# SUBLETHAL EFFECTS OF SMOKE ON SURVIVAL AND HEALTH'

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*Fire smoke toxicity has been a recurring theme for fire safety professionals in the U.S. (and around the world). The International Study of the Sublethal Effects of Eire Smoke on Survival and Health" (SEFS) is intended to resolve this difficulty by identifying the fire scenarios where sublethal exposures to smoke lead to significant harm, compiling the best available toxicological data on heat and smoke and their effects on escape and survival, developing a validated method to generate product smoke data for fire hazard and risk analysis, and generating practical guidance for using these data correctly in fire safety decisions. This paper presents the first results from the SEFS study: characterization of those fire scenarios for which sublethal smoke exposures are of most concern and guidance for including toxic potency data in calculations of fire hazard and risk.*

## I. INTRODUCTION

Fire smoke toxicity has been a recumng theme for fire safety professionals in the U.S. (and around the world) for over four decades. This is because:

- all combustible construction and furnishing products can produce harmful smoke;
- about 70-75 % of the U.S. fire victims succumb to smoke inhalation, a fraction which has been generally increasing for at least two decades;[2] and
- the problem of how to address smoke toxicity in standards and codes has not yet been "solved."

The danger from smoke is a function of the *toxic potency* of the smoke 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 almost instantaneously.

*Lethality* is the most immediate effect that smoke can have on occupants or on fire service personnel responding to the fire. This has driven the development and adoption of a standard (NFPA 269[3], ASTM E1678[4]) for measuring the lethal toxic potency of smoke form burning products for use in hazard and risk analyses. The capability to estimate potentially lethal smoke exposures has also developed. Tools like HAZARD I[5] enable combining all the above factors and predicting the outcome of a given fire. The EXITT routine in HAZARD I, EXIT89[6] and EXODUS' offer the ability to simulate people movement through a burning facility. The Fire Protection Research Foundation has developed a method for calculating fire lethality risk by combining scenario analysis with hazard analysis.[8]

There have also 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. The ***sublethal*** effects that smoke can have on people include:

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

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 from:

- the tendency to ascribe toxicity to each product potentially involved in a fire, even though other factors in the fire affect toxic smoke yield more than product characteristics **do,** and even though there are many factors, unrelated to products, that affect toxic smoke exposure;
- 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 smoke and smoke component yields 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.

Indicative of this overall uncertainty regarding sublethal effects of fire smoke hgs been the response to draft document 13571 being developed by ISO TC92 SC3 (Fire Threat to People and the Environment) and which formalized consideration of incapacitation. Early drafts incorporated estimates of toxicant thresholds for very susceptible people. These conservative figures led to implied limitations on product flammability that would be impossible to meet. Recognition of this potential outcome led to extensive redrafting of the document and moderated constraints on smoke toxic potency. This document will likely become an ISO Technical Specification within the next year or so. Documents addressing other sublethal effects of smoke are likely to follow.

There is little doubt that the sublethal effects of fire smoke continue to affect life safety and that the professional community does not yet have the knowledge to develop 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. Emng on the conservative side could inappropriately bias the marketing of construction and furnishing materials, constrain and distort building design options, and drive up construction costs. Meanwhile, competition in the marketplace is already being affected by poorly substantiated or misleading claims regarding smoke toxicity.

## II. THE SEFS PROJECT

In May 2000, the Fire Protection Research Foundation (FPRF) and the National Institute of Standards and Technology (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 Eire 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 would be 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 in May 2000 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 fiom building fires.

determine the potential for various types of fires to produce smoke yields fiom ½ to 1/100 of those that result in lethal exposures in selected scenarios.

## PHASE ONE ACCOMPLISHMENTS

### Prevalence of Sublethal Effects in Fires

Both current prescriptive fire and building codes and the emerging performance-based fire and building codes operate on a set of fire scenarios, which are detailed descriptions of the facility. in which the fire occurs, the combustible products potentially involved in the fire, a specific fire incident, and the people occupying the facility.

There are a large number of possible fire scenarios, with sublethal (and lethal) effects of fire smoke important in some fraction of these. It is tempting to identify that subset by focussing on those scenarios for which the largest fractions of fire deaths and injuries have occur, capturing those' scenarios in which the sublethal effects of smoke led to the two "markers" we have of real-world fire casualties: death or hospitalization proximate to the fire event. We would rely on the findings of fire data analysis that show:[9,10]

- fire deaths in homes outnumber fire deaths in all other buildings by ***20*** to 1;
- the majority of fire deaths involve victims remote from the point of fire origin and fires that spread flames beyond the first room, presumably through flashover;

• The word "facility" is used throughout this document for economy of expression; it comprises all types of buildings as well as transportation vehicles, whether at ground level or above.

- most fire deaths occur in buildings lacking sprinklers and working smoke alarms; and
- one-third of the fatal fires start with upholstered furniture, mattresses or bedding.

This approach would not, however, capture those scenarios in which people receive sublethal exposures to smoke that result in deleterious health effects or in which their survival was made more difficult. Essentially the entire 280 million citizens of the United States spend much of their time in residential, commercial or transportation occupancies, and only one hundred thousand (civilians and fire fighters) suffer a serious or fatal injury in a fire. Thus, it is incumbent to have estimates for the following two pivotal questions:

1. ***How many people might receive sublethal fire smoke exposures of any consequence?***
   - Knowing the magnitude of the population exposed to fire smoke would be a first step in a risk assessment where the heightened sensitivity of vulnerable subpopulations would be balanced by explicit use of the probabilities that those people will be the ones exposed in any particular fire.
   - If this total number of exposed people were, as expected, far greater than the number of reported victims, then conservative (low) fire safety thresholds that imply that ***any*** exposure to toxic fire smoke ***always*** results in unacceptable injury are not suitable for prediction.
2. ***How many of the recorded fatalities might have been the direct result of a sublethal exposure to fire smoke?*** It has frequently been stated that:
   - fire fatalities often result from incapacitating injuries that occur earlier and from less severe fire exposures than do fatal injuries and
   - incapacitation is nearly always followed by death.

   Establishing the degree of validity of this position defines the proper data to be used to characterize the most harmful smoke exposures.

To answer the first question, use was made of occupant location sets developed for the FPRF fire risk analysis method ***FRAMEworks***,[8] other U.S. Census Bureau estimates of numbers of households, and U.S. fire incident statistics on reported unwanted fires by time of day, area of origin (corresponding to occupant location categories), and final extent of smoke damage.

From these inputs, we estimated that between 310,000 and 670,000 people in the U.S. are exposed to fire smoke each year. This compares to an average of 3,318 home civilian fire deaths and 11,505 injuries per year from 1993-97 involving smoke inhalation in part or in whole." There are thus **21** to **45** civilians exposed to toxic fire smoke per year for every one with a reported fire injury involving smoke inhalation. [While these figures are for home fires only, the much smaller fire and injury incidence in all other types of buildings means that the qualitative conclusions would be unlikely to change if other occupancies were added to the analysis.]

It is unlikely that these high ratios are due to unreported injuries from reported fires, since a recent survey indicates the injuries from unreported fires are mostly bums from small cooking fires.[12] It seems more likely that most of the exposures are to the dilute smoke that is present outside the room of fire origin, where most survivors are located.

To answer the second question, cases from the NFPA major fires database, Fire Incident Data Organization **(FIDO)**, were examined to identify what victims and survivors of fires were doing at the time of injury or escape. Incapacitating exposures to smoke are generally shorter than lethal exposures. Certain activities (*e.g.*, "acting irrationally") or conditions (e.g., intoxicated) would make it less likely that a person could have used the additional time to effect their escape. The analysis indicates that roughly half of the deaths and two-thirds of the injuries might have resulted from an incapacitating exposure to smoke and heat. While this is based on analysis of 127 cases, the patterns of interest from these were clear enough that it is unlikely additional data coding would have produced significantly different results.

### B. Characteristics of Fire Scenarios in Which Sublethal Effects are Important

A second approach led to hrther guidance in identifying a lesser number of fire scenarios in which consequential sublethal exposures to fire smoke might occur.

A number of simulations were performed using the CFAST version 3.1 zone fire model.'' These predicted the environment in a structure that resulted from specified fires and produced time-varying profiles of smoke concentration and temperature distributions. The main output was to be the relative times at which smoke inhalation and heat exposure would result in incapacitation. Fires in three buildings were modeled:

- a ranch house, consisting of three bedrooms, a central hallway, a combined living room and dining room, as well as a kitchen;
- a hotel, consisting of two sleeping rooms and a long hallway connecting them; and
- an office, consisting of four equally sized office spaces (large open floor plan) enclosing a hallway and elevator lobby.

Gas species yields and rates of heat release for these design fires were derived from real-scale fire test data. Post-flashover simulations were known to result in both lethal and sublethal smoke exposures and thus were not performed here.

The incapacitation criteria were taken from draft 14 of ISO document 13571[14]:

$$\mathrm{FED}_{\mathrm{GASES}} = \sum_{t_1}^{t_2} \frac{CO}{35000}\,\Delta t + \sum_{t_1}^{t_2} \frac{\exp(HCN/43)-1}{220}\,\Delta t$$

$$\mathrm{FED}_{\mathrm{HEAT}} = \sum_{t_1}^{t_2} \frac{q^{1.33}}{1.33}\,\Delta t + \sum_{t_1}^{t_2} \frac{T^{3.4}}{5\times 10^{7}}\,\Delta t$$

Irritant gas effects were not included since few sets of yield data in large-scale fire tests are available. Generally, the asphyxiant gases account for half to all of the lethal toxic potency of smoke, and as noted below, that range of ratios is maintained for incapacitation.

Two FED values were used: FED = 0.3, indicating incapacitation of the susceptible population, and FED = 0.01 (1 % of the lethal FED value for the susceptible population), a value below which significant sublethal effects would not occur. Sublethal effects of smoke were deemed important when incapacitation from smoke inhalation occurred before harm from thermal effects occurred.

For a set of baseline tests, the doors were fully open and the fire had a maximum HRR of 90% of the minimum HRR necessary for room flashover. Additional simulations assessed the impact of smaller fires (including a steady 10 kW smoldering fire) and partial door closing. The conclusions were:

- In the room of fire origin, incapacitation from thermal effects always occurred before incapacitation from smoke inhalation, generally before exposure to combustion gases reached even 1 % of lethal conditions.
- Outside the fire room, for all but the smallest fire sizes and smallest vent openings, occupants would have been incapacitated by heat before the smoke reached 1% of a lethal exposure.

These findings are consistent with analyses of U.S. fire incidence data.[15] Fire deaths from smoke inhalation occur predominantly after fires have progressed beyond flashover. Within the room of fire origin, deaths mostly result from heat. A small fraction of the smoke toxicity victims are overcome within the fire room, presumably from inhaling the effluent from smoldering fires.

### C. Toxic Potency Values for Products and Materials

To calculate the toxicity component of a fire hazard or risk analysis, the practitioner needs to know how much smoke will produce undesired effects on people. Scientists have developed numerous test methods and extensive data for a variety of single materials and commercial products. Each method involves combusting, a small sample in an apparatus that simulates some type of fire; exposing laboratory animals, generally rodents, to the smoke; and characterizing the result. The typical measurement is an $LC_{50}$ or $IC_{50}$, the concentration of smoke (*e.g.*, in $g/m^3$) needed to produce death or incapacitation an effect in half of the animals in a given exposure time. We examined that wealth of data (over 200 citations) and sorted it by the combustion conditions (related to a type of fire) producing the smoke, the specimens tested, and the animal effect measured.

The results from the various test methods were categorized by:

***Combustion/pyrolysis condition.***

- All the data were classified as resulting from well-ventilated flaming combustion (typical of pre-flashover fires), ventilation-limited combustion (typical of post-flashover fires or fires in nominally airtight spaces), or oxidative pyrolysis (typical of products being heated without bursting into flames themselves).
- The combustors in the 13 small-scale apparatus were of three types: cup furnace (well-ventilated flaming or oxidative pyrolysis), radiant heater (well-ventilated flaming or ventilation-limited flaming), or tube furnace (mixed mode or not defined).
- Since the combustion conditions represented in a test were ill-defined by the original authors, we attempted our own assignments using $[CO_2]/[CO]$ ratios, analysis of the air access to the sample, and autoignition temperatures of the samples. None of these were successful for the tube furnaces, and those data were not used in this analysis.
- None of the devices accurately replicated true smoldering combustion. Achievement of the low heat losses needed for this self-sustained process requires a physically larger sample than that which can be accommodated by these bench-scale devices.

***Materials and Products Examined.*** Very few references provided a detailed composition of the test specimens. We grouped the tested items into generic classes as follows: acrylic fibers, acrylonitrile butadiene styrenes, bismaleimide, carpet (modacrylic/acrylic), carpet foam (with nylon), carpet jute backing (with nylon), chlorofluoropolymers, epoxy, vinyl fabric, fluoropolymers, modacrylics, phenolic resins, polyacrylonitriles, polyamides, polycarbonates, polyesters, polyester fabric/polyurethane foams, polyethylenes, polyphenylene oxide, polyphenylene sulfide, polyphenylsulfone, polystyrenes, flexible polyurethanes, rigid polyurethanes, plasticized polyvinyl chloride, polyvinyl chloride resin, urea formaldehyde, NFR cross-linked EVA wire insulation, PTFE coaxial wire insulation, THHN wire insulation with nylon-PVC jacket, wood. The data for the fluoropolymers fell into two distinct sets that were two orders of magnitude apart. Because real-scale experiments have shown that the very high toxic potencies are not realized in realistic fires,[16] this set of values was not used in the analyses. The fluoropolymers were the only product group for which the data warranted this separation.

***Test Animals.*** After setting aside the tube furnace data, all the test subjects were rats.

***Toxicological Endpoint.*** The toxicological effects encountered were lethality, represented by an $LC_{50}$ value, or incapacitation, expressed as an $IC_{50}$ value. There were no data found on other sublethal effects from the smoke from burning materials or products. [There is a parallel literature on the effects of single or combined combustion gases on test animals. That will be the subject of a future analysis.] All the $LC_{50}$ and $IC_{50}$ values in the following discussions and analyses are for 30-minute exposures.

Statistical analysis of the data for all materials for the three modes of combustion showed that the $LC_{50}$ values could be represented as a single set, with a value of (32 ± 18) $g/m^3$ for 30-minute exposures of rats. The exposures to narcotic gases (CO and HCN that cause incapacitation are 1/3 to 1/2 the exposure that resulted in the death of different animal species.[17] For the data collected here, the mean value of the ratios of $IC_{50}$ values to $LC_{50}$ values is 0.50 ± 0.17, consistent with this. Since there is a broad set of expected toxic gases (CO, halogen acid gases, HCN, partially-oxidized organics) in the smoke fiom this group of materials, it is not unreasonable to generalize that an incapacitating exposure is about half that of a lethal exposure. This leads to a generic $IC_{50}$ value (for rats) of (16 ± 9) $g/m^3$ for a 30-minute exposure. There are some materials with lower values, indicating higher smoke toxicity. If materials like these (*e.g.*, phenolics, modacrylics, urea formaldehydes, and epoxies) are expected to comprise a large fraction of the fuel load in a facility, a lower generic value can be used.

Our objective is to estimate conditions of safety for *people*, including those that are more sensitive to fire smoke than the average (or predominant) population. The information on which to base such an extrapolation is far from definitive. Our analysis was directed at obtaining order-of-magnitude factors and estimated uncertainties at the current state of an imperfect art.

We relied on the reviews and judgment of the team currently producing the Acute Exposure Guideline Levels (AEGLs) for Hazardous Substances,[18] particularly AEGL Level 2, defined as "the airborne concentration of a substance at or above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting effects, or an impaired ability to escape." We noted that their mission is different from ours and not all of their analysis applies to exposure to fire smoke.

The following contributed to the extrapolation:

- Since the incapacitating exposure to fire smoke is about half the lethal exposure whether dealing with pure narcotic gases or the complex mix of gases in the smoke fiom a burning product, we assumed that the factor of two holds for irritant gases too.
- We assumed that the toxic component of the smoke behaved like the sum of a single narcotic gas and a single irritant gas, CO and HCl.
- In two room-scale studies involving the burning of a halogenated combustible)[19,20], the CO concentration was significantly larger than the acid gas concentration.
- Children (a quite susceptible sub-population) showed symptoms that would impair escape at about 25 % COHb.[21] Using the Peterson-Stewart curves,[22] this appears to result from, *e.g.*, a 30-minute exposure to about half of the median exposure for the rat $LC_{50}$. Therefore, for CO we estimate half the rat $LC_{50}$ as the human $I_C$
- For CO, an exposure time-scaling fit for lethality[23] or AEGL-2 effects[24] is $C^2$ t = constant, where C is the incapacitating concentration for a time interval t. Thus, the (32 ± 18) $g/m^3$ for a 30-minute exposure of rats equates to (45 ± 25) $g/m^3$ for a 15-minute exposure.
- Baboons exposed to 190-17290 ppm of HCl for 5 minutes were able to escape.[25] Exposure to over 16,570 ppm resulted in delayed deaths, but exposures at up to 10,000 ppm for 15 minutes produced no long-term problems.[26]
- There are no citations for relating incapacitation by HCI of the median person to include the sensitive fraction of the human population. The AEGL draft report uses a factor of 3 for this.[27] This translates to about 3500 ppm for up to 15 minutes. Upper respiratory tract irritation effects are not exposure time dependent. Experiments with rats had found a 30-

minute $LC_{50}$ for exposure to HCI of about 3700 g/m³. Therefore, for HCl we can use the rat $LC_{50}$ as the human $IC_{sens}$.

- Thus, the estimated human $IC_{sens}$ values for CO and HCl are comparable for 15-minute exposures.
- For materials and products that do not generate strong acid gases, we assume that CO (as a surrogate for asphyxiants) is the primary toxicant and use half the rat $LC_{50}$ as the human $IC_{sens}$. For materials and products that do generate strong acid gases, narcotic gases account for the majority of the total incapacitating effect. Since the $IC_{sens}$ values for the two are comparable, using one third of the rat $LC_{50}$ as the human $IC_{sens}$ accommodates the additional effect of the irritants. We estimate that the uncertainty in these conclusions is within a factor of two.

In summary, combining this result with the generic 15-minute $LC_{50}$ value for rats (above), an estimated generic value for the concentration that will incapacitate smoke-sensitive people in 15 minutes ($IC_{sens}$) is **15** g/m³. The uncertainty in this estimate is about a factor of three.

## D. Generation and Transport of Smoke Components

Smoke is a mixture of gases and aerosols. The latter include both micro-droplets formed from condensed organic vapors and highly carbonaceous agglomerated structures (soot) consisting of hundreds or thousands of nearly spherical primary particles. A range of adverse health effects is associated with inhalation of smoke aerosols, depending on the amount and location of their deposition within the respiratory tract. The depth of penetration into the lungs and the likelihood of being exhaled depend on the particle size, and the degree of damage at a given site depends on the quantity of particles deposited there, which is related in turn to the concentration of smoke aerosol in the inhaled air.

**1.** Initial Character. The size distribution of soot particles produced in a fire is skewed toward the larger particle sizes. For the purpose of assessing health risk due to deposition in the respiratory tract, the most appropriate measure of size is the aerodynamic diameter, the diameter of a unit density (1 g/cm³) sphere having the same aerodynamic properties as the particle in question. The relationship to the physical size of an agglomerate is not straightfcrward. Particle sizes are generally smaller for flaming combustion than non-flaming, with mass median aerodynamic diameters around 0.5 μm for the former and from 0.8 μm to 2.0 μm for the latter.

Smoke yield, the mass of smoke generated for a given mass of fuel burned, varies from near zero to 30% of the fuel mass. Flaming combustion of wood is at the low end of this scale and aromatic fuels are at the high end. The smoke yields under non-flaming conditions considerably exceed those for flaming combustion. In general, smoke yield increases moderately with increasing fuel size. Underventilated fires usually yield more soot due to reduced oxidation.

**2.** Smoke Evolution.

Surface ***Deposition.*** Should there be significant loss of smoke components at surfaces, the tenability of the fire environment could increase. There are three processes that can lead to wall losses of particles: sedimentation, particle diffision in the boundary layer region to the surface, and thermophoretic deposition from hot smoke near a cooler surface. Generally, loss from thermophoresis is most important, except for sedimentation of the largest particle sizes. We estimate that about 10 % to 30 % of the particulates would be deposited over a period of 10 min to 30 min for a fire in a building. The deposition over a long period could also be larger if there is very little flow into the enclosure/building.

The only quantitative data for gas loss at surfaces is for HCI, although it is likely that the other halogen acids would behave similarly. A five-parameter model can predict the adsorption of HCl vapor on a variety of surfaces to within 20 %.[28] Data from multi-room experiments showed 15 % of the HCl deposited on walls for a 200 kW fire, 25 % for a 50 kW fire, and 60 % to 85 % for a 10 kW fire.[29,30] Losses for less polar or less water soluble toxicants are expected to be no larger than these.

***Coagulation.*** The particle size distribution could also change as a result of particles colliding and sticking. We estimate that there will be at most modest changes in the mass median aerodynamic diameter as a result of coagulation for an enclosure fire. This is based on a limited data set for a single fuel burning at a fixed heat release rate; more diverse data would help. The coagulation process may, however, greatly reduce the concentration of very small particles in the range 10 nm to 40 nm. (See below.)

***Adsorption and Desorption of Toxic* Gases.** It is important to know which toxic gases are likely to be carried on the aerosols and how much is transported to and deposited in the lungs. Qualitatively, it is known that:

- Gases may adhere by chemisorption (formation of a true chemical bond) and physisorption (controlled by weaker electrostatic forces). Physisorption is reversible and occurs over a much more rapid times scale than chemisorption. Only physisorbed molecules are desorbed in the lungs after transport there by smoke particles.
- The surface chemistry and pore structure of the soot affect the types and masses of molecules that are adsorbed.
- The nature of the gas molecules also plays a role. Aromatic molecules, such as benzene and toluene, are favored for adsorption because of their structural similarity to the graphitic soot. Polar molecules (*e.g.*, $H_2O$, HF, HCl, HBr, CO, $NH_3$, NO, and HCHO) and paramagnetic molecules (*e.g.*, $O_2$, $NO_2$, and NO) can be adsorbed due to local acidic sites.
- Especially important is the adsorption of water molecules onto the surface. The more $H_2O$ molecules adsorbed, the stronger is the surface attraction toward additional $H_2O$ molecules. Eventually, the surface can look like a droplet to nearby gases, and solubility functions take over. Since the fire produces significant water vapor, the surfaces of the particles are likely wet to some significant degree.

However, there is little quantitative information regarding the transport on particles of sufficient mass of noxious molecules to cause toxicological effects, most of which is for HCl:

- 0.7 % of the chlorine from combusted PVC was physisorbed on soot, about 20 mg of HCl per gram of soot.” Each particle was coated to 1.5 monolayers. This thick coating is best explained by adsorption by the soot of water vapor and HCl together. The authors estimated that over an exposure time of 1 hour, the amount of HCl retained in the lower lungs would be 13 mg. Their soot density was very high, and a more likely concentration would result in a deposition of about 2 mg of HCl per hour. Inhalation of smoke and gases from a fire containing halogenated products is therefore expected to result in transport of a small amount of HCl deeply into the lungs by small soot particles in addition to significant irritation to the upper respiratory tract from HCl gas.
- Since HCl gas is highly water-soluble, it could also attach to small water droplets in addition to soot for transport deeply into the lungs. Water droplets of 3 $\mu$m or less in diameter are estimated to be nine times as effective as soot in transporting HCl into the lungs.” Our reanalysis of the data indicates a relative effectiveness of about 65 times greater. This estimation should hold for the transport of the analogous halogen acids (HBr and HF) and any other combustion products with high polarity and high solubility in water.
- Similar work on HCN transport indicated that negligible HCN was carried on the water droplets and thus water aerosol transport of HCN into the lungs is not a strong concern.[33]

*Ultrafine Particles.* There is evidence that even non-toxic particles of diameter about **20** nm can cause inflammation in the respiratory system, a response not seen with particles about **250** nm in diameter. For ultrafine particles with intrinsic toxicity, the cell damage and release of inflammatory mediators is much greater than for larger particles.

Under certain laboratory conditions, the toxic vapors from combustion of perfluoropolymers were found to be have toxic potency values up to a thousand times those of the smoke from other materials. Experiments[34] pointed to superfine particles as the active species. As the aerosol ages, or in the presence of a dense particle concentration, thermal coagulation of these primary particles causes the formation of much larger aggregates, and the high toxicity is eliminated.

## IV. SUMMARY

**Important fire scenarios:**

- Far more people are exposed to fire smoke than are suffering consequences, either immediate to the tire 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.
- Computer simulations show that in pre-flashover flaming fires, incapacitation from smoke inhalation rarely occurs before incapacitation from heat and thermal radiation or escape or rescue. These occurrences of incapacitation from smoke occur remote from the room of fire origin at times long after ignition. It had been previously **known** that for post-flashover fires, lethal or incapacitating exposures could precede intolerable thermal conditions in rooms remote from the fire room.
- **Thus,** the flaming fire scenarios for which sublethal smoke exposures are of most concern are those for which flashover occurs and in which people do not escape or cannot be rescued promptly.

**Guidance for calculating toxic hazard:**

- The toxic potency of smoke, 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 minutes (IC) 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** minutes, a reasonable scaling function is $(IC)^2\ t = \text{constant}$.
- For the large fires of most consequence, there is little change in the nature of the smoke as one moves hrther 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 and
- the relationships between smoke exposure and escape behavior.

## V. REFERENCES


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