fires reported to fire departments

	Final extent of flame damage		
Victim location	Confined to room of origin	Extended beyond room of origin	Total
Intimate with ignition of fire	201 (6.9%)	326 (11.3%)	527 (18.2%)
In room of fire origin but not intimate with ignition of fire	174 (6.0%)	544 (18.8%)	717 (24.8%)
Outside room of fire origin	104 (3.6%)	1523 (52.8%)	1628 (56.4%)
Unclassified	2 (0.1%)	13 (0.5%)	15 (0.5%)
Total	481 (16.7%)	2406 (83.3%)	2887 (100.0%)

Source: 1986–90 NFIRS and NFPA survey.

Despite these limitations, the qualitative picture this database provides is not greatly different from that given by the other two databases. For 1986–1990 structure fire deaths, smoke inhalation alone outnumbered burns alone by 3.6 to 1. More importantly, this third database provides the only available data on fire size, victim location and other characteristics relevant to an understanding of the kinds of toxic and thermal effects producing the deaths. Tables 1–3 provide such a breakdown for structure fire deaths coded as due to smoke inhalation only, burns only, and smoke inhalation and burns, respectively. The testimony of these data to the importance of the post-flashover fire will be discussed in the next section.

In summary, then, the major fire incidence analyses show that two-thirds to three-quarters of the fire deaths in the United States are due to smoke inhalation.

THE PREVALENCE OF POST-FLASHOVER FIRES IN FIRE DEATHS DUE TO SMOKE INHALATION

Types or stages of fires

The characteristics of unwanted fires are almost endlessly diverse. Yet while various fire types can occur, they are not at all equally represented in national fire death statistics. Based on these statistics, we can identify the real fires in which smoke toxicity is most critical.

The British Standards Institution (BSI) has developed a method,[14] which has gained international acceptance, for grouping fires into six types:

I. Self-sustained smoldering decomposition (i.e. a cigarette on upholstered furniture or bedding).
II. Non-flaming oxidative decomposition.
III. Non-flaming pyrolytic decomposition.
IV. Developing fires, flaming (pre-flashover fires).
V. Fully developed fires, high ventilation (post-flashover, fuel-controlled fires).

VI. Fully developed fires, low ventilation (post-flashover, ventilation-controlled fires).

The transition between fire types V and VI occurs when the amount of fuel being gasified becomes great enough so that not all the pyrolyzate can burn within the room of fire origin. Thus, in a type VI fire, considerable burning also occurs outside the room, at doors, windows or other openings. The distinction between types V and VI is often difficult to determine in either real fires or laboratory tests. (Accidental post-flashover fires are almost always ventilation-controlled, type VI).

The (now) five categories can be used to describe a *type* of fire or a *stage* of a fire. For example, many deaths occur in fires that *begin* as type I. In the United States, the largest single cause of structure fire deaths (and over one-quarter of the annual total) is smoking materials, defined as cigarettes and other lighted tobacco products.[15] Such a fire starts out as type I, but full-scale laboratory tests show that only relatively small amounts of smoke are produced during the smoldering phase. The bulk of the smoke is produced *after* the smoldering furniture item bursts into flames.[16,17] Of most importance, these studies found that only after the smoldering transitions to flaming do animal deaths occur. These results can be extrapolated safely to other smoldering-initiated fires (such as those due to heating equipment).

Fire types II and III in themselves rarely become severe enough to cause fire deaths in residences, since they produce little heat or smoke, and these are rapidly ameliorated by room air. Typical scenarios include overheated electric wiring (but without accompanying flaming) and overheated combustibles placed near heating appliances (again, without flaming). The fire incident databases do not show these types because an overheat condition is not defined as a fire. Thus, these fires become important when they proceed to types IV, V and VI.

Thus, while many US fire deaths occur in fires that *start* out as types I, II and III very few occur in fires that *end* there. This means that an examination of the key factors in producing toxic hazard in fires needs to address two questions in sequence:

- Which types of fires, defined by their most severe stage, account for most fire deaths due to smoke inhalation?
- Within those fire types, which stage of fire produces the lethal conditions that lead to death?

The remainder of this section will answer these two questions. We will see that fire statistics demonstrate that most fire deaths due to toxic effects occur in fires of types V and VI. Fire statistics imply and laboratory tests show that types I, II and III do not create sufficient quantities of smoke to cause lethal effects, except for a small fraction of victims relatively near the fire.

Evidence from US fire statistics

In the United States most fatal victims of fire involving smoke inhalation, either as the sole cause or as a contributing cause, were:

- Themselves located outside the room of origin when the fire began and
- Killed in fires that spread flames beyond the room of origin.

While the data are not tabulated according to 'pre-flashover' or 'post-flashover', they do include a roughly equivalent concept, namely whether there has been 'flame damage beyond the room'. Such flame damage does not typically occur if the fire does not progress beyond the pre-flashover stage, but does if flashover is reached and burning continues.

For deaths coded as smoke inhalation only, nearly two-thirds (65.8%) of victims fit this description (Table 1). For deaths coded as smoke inhalation and burns, just over half (52.8%) fit this description (Table 3).

Deaths due to burns-only were much more likely to involve victims close to the point of origin of the fire. Nearly half of these (47.0%) were so close that the reports described them as 'intimate with ignition'. This might include clothing or bedding ignitions, spills of combustible or flammable liquids, etc. For the victims of burns and smoke inhalation, only 18.2% were coded as intimate with ignition. For the victims of smoke inhalation alone, only 5.2% were so coded. Nearly three-quarters of burn-only fatal victims (73.0%) were somewhere in the room of origin when fire began, compared to 43.0% of the fatal victims of burns and smoke inhalation and only 19.7% of the fatal victims of smoke inhalation alone.

An important caution is that the fire records cannot and do not indicate when in the course of a fire any victim received fatal injuries. It is therefore possible that lethal conditions were reached long before the fire reached its final size and that the fire conditions producing lethal conditions were not those of the advanced post-flashover fire indicated by the data from actual fires. If this were true of a large share of victims, however, then one might expect that all fires reaching the modest size sufficient to produce lethal conditions would be equally likely to cause deaths, which would mean that the death rate per 100 fires would be largely independent of the size of the fire. This is clearly not the case. As one moves up the qualitative scale used to measure fire size in fire incident reports (from confined to object of origin to confined to area, confined to room, confined to floor, and confined to building), there tends to be a factor of 2–4 jump in the rate of deaths per 100 fires for each change in the scale of fire size. This relationship between the death rate and fire extent also is noted in reference 18, which also uses NFIRS data. In short, the earlier interpretation of the data is the most plausible: most fire victims, and in particular most fire victims killed by toxic effects, are located away from the room of origin when fire begins and are killed by the fire that reaches flashover in the room of origin.

Evidence from real-scale fire test results

The earlier conclusions on fire stages producing deaths due to toxic effects are also supported by animal mortality data from real-scale fire tests. The following references are to three sets of tests conducted at NIST over the past few years. In each case, test animals were exposed for 30 min to (cooled) samples of smoke from either the hot upper layer of the fire room or the hot upper layer of a room into which the fire room smoke had progressed. The smoke concentrations in the corresponding lower layers, where people are more likely to be during a fire, are far lower. As a result, these animal deaths are a very conservative indicator (i.e. an overestimate) of the toxic hazard during the pre-flashover stage of the test fires.

In 1988, NIST reported an extensive series of real-scale laboratory tests in which the focus was comparison of the fire hazards from fire-retarded versus non-fire-retarded commodities.[19] All the tests involving non-fire-retarded products led to flashover prior to the first animal exposures being made. The tests involving fire-retarded products did not. Thus, their data can be examined for pre-flashover animal mortalities. In each test, three chambers containing six animals were used. The smoke in each chamber represented the upper layer composition at a different time during the test. These times were not uniform among the tests. Table 4 shows the results. Out of a total of 54 animals exposed, only 11 died during pre-flashover conditions. These all occurred in the one test that showed the most vigorous burning. (By comparison, the smoke from those tests that proceeded beyond flashover killed 24 of the 36 animals exposed, and the 12 surviving animals were exposed to smoke levels generated either before flashover or well after most of the fuel had been consumed.)

In 1991, NIST reported the validation of bench-scale toxicity measurement techniques against real-scale fire data for three materials: Douglas fir planks, a rigid polyurethane foam and a rigid PVC sheet.[20] For those tests where animals were exposed to smoke during the pre-flashover period, the results in Table 5 were obtained. (No pre-flashover data for the polyurethane foam fires were available.) Again, the results show only few (1/3) animal deaths prior to flashover.

A third relevant study is a second NIST toxicity validation series.[21] The design of this experimental program was similar to the first validation series, except that additional materials were examined. Table 6 shows that in this series also, few (4/48) animal deaths resulted in those test runs where pre-flashover data were available.

In all, from a total of 120 animals exposed during pre-flashover fire conditions, only 21 fatalities (< 20%) were recorded, even for exposure to the upperlayer fire effluent. This is far lower than the virtual certainty of death observed from exposure to post-flashover smoke, as noted earlier in this section. Prior to flashover, most of the fire room will have a far lower concentration of smoke, and people are most likely to be breathing in that lower layer. Thus, to the extent that smoke lethality in rats has been shown to relate will to human survival, this confirms experimentally that lethalities from smoke inhalation are far less frequent in pre-flashover fires.

Table 4. Results from pre-flashover animal exposures in tests of FR commodities

Test	Total animals exposed	Total animals dead
F1	18	0
FX1	18	0
FX1a	18	11

Table 5. Results from pre-flashover animal exposures in first validation series

Test material	Total animals exposed	Total animals dead
Douglas fir	12	6
PVC	6	0

Table 6. Results from pre-flashover animal exposures in second validation series

Test material	Total animals exposed	Total animals dead
Cork board	12	0
Melamine/vermiculite composite marine board	36	4

Evidence from fire modeling results

In this section we present further evidence that pre-flashover fires infrequently produce sufficient effluent for people to die of smoke inhalation alone in the room of fire origin. (Note from Tables 1–3 that those dying in the room of fire origin comprise only about one-fifth of the total fatalities.) The evidence comes from computer modeling of room fires and the reconstructions of actual fatal fire incidents using these models.

The models of building fires that are currently available vary considerably in scope, complexity and purpose. Most of them are of the zone (or control volume) type. As noted earlier, they assume that the buoyancy of the hot fire product gases causes them to stratify into two layers: a hot, smoky upper layer and a cooler lower one. With limitations (see below), experiments have shown this to be an appropriate approximation.[22,23] For a review of all of the commonly used computer fire models, the reader is referred to Friedman's recent compilation.[24] Reference 25 reviews several of both the simple computational methods and the computer fire models and gives further references to example hazard analyses which have been conducted by using these tools.

Figure 1 shows a comparison of the relative development of toxicity and thermal hazards in the upper layer of the room of fire origin and a connected room for a range of fire growth rates. (The independent variable, elapsed time, is not explicitly shown.) The upper layer was chosen since it fills most of the room; the results are similar for the lower layer. The data were obtained using CFAST, version 1.6.[26] The accuracy of this and other zone models in predicting the extent and carbon monoxide content of the lower layer has been validated using real-scale experiments[27,33] and reconstructions of actual fires (see below).

The tenability limits shown in the figure are for visualization purposes and were estimated as follows. (As will be seen, the current comparison is not sensitive to the chosen values.)

- *Temperature*: The effects of temperature as an exposure limit under fire conditions have not been well studied. They depend not only on the exposure time but also on additional factors such as the relative humidity and the interactions of heat and toxic gases. The comparison here assumes (Conservatively) that death occurs when

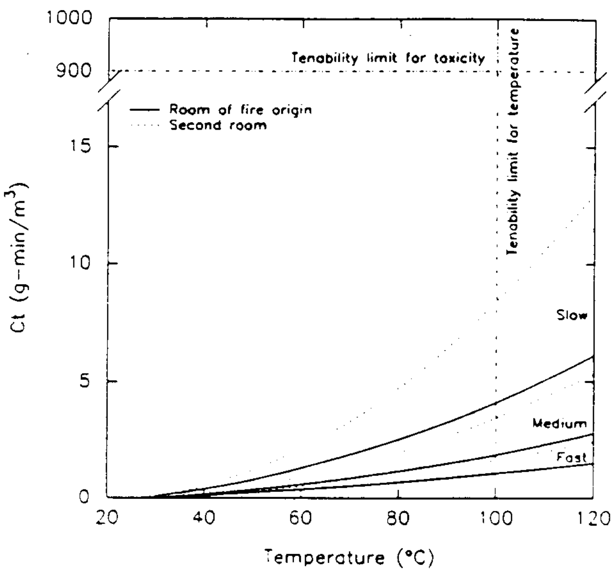

Figure 1. Relative impact of toxicity and thermal effects in the room of fire origin and a second connected room for a range of fire growth rates.

the temperature reaches 100°C. This was approximated from experimental data that showed *no* lethal threat. One set showed that clothed, inactive adult males could withstand temperatures of 100°C for about 30 min before their discomfort became intolerable; a 75°C exposure could be withstood for about 60 min.[28] These experimental values seem high. Zapp[29] has stated the '. . . air temperatures as high as 100°C can be tolerated only under very special conditions (i.e. still air) for more than a few minutes and that some people are incapacitated by breathing air at 65°C'. Experimental data from studies with pigs have shown no injuries at 120°C for 2 min, 100°C for 5 min and 90°C for 10 min.[30,31]

- *Toxic potency*: The toxic threat to life safety in a fire depends on how long a person is exposed to the smoke (t) and the concentration (C) of smoke present. The product of these (Ct) is typically used to denote a person's exposure, and the concentration–time effects of toxic gases have been studied by many researchers. A value of 900 $\mathrm{g\,min\,m^{-3}}$ has been proposed as a reference value for the lethality of smoke from most common building materials.[32,33] This comes from a 30-min exposure to smoke of a presumed typical toxic potency (LC_{50}) of approximately 30 $\mathrm{g\,m^{-3}}$.

There are differences among the curves for the three different fire growth rates. These result from the fact that heat loss from the hot upper layer to the walls occurs faster than dilution of the smoke. Thus, at the (three different) times when the three fires have produced the same temperature in their respective upper layers, the slowest-growing fire has produced the highest smoke concentration.

For all three fire growth rates, the tenability limit for temperature is reached long before the limit for toxicity is approached. Ct levels of ≈ 1–$3\ \mathrm{g\,min\,m^{-3}}$ would be needed for death from smoke inhalation to occur as soon as from heat in the room of fire origin. Over the time period necessary to reach the lethal level from temperature, an equal life safety threat due to smoke toxicity would require a 30-min LC_{50} value of under 0.1 $\mathrm{g\,m^{-3}}$. This is at least 100 times more toxic than values measured for typical building materials; virtually no commercial products exposed under realistic fire conditions have LC_{50} values so low. In this context, the value of a toxic potency measurement method is the identification of those products that produce smoke of extreme toxic potency.

It can also be seen from Fig. 1 that the relative importance of smoke inhalation increases as one moves away from the room of fire origin. This is because heat loss from the smoke occurs faster than dilution of the smoke with room air.

It should not be inferred from this that *no* deaths from smoke inhalation can occur within the room of fire origin. From Table 1, about 7% of the smoke inhalation only victims from one-room fires are overcome within that room. Based on the computational example above, it is reasonable to presume that in these cases, these victims must have been close to the ignition site. They breathed the smoke long enough to cause death, but before the smoke became well dispersed into the upper layer. Since burns were not identified as a contributor to the fatalities (as they are in Table 3), the fires must not yet have produced enough flames or heat to do harm. This is consistent with fires that start as type I and remain that way long enough for the deaths to occur. A typical example involves the sleeping smoker whose dropped cigarette has ignited the bed or chair. In accord with this, it has been noted that cigarette-initiated fires can smolder as long as an hour before breaking out in flames.[17]

Several researches have modeled actual fire incidents to understand the relative effects of thermal and toxic impacts. Levine and Nelson[34] used a combination of full-scale fire testing and modeling to recreate a fire in a residence. The 1987 fire in a first-floor kitchen resulted in the deaths of three persons in an upstairs bedroom, one with a reported blood carboxyhemoglobin content of 91%! Considerable physical evidence remained. The fire was successfully simulated at full scale in a fully-instrumented seven-room-storey test structure. Both FAST version 18 and HARVARD V predicted the pre-flashover temperature rise and the carbon monoxide buildup in the room most remote from the fire. (Prior to flashover, CO levels in the burn room were near 2000 ppm, barely the incapacitation limit for a *30-min* exposure. After flashover at 3 min, these levels quickly rose to over 60 000 ppm. Levels elsewhere in the structure also rose to more than 50 000 ppm. This is one more verification of the unlikelihood of smoke inhalation deaths prior to flashover.)

Bukowski used the FAST model within HAZARD I[11] to analyze a fire which took the lives of 87 persons at a neighborhood club in the Bronx, New York.[35] He provided details of the progress of the fire which were representative of the actual conditions that occurred, including times to and causes of death for the building occupants consistent with observations. In the room of fire origin (the entry hall of the two-storey building), he estimated that temperature and heat flux would have caused incapacitation within 30 s of ignition. Toxic gases would not cause incapacitation for another 10–30 s. On the second floor, from which most of the victims were recovered, toxic gases were estimated to cause incapacitation in 320–390 s and death in 520 s. Temperatures never reached levels sufficient to cause incapacitation due to an operating sprinkler at the top of the back stairs, which was predicted to activate at 240 s.

CONCLUSION

In the United States, fire deaths from smoke inhalation occur predominantly after fires have progressed beyond flashover. The victims are most often in a room other than the fire room. Within the room of fire origin, toxic hazard is much less likely a threat than is thermal hazard. A small fraction of the smoke toxicity victims are overcome within the fire room, presumably from inhaling the effluent from smoldering fires. These findings result from analyses of US fire incidence data, actual fire incidents, real-scale laboratory fire tests and computer modeling of fire hazard.

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