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International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS): Phase I Final Report

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ABSTRACT

Fire smoke toxicity has been a recurring theme for fire safety professionals for over four decades. There especially continue to be difficulty and controversy in assessing and addressing the contribution of the sublethal effects of smoke in hazard and risk analyses. The Fire Protection Research Foundation (FPRF), the National Institute of Standards and Technology (NIST), and NFPA have begun a private/public fire research initiative, the "International Study of the Sublethal Effects of Fire Smoke on Survival and Health" (SEFS) to provide scientific information on these effects for public policy makers. This report on the first phase of the project estimates the magnitude and impact of sublethal exposures to fire smoke on the U.S. population, provides the best available lethal and incapacitating toxic potency values for the smoke from commercial products, determines the potential for various sizes of fires to produce smoke yields that could result in sublethal health effects, and provides state-of-the-art information on the production of the condensed components of smoke from fires and their evolutionary changes during transport from the fire.

Keywords: fire, fire research, smoke, toxicity, toxic hazards

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EXECUTIVE SUMMARY

I. INTRODUCTION

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, most U.S. fire victims succumb to smoke inhalation, 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 *exposure* a person experiences to the (changing) smoke concentration and thermal stress over the time they are in the vicinity of the fire. Some of the effects of smoke increase with continued exposure, others occur almost instantaneously.

Lethality is the most immediate effect smoke can have on occupants or on fire service personnel responding to the fire, and the U.S. has a standard for measuring the lethal toxic potency of smoke from burning products for use in hazard and risk analyses. Tools like HAZARD I, a widely used PC-based fire hazard assessment methodology, enable predicting the life safety outcome of a given fire. The Fire Protection Research Foundation has developed a method for calculating fire lethality risk by combining scenario analysis with hazard analysis.

There have also been anecdotal reports from fire survivors telling how smoke and heat impeded their progress toward exits, caused 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 (beyond that from the flames themselves), reduced motor capability, and visual obscuration; choice of a longer egress path due to, *e.g.*, decreased mental acuity and visual obscuration; and chronic health effects on fire fighters.

There continue to be difficulty and controversy in assessing and addressing the contribution of these sublethal effects of smoke in hazard and risk analyses. 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 resolution, inconsistent representation in the marketplace, and continuing liability concerns.

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. Erring on the conservative side could inappropriately bias the distribution and regulation 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), the National Institute of Standards and Technology (NIST), and NFPA began a major private/public fire research initiative to provide scientific guidance 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 would be on incapacitation (inability to effect one's own escape), since it is the most serious sublethal effect and since there is more quantitative information on this effect than the other sublethal effects. The first phase of the research included 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 phase 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 (incapacitating) to 1/100 (very low harm potential) of those that result in lethal exposures in selected scenarios.

III. PHASE ONE ACCOMPLISHMENTS

A. 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. These 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.

[*] 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.

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 occurred. This approach would not, however, capture those scenarios in which people receive sublethal exposures to smoke that result in adverse health effects or from which their survival was made more difficult.

The entire 280 million citizens of the United States spend much of their time in residential, commercial or transportation occupancies, and annually only 110,000 (residents 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 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.

   Based on analyses of demographic and fire incidence data, we estimated that between 310,000 and 670,000 people (excluding firefighters) 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 civilian fire injuries per year 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. It is unlikely that these high ratios are due to unreported injuries from reported fires, since the last national survey of unreported fires indicates these injuries are mostly burns from small cooking fires. It seems more likely that most of the exposures are brief or are to the dilute smoke that is present outside the room of fire origin, where most survivors are located, and do not result in any noticeable consequences, let alone injury or death.

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 that 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.

   Our analysis indicates that roughly half of the deaths and roughly two-thirds of the injuries could be prevented were the times to incapacitating exposures lengthened sufficiently to result in a more favorable outcome. Many of these savable victims were asleep when fatally injured and could have gained the necessary additional time to escape had they been awakened, *e.g.*, by an operational smoke alarm, but would not likely have gained any additional usable time through changes to the fire timeline alone.

B. CHARACTERISTICS OF FIRE SCENARIOS IN WHICH SUBLETHAL EFFECTS ARE IMPORTANT

A second effort led to further 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 zone fire model. These predicted the relative times at which smoke inhalation and heat exposure would result in incapacitation. Fires in three building types were modeled: a ranch house, a hotel, and an office building. Gas species yields and rates of heat release for these design fires were derived from real-scale fire test data. The incapacitation equations were taken from draft 14 of ISO document 13571. Sublethal effects of smoke were deemed important when incapacitation from smoke inhalation occurred before harm from thermal effects occurred. The rare real-scale HCl yield data were incorporated as appropriate; the modeling indicated that the yield would need to be 5 to 10 times higher if incapacitation from HCl were to precede incapacitation from narcotic gases.

Post-flashover fires were known to result in both lethal and sublethal smoke exposures and thus were not examined further. In the current series of simulations, the fires ranged from a small smoldering fire to those having a peak heat release rate of 90 % of the value necessary for room flashover. The doors to the fire room ranged from open to nearly shut.

The results suggest that occupancies in which sublethal effects from open fires could affect escape and survival include multi-room residences, medical facilities, schools, and correctional facilities. In addition, fires originating in concealed spaces in any occupancy pose such a threat.

Sublethal effects of smoke are not likely to be of prime concern for open fires in single- or two-compartment occupancies (*e.g.*, small apartments and transportation vehicles) themselves, although sublethal effects may be important in adjacent spaces; buildings with high ceilings and large rooms (*e.g.*, warehouses, mercantile); and occupancies in which fires will be detected promptly and from which escape or rescue will occur within a few minutes.

C. TOXIC POTENCY VALUES FOR MATERIALS AND PRODUCTS

To calculate the toxicity component of a fire hazard or risk analysis, the practitioner needs to know the amount of smoke that will produce particular 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 attempts to simulate 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 in half of the animals in a given exposure time. We examined that wealth of data and sorted them by the combustion conditions (related to a type of fire) producing the smoke, the specimens tested, and the animal effect measured. Analysis of published data on the effects of gases, singly or in combination, on test animals or people is to be performed in a future project.

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).
- All the combustors in the 12 small-scale apparatus for which animal exposure data were available were of just 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).
- We assessed the combustion conditions represented in the devices using [CO_2]/[CO] ratios, analysis of the air access to the sample, and autoignition temperatures of the samples. None of these approaches led to successful identification of a specific combustion condition for most of the tube furnaces, and thus most of those data were not used in this analysis.
- Only one of the devices had been validated against room-scale test data. None of the devices accurately replicated true smoldering combustion.

Materials and Products Examined. Very few references provided a detailed composition of the test specimens. We grouped the fuels in the usable reports into generic classes as follows: acrylonitrile butadiene styrenes, bismaleimide, carpet foam (with nylon), carpet jute backing (with nylon), chlorofluoropolymers, epoxy, vinyl fabric, fluoropolymers, modacrylics, phenolic resins, polyesters, polyester fabric/polyurethane foams, polyethylenes, polyphenylene oxide, 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.

Test Animals. After setting aside much of the tube furnace data as not clearly replicating any of the relevant combustion conditions in fires, 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.

The data showed a wide range of smoke toxic potency values for the materials and products tested. For a given combustible, any possible difference in lethal or incapacitating toxic potency between the smoke from the different combustion modes was masked by the uncertainties in the reported test results.

There are instances where the mix of combustibles is unknown and a generic value of smoke toxic potency is desired for a hazard analysis. Statistical analysis of the LC_{50} values for all materials generated a value of 30 g/m^3 $\pm$ 20 g/m^3 (one standard deviation) for 30 minute exposures of rats for pre-flashover smoke. For post-flashover fires, a value of 15 g/m^3 $\pm$ 5 g/m^3 is suggested. The mean value of the ratios of IC_{50} values to LC_{50} values is 0.50 $\pm$ 0.21, consistent with a prior review.

For pre-flashover fires, a generic 30 minute IC_{50} value (for rats) would be 15 $g/m^3 \pm 10\ g/m^3$; for post-flashover fires, the corresponding number would be 7 $g/m^3 \pm 2\ g/m^3$. It is important to note that there are some materials with appreciably lower potency values, indicating higher smoke toxicity. If materials like these are expected to comprise a large fraction of the fuel load, a lower generic value can be used.

Our objective is to estimate conditions of safety for *people*, including those who 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. Nonetheless, making a number of assumptions, we estimate that the values for the concentration of smoke that would incapacitate smoke-sensitive people in 5 min would be 6 g/m^3 for a well-ventilated fire and 3 g/m^3 for a post-flashover fire. [This increase in toxic potency after flashover results from the sharp increase in carbon monoxide yield during underventilated burning.] Both numbers have an estimated uncertainty of a factor of two. The user of these values needs to be mindful that there is a wide range of smoke toxic potency values reported for various materials and that some of these have significantly higher or lower values than these generic figures.

D. GENERATION AND TRANSPORT OF SMOKE COMPONENTS

Smoke is a mixture of gases and aerosols. The latter include both micro-droplets and 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; the degree of damage depends on the quantity of particles deposited, which is related in turn to the concentration of smoke aerosol in the inhaled air.

1. Initial Character. Most soot particles are sufficiently small to pose a respiratory hazard. Particle sizes are generally smaller for flaming combustion than non-flaming, with mass median aerodynamic diameters *ca.* 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. 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 would decrease less rapidly. Generally thermophoretic deposition from hot smoke near a cooler surface is the most important loss mechanism, 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 only quantitative data for gas loss at surfaces is for HCl, although it is likely that the other halogen acids would behave similarly. 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. 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. However, the number of very small particles in the range 10 nm to 40 nm may decrease significantly. There is evidence that ultrafine particles (diameters about 20 nm) can cause inflammation in the respiratory system, a response not seen with larger particles.

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). Only physisorbed molecules are desorbed in the lungs after transport there by smoke particles.
- 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 at local acidic sites.
- The adsorption of water molecules onto the surface enhances the adsorption of polar gases. Since the fire produces significant water vapor, the surfaces of the particles are likely wet to some significant degree.

There is little quantitative information regarding the transport on particles of sufficient mass of noxious molecules to cause toxicological effects; most of this is for HCl. From literature data, we estimate that over an exposure time of 1 hour, about 2 mg of HCl would be deposited in the lower lungs by soot. Small water droplets are estimated to be 65 times as effective as soot in transporting HCl into the lungs. This should also hold for the transport of 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.

IV. RESEARCH NEEDS

These findings suggest that key 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 physiological effects of smoke exposure and escape behavior.

Additional areas needing further research to improve the quality of fire hazard and risk assessments are:

- enhanced information on the subsequent health of people exposed to fires;
- time-dependent yield data for typical fire-generated gases, especially irritant gases, from room-scale fires;

- toxic potency data for rats for smoke from a wide range of materials and products obtained using a validated bench-scale apparatus;
- quantitative information on the losses of toxicants for a range of realistic fires;
- identification of whether nanometer smoke aerosol can be generated in realistic fire scenarios; and
- determination of whether a cloud of water droplets forms during a fire and, if so, the conditions under which it may form and the size distribution of the droplets.

I. INTRODUCTION: THE HAZARD OF FIRE SMOKE

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, a fraction which has been generally increasing for at least two decades;[1] 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 (often expressed as an EC_{50}, the **c**oncentration needed to cause an **e**ffect on half (**50** %) 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 almost instantaneously.

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.

A. SMOKE LETHALITY

Of the effects that smoke can have on occupants or on fire service personnel responding to the fire, the most severe is the loss of life. This has driven the development, validation and adoption of a standard laboratory-scale device (NFPA 269[2], ASTM E1678[3]) for measuring the lethal toxic potency of smoke form burning products for use in hazard and risk analyses.

The capability of fire safety professionals to estimate potentially lethal smoke exposures has developed extensively over the past decade. Tools like HAZARD I enable combining all the above factors and predicting the outcome of a given fire. The EXITT routine in HAZARD I, EXIT 89[4] and EXODUS[5], for example, offer the ability to simulate people movement through a burning facility. The Fire Protection Research Foundation has developed a method for calculating fire risk by combining scenario analysis with hazard analysis.[6]

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 (a) when the analyses are performed by knowledgeable people and (b) when there are proper input data for the calculations.

B. 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 (beyond that from the flames themselves)
  - reduced motor capability
  - visual obscuration
  - decreased mental acuity
- long-term physiological effects
- chronic health effects on fire fighters.

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. These result from:

- 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, and even though there are many factors, unrelated to products, that affect the conversion of toxic smoke yield at the site of the burning product into toxic smoke exposure at the site of 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 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 misusing toxicity data 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 resolution, inconsistent or inaccurate representation in the marketplace, and continuing liability concerns.

C. 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, defined as 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 fire size that would be impossible to achieve in practice. When this became broadly recognized, the document was voted down and drafted as a candidate ISO Technical Specification. The ensuing drafts of ISO 13571 have moderated the constraints on smoke toxic potency, while retaining the basic concept of toxic effects resulting from accumulated fractional effective dose (FED) or concentration (FEC).

D. 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 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 and the National Institute of Standards and Technology began a major private/public fire research initiative to provide this scientific information for public policy makers. The 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.

To meet these objectives, the project team and the Technical Advisory Committee constructed a set of tasks (Table 1).

Table 1. Research Tasks for the International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS)

1.0. Toxicological Data
1.1. Report on evaluation of literature values of LC_{50}, IC_{50} and EC_{50} for products and materials, adapted for human exposures, and with generic values for use in hazard analysis.
1.2. Review the existing data on the relationships between *lethality* and exposure to heat, thermal radiation, narcotic gases, irritant gases, aerosols, and their combinations for animal species and humans; identify the best such relationships (including from non-fire literature) and determine uncertainty bars
1.3. Review the existing data on the relationships between *sublethal physiological effects* and exposure to heat, thermal radiation, narcotic gases, irritant gases, aerosols, and their combinations for animal species and humans; identify the best such relationships (including from non-fire literature) and determine uncertainty bars
1.3a. Review the literature on the relative penetration into the lungs of gases and aerosols of differing dimension
1.3b. Review the data on distribution of people's susceptibility as a function of age, physical condition, etc.
1.4. Examine the methods for quantitative extrapolation of the animal data to people, and estimate the associated uncertainty levels
1.5. Lay out means to obtain more/better data without using human subjects.

1.6. Fully documented report on the best data relating combustion products and physiological effects (temporary and lingering) on people.
2.0. Smoke Transport Data
2.1. Review the literature on the dimension of aerosols produced in fires.
2.2. Review the literature on the wall losses, agglomeration, and chemical reaction of gases and aerosols as the smoke moves (from the fire)
2.3. Review the literature on and models of the solubility in and evaporation from aqueous aerosols of toxic gases in the humid fire effluent
2.4. Report on the generation and evolution of aerosols of potential toxicological concern.
3.0. Behavioral Data
3.1. Select contractor(s)
3.2. Review the relationships between physiological effects and impairment of human escape, especially from irritant gases and including smoke obscuration and subsets of the population who are more susceptible or less able to react to fire-generated smoke
3.3. Appraise methods for extrapolating such effects in animals to people and estimate the uncertainty levels
3.4. Lay out means to obtain more/better data without using human subjects
3.5. Report on magnitude of sublethal exposures that compromise survival
3.6. Decision: Do sublethal exposures to smoke result in impeded escape?
4.0. Fire Data
4.1. Review data from reports on fires, on chemical exposures, from hospitals, etc. to characterize our ability to determine quantitatively (with uncertainty assessment) the importance of sublethal exposures on escape, survival, and health
4.2. Estimate the magnitude of the importance (relative to lethality) of sublethal exposures, with uncertainty bars
4.3. Identify ways to improve future gathering of case and epidemiological data
4.4. Report estimating the hazard of sublethal exposures to smoke relative to lethal exposures by fire scenario

5.0. Risk Calculations
5.1. Compile a "full" list of fire scenarios; based on past fire risk analyses, identify those fire scenarios for which significant incidence data exist
5.2. Compilation of primary intervention strategies that would mitigate the outcome of fire and accompanying casualties
5.3. Decision on scenarios for which to perform calculations and case studies
5.4. Perform calculations to estimate the decreased chance of escape and survival in these fire scenarios when people are exposed to sublethal levels of smoke
5.5. Verify calculations, to the extent possible, using the data from Task 4 or from specific fires where the exposure information can be inferred
5.6. Report on calculated increased risk from sublethal smoke exposures for predominant fire scenarios
6.0. Product Characterization
6.1. Characterize the fire types (*e.g.,* smoldering, ventilated flaming) and sizes (e.g., single object, spread to successive objects) that can produce exposures within 1/100 of lethal exposures; compare with smoke yields from wanted *(e.g.,* cooking) fires
6.2. Develop accurate reduced-scale measurement methodology for obtaining smoke (component) yield data for commercial products; generate data for generic products
6.3. Develop methodology for including sublethal exposures in fire safety analysis
7.0. Societal Analysis
7.1. Develop a method and case studies for projecting the enhancements of public safety and the costs/benefits to society that would accrue from the inclusion of exposure to sublethal levels of smoke in design specifications
8.0. Dissemination
8.1. Compile reference document(s) for the subject
8.2. Archive the research findings
8.3. Prepare practical guidance sheets for decision makers, based on the existing literature and the Project outcome, and delineating the relative importance of lethal and varying levels of debilitating smoke exposures; identify means of dissemination (web, flyers, etc.)

The timeliness of the project was a significant issue. The project team estimated that completing all the tasks could take as little as 30 months. This afforded the opportunity to provide a sound technical basis for emerging domestic and international standards.

However, the full resources were not yet available. Thus the sponsors and project team agreed that the first Phase would focus 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. This would ensure having useful output early in the project.

The first phase of the research began in May 2000 with 5 tasks or subtasks:

- **Task 1a (1.1 in Table 1): Toxicological Data for Products and Materials:** provide decision-makers with the best available lethal and incapacitating toxic potency values for the smoke from materials and commercial products for use in quantifying the effects of smoke on people's survival in fires.
- **Task 2: Smoke Transport Data:** 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.
- **Task 4: Incidence Analysis of Sublethal Effects:** 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.
- **Task 5a (5.1 & 5.2 from Table 1): Scenarios for Fire Risk Calculations:** 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.
- **Task 6a (6.1 from Table 1): Characterization of Fire Types:** 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.

These tasks comprise the effort needed to accomplish the first objective of the project and to begin the second objective. Completion of the tasks in the first phase of the SEFS project has provided the context for the tasks to come, indicated the capabilities and limitations of currently available information, and generated useful products in its own right. The remainder of this report describes what we have learned from these tasks and the value of that knowledge.

III. PHASE ONE ACCOMPLISHMENTS

A. DEFINITION OF FIRE SCENARIOS

Both current prescriptive fire and building codes and the emerging performance-based fire and building codes utilize a form of hazard or risk assessment. In the former, neither the safety objective nor the improvement derived from a code change is explicit. Rather, the code body implicitly recognizes there is cumulative benefit from each product or design specification. If the benefit proves insufficient or if new hazards are identified, additional specific code changes are considered. In the latter, the safety objective of each section of the code is explicit. The facility designer is given wide latitude in selecting a combination of features to meet that objective. A hazard or risk analysis incorporating the properties of the facility and its contents is then performed to demonstrate that the safety objective will be met.

What the two approaches have in common is that they both operate on a set of fire scenarios. A fire scenario is a detailed description of:

- the facility[†] in which the fire occurs, including the occupancy type (Table 2), its geometry and topology, potential escape routes and places of refuge, and any installed fire mitigation devices (Table 3);
- the combustible products potentially involved in the fire (Table 4);
- a specific fire incident, comprising an ignition event (type and location), the involvement of one or more combustible products at some rate of fire growth and heat and smoke production, various stages of fire development (Table 5), the eventual extent of the fire;
- the people occupying the facility at the time of the fire, including the types of people normally in the facility, their ages, their physical capabilities, their sensitivities to smoke and heat, and their locations relative to the fire.

There are interactions between each of these components, *e.g.*, different types of people will be exposed to fires of differing growth rate from different combustibles in different facilities. Thus, there are large numbers of combinations of these factors. Presumably, the sublethal (and lethal) effects of fire smoke are important in some fraction of these. It is tempting to identify this subset by focussing on those scenarios for which the largest fractions of fire deaths and injuries have occurred to date. That would certainly capture 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:[7,8]

- 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;
- 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.

[†] 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.

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, but not unsuccessful. The next two sections provide insights into identifying those scenarios in which sublethal effects of fire smoke might be important.

Table 2. Classification of Facilities

[The following classification scheme, taken from the NFPA Life Safety Code[9], groups facilities according to their common usage. Implied in this classification are a number of factors related to use, the typical fuel load, and consideration of egress. Other factors, such as specific occupancy populations, must be considered as well.]

Buildings	Vehicles
Residences (single- or multiple family) Hospitals Nursing homes Board and care buildings Office buildings Day care facilities Stadiums and large recreational facilities Industrial (warehouses) Industrial (high hazard) Schools Detention/correctional facilities Mercantile	Automobiles and trucks Buses Passenger rail vehicles Urban mass transit vehicles Aircraft Spacecraft

Table 3. Fire Hazard Mitigation Strategies and Examples

Active	Passive
Suppression system (water deluge, water mist, halon, dry powder, carbon dioxide) Cooling devices (fog nozzles) Smoke exhaust system (whole building, stairwell, roof vent) Detectors (automatic or manual, monitored or not) Pressurization (compartments, elevators) Evacuation aids (emergency lights) Automatic door closure	Barriers (fixed walls, draft curtains) Low flammability materials (interior finish, cable, furnishings)

Table 4. Potential Residential Combustibles

Combustible Class	Typical Fire Growth Rate
Upholstered furniture	Medium to fast
Wood furniture	Slow
Wardrobes (with clothes)	Medium to fast
Mattresses/bedding	Medium to fast
Kitchen cabinets	Slow
Interior finish	Medium to fast
Cooking materials (*e.g.*, oil)	Fast
Paper trash	Fast

Table 5. Stages of Fire Development

Fire Stage	Characteristics
1. Non-Flaming	
1.1. Smoldering	Self-sustaining; no external radiation
1.2. Oxidative pyrolysis	Fuel subjected to thermal radiation or in contact with a hot object
1.3. Non-oxidative pyrolysis	Pyrolysis in a space so highly vitiated that no oxygen reaches the fuel surface
2. Well Ventilated Flaming	Flames below the base of hot gas layer Burning rate is fuel controlled
3. Low Ventilated Flaming	Flames extend into the hot gas layer Burning rate is ventilation controlled
3.1. Small fire in closed compartment	Air flow into the room or concealed space is well below that needed to replace the consumed oxygen
3.2. Post-flashover fire	

B. IMPORTANCE OF SUBLETHAL EXPOSURES

Essentially the entire 280 million citizens of the United States spend much of their time in the facilities listed in the previous Section. Of these, we know of about three hundredths of one percent (civilians and fire fighters) who suffer a serious or fatal injury in a fire. In order to assess the importance of the sublethal effects of fire smoke, it is incumbent to have estimates for the following two pivotal questions:

1. How many people might receive sublethal exposures to fire smoke of any consequence? It is possible to estimate the number of people each year that probably shared space with some quantity of toxic smoke from a reported home 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. [These low thresholds might assure the avoidance of lesser or delayed injuries, even by smoke-sensitive people. However, using such thresholds in a hazard assessment that as a result predicts an unrealistically large number of injuries is of little value to responsible decision makers, who must provide for safety without other undue restrictions on the public.] And knowing the magnitude of the population exposed to fire smoke would be a first step in a risk assessment (*e.g.*, of proposed code provisions or new products) where the heightened sensitivity of vulnerable subpopulations would be balanced in calculations by explicit use of the probabilities that those people will be the ones exposed in any particular fire.

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 (a) fire fatalities often result from incapacitating injuries that occur earlier and from less severe fire exposures than do fatal injuries and that (b) 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.

1. Statistical Methodology

It had been hoped that databases other than those currently used to estimate the U.S. fire experience would contain sufficient detail on incident and exposure circumstances to develop answers to these two questions. However, based on discussions with people familiar with these compilations, most were not likely to be helpful for our purpose. For instance:

- The Federal agencies responsible for airline safety prepare detailed reports after fatal incidents, including timelines of human behavior and autopsy data on toxic exposure. Unfortunately, they do not include details of non-fatal injuries.
- The National Electronic Injury Surveillance System (NEISS) hospital emergency room injury database, operated by the U.S. Consumer Product Safety Commission, is the most potentially useful database on non-fatal fire injuries. They do not, however, include even the E-coding used on death certificates, which is necessary to achieve even a simple separation of smoke inhalation from other injuries.
- NFPA has a major fires database called the Fire Incident Data Organization (FIDO). It has more solidly based detail than any other national fire incident data base, but its typical level of detail is still limited, and the data base itself is representative in most

years only for multiple-fatality or other unusually large fires. Recently, FIDO was expanded to attempt to capture all fatal fires for two years, and it was hoped that there would be a number of incidents in which timelines of occupant movement could be constructed, permitting estimation of exposure as a function of fire size, smoke extent, and occupant location. This could then be linked to the reported health status of the occupants: fatally injured, non-fatally injured, or uninjured. While the degree of detail in the reports was too low to accomplish this, FIDO does provide insight into the victim's condition like "unable to act" or "rescuing," and these victim condition codes are also used in representative national data bases, *e.g.*, the National Fire Incident Reporting System (NFIRS). By indicating in some detail what people do in responding to fires that is then generically described by one of the brief coding phrases, FIDO supported some estimates of the timeline of exposure for those victims and the criticality of incapacitation in that timeline.

The components used to estimate the number of people exposed to fire smoke annually were as follows:

- Use was made of some occupant location sets developed for the FPRF fire risk analysis method *FRAMEworks*.[6] These sets translated 1980 U.S. Census Bureau data on typical occupant activity by household structure, age and ability of person within the household, and time of day, into estimated assignments of typical occupant locations by household structure, age and ability of person, and time of day.
- While there have been changes in the mix of population characteristics since 1980, the changes have been gradual and would not significantly affect the analysis. For example, in 1980 11.3 % of the resident U.S. population was at least 65 years old, while by 1998, the share had risen to 12.7 %. Even if all the people shown as injured in the calculation were elderly, this would only increase the estimate of people exposed to injurious smoke by about 13 %. Increases in the estimate of people exposed to smoke strengthen the conclusions.
- Other 1980 U.S. Census Bureau data provided estimates of numbers of households by household structure.
- U.S. fire incident data supported the development of 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, high and low estimates were made of numbers of people exposed, based on matching the locations of people, by time of day, with the number of fires either originating where they were located or spreading from their points of origin to the individuals' locations.

For the analysis of the role of incapacitation in creating an extended time of exposure to fire smoke, the characteristics of fatal fire victims, especially their activity at the time of injury, were culled from FIDO reports. An escaping victim, knocked down in flight by incapacitating smoke, exemplified the critical role of incapacitation in creating lethal exposure. By contrast, for a bedridden individual incapacitation by the smoke would be relatively unimportant, since the individual could do nothing to save himself or herself and would be exposed to as much smoke as the fire could move to him or her, absent a rescue.

2. Estimating the U.S. Population Annually Exposed to Smoke from Unwanted Fires

Table 6 provides the number of U.S. households, by structure, for non-family and family households.[10] Household structure is defined by the number of people (up to a maximum size of 5 or more, which is treated as 5), the number of adults (a "non-family" household does not include children), the number of adults who are elderly (at least 65 years old), and the number of adults who are non-working. To simplify the set-up, the number of adults who are elderly or non-working is expressed in fractional terms, representing an average across all households with that number of adults and total people. This simplification is possible because all people of a common type share a common fate from a given fire; there is no need to stick to integer numbers of people by type in order to support separate calculation of the fates of each one.

The analysis here (and in Tables 7-18) differs from the published analysis in that the published exercise had to create occupant sets with integer numbers of persons by type, while this exercise can work with fractional numbers of persons, overall and by type. Also, this and all the succeeding analyses eliminate the separate treatment of incapacitated adults (most of whom are also elderly) and of babies (under 3 years old).

Table 6. Numbers of U.S. Households, by Size of Household, Number of Adults, and Number of Elderly or Other Non-Working Adults[10]

A. Non-family Households [Estimated 30.3 % of adults in non-family households are elderly, and all of the adults of working age are working]

Number of Persons per Household				Number of Households
Persons	**Adults**	**Elderly**	**Non-working adults**	
1	1	0.303	0	20,602
2	2	0.606	0	2,768
3	3	0.909	0	497
4	4	1.212	0	155
5	5	1.515	0	70

B. Family Households (Married Couple and/or Children Present) [Estimated 9.3 % of adults in family households are elderly, 55 % of adults in two-adult families are non-working, and 44 % of single parents are non-working.]

Number of Persons per Household				Number of Households
Persons	**Adults**	**Elderly**	**Non-working adults**	
2	2	0.186	1.10	19,220
2	1	0.093	0.44	6,129
3	2	0.186	1.10	11,346
3	1	0.093	0.44	3,458
4	2	0.186	1.10	11,666
4	1	0.093	0.44	1,601
5	2	0.186	1.10	8,118
5	1	0.093	0.44	1,176

Table 7 translates the entries of Table 6 from numbers of people, by type, per household, by type, into entries on numbers of people, by type, in all households of a particular type. It also provides summary data on the number of people, by type, in an average household. Again, the published analysis treated all households with more than 5 persons as having 5 persons. Tables 7A and 7B are calculated directly from Tables 6A and 6B. Table 7C is calculated directly from Tables 7A and 7B. The data used here are nearly 20 years old, but because they are reduced to numbers of persons, by type, per household, that fact should not create a problem.

Table 7. Total Numbers of U.S. Persons, Elderly, and Non-Working Adults, by Size of Household and Number of Adults in Their Household[10]

A. Non-family Households

Number of Persons per Household		Total Number of Persons in All Households Combined		
Persons	**Adults**	**Persons**	**Elderly**	**Non- working adults**
1	1	20,602	6,242	0
2	2	5,536	1,677	0
3	3	1,491	452	0
4	4	620	188	0
5	5	350	106	0

B. Family Households (Married Couple and/or Children Present)

Number of Persons per Household		Total Number of Persons in All Households Combined		
Persons	Adults	Persons	Elderly	Non- working adults
2	2	38,440	3,575	21,142
2	1	12,258	570	2,697
3	2	34,038	2,110	12,481
3	1	10,374	322	1,522
4	2	46,664	2,170	12,833
4	1	6,404	149	704
5	2	40,590	1,510	8,930
5	1	5,880	109	517

C. Number of Persons, by Type, per Household, Overall Average

People per household	2.57
Elderly persons per household	0.22
Non-working adults per household	0.70

Table 8 indicates the assumed (and most likely) location for a person of a particular type, by time of day, for 3 time of day ranges. There are three candidate locations – bedroom; living room, family room, or den; and outside the building (as when an adult is at work or a child is at school). This analysis eliminates the separate treatment of incapacitated adults (most of whom are also elderly) and of babies (under 3 years old). All other children and working adults have the same assignments and so can be combined. It is further assumed that the room of fire origin, if not otherwise estimated to have anyone occupying it, may have no one or one person present, corresponding to fires whose causes point to someone present at the time and the less frequent fires whose causes do not.

Table 8. Most Likely Locations of U.S. Persons, by Type of Person and Time of Day[10]

Type of Person	During 7 am – 6 pm	During 6 pm – 11 pm	During 11 pm – 7 am
Child or Working adult	Outside building	Living room, family room, or den	Bedroom
Non-working adult	Living room, family room, or den	Living room, family room, or den	Bedroom
Elderly person	Living room, family room, or den	Bedroom	Bedroom

Table 9 uses data from Tables 7 and 8 and two assumptions to indicate, for each of four candidate locations (*i.e.*, type of room) in the home and each of the same three time-of-day ranges, how many of what types of people are in that room, in another room, or outside the building. The four candidate locations are candidate areas of origin for fire: kitchen; bedroom; living room, family room, or den; and any other room or area. The additional assumptions needed are these:

- Notwithstanding the assumptions in Table 8, if fire begins in a room, there is a good chance that someone was there to start the fire, either intentionally or (more often) unintentionally. The range of assumptions regarding the number of people present, if Table 8 would indicate no one present, is 0 to 1, that is, yes, someone is present, or no, someone is not. Since a person present will be, by definition, close to the point of origin of the fire, then person-present will yield a higher estimate of exposed people and person-absent will yield a lower estimate.
- At night, when everyone in the household is assumed to be located in a bedroom, the number of people in any one bedroom will range from one to two. Again, the assumption of two people in the bedroom of fire origin will produce a higher estimate of exposed people, while the assumption of one person will produce a lower estimate.

Table 10 uses the data from Table 8 on average number of people, by type, in an average household, with the entries in Table 9, to produce a range of number of people, without differentiating them by type, based on time of day, who are in the same room, another room, or outside the building, for each of the four possible areas of fire origin.

Table 11 provides the linkage between how far smoke extends and how far away occupants might be affected. Again, ranges are provided. When the extent of smoke ranges from zero up to confined to the room of fire origin, the number of people exposed is estimated to range from no one (zero) up to everyone assumed to be located, when fire begins, in the same room as the room of fire origin. When the extent of smoke ranges from filling the first room up to anything larger, the number of people exposed is estimated to range from everyone located in the same room as the room of fire origin up to everyone located anywhere in the home. Table 11 uses these assumptions with data from the earlier tables to indicate, based on what type of room is the area of fire origin, time of day, and final extent of smoke damage, how many people will be exposed to toxic fire smoke. A fire that spreads smoke through enough of the room of fire origin will expose everyone who is still in that room. A fire that spreads smoke through enough of the housing unit will expose everyone who is still in the room of fire origin and in any other room in the housing unit. People located outside the housing unit will not be exposed, regardless of smoke spread.

Table 9. Numbers of U.S. Persons, by Type of Person and Time of Day, within 3 Exposure Zones – Same Room, Another Room, Outside Building, by Room of Fire Origin[10]

Room of Fire Origin	Who's Located in?	During 7 am – 6 pm	During 6 pm – 11 pm	During 11 pm – 7 am
Kitchen	Same room	0 to 1 person	0 to 1 person	No one
Kitchen	Another room	Non-working adults and elderly	Rest of household	Entire household
Kitchen	Outside building	Rest of household	No one	No one
Bedroom	Same room	0 to 1 person	0 to 1 person	1 to 2 people
Bedroom	Another room	Non-working adults and elderly	Rest of household	Rest of household
Bedroom	Outside building	Rest of household	No one	No one
Living room, family room, den, or associated chimney	Same room	Non-working adults and elderly	Entire household except elderly	No one
Living room, family room, den, or associated chimney	Another room	No one	Elderly	Entire household
Living room, family room, den, or associated chimney	Outside building	Entire household	No one	No one
Other room	Same room	0 to 1 person	0 to 1 person	No one
Other room	Another room	Non-working adults and elderly	Rest of household	Entire household
Other room	Outside building	Rest of household	No one	No one

Table 10. Numbers of U.S. Persons, by Time of Day, in Average Home within 3 Exposure Zones – Same Room, Another Room, Outside Building, by Room of Fire Origin[10]

Room of Fire Origin	How Many Are Located in?	During 7 am – 6 pm	During 6 pm – 11 pm	During 11 pm – 7 am
Kitchen	Same room	0-1	0-1	0
Kitchen	Another room	0.92	1.57-2.57	2.57
Kitchen	Outside building	0.65-1.65	0	0
Bedroom	Same room	0-1	0-1	1-2
Bedroom	Another room	0.92	1.57-2.57	0.57-1.57
Bedroom	Outside building	0.65-1.65	0	0
Living room, family room, den, or associated chimney	Same room	0.92	2.35	0
Living room, family room, den, or associated chimney	Another room	0	0.22	2.57
Living room, family room, den, or associated chimney	Outside building	1.65	0	0
Other room	Same room	0-1	0-1	0
Other room	Another room	0.92	1.57-2.57	2.57
Other room	Outside building	0.65-1.65	0	0

Table 11. Numbers of U.S. Persons Exposed to Smoke, by Time of Day, in Average Home, Based on Extent of Smoke[10]

How Far Must Smoke Extend?	Room of Fire Origin	During 7 am – 6 pm	During 6 pm – 11 pm	During 11 pm – 7 am
Between any smoke and filling first room	Kitchen	0-1	0-1	0
Between smoke past first room and filling housing unit	Kitchen	0.92-1.92	2.57	2.57
Between any smoke and filling first room	Bedroom	0-1	0-1	1-2
Between smoke past first room and filling housing unit	Bedroom	0.92-1.92	2.57	2.57
Between any smoke and filling first room	Living room, family room, den, or associated chimney	0.92	2.35	0
Between smoke past first room and filling housing unit	Living room, family room, den, or associated chimney	0.92	2.57	2.57
Between any smoke and filling first room	Other room	0-1	0-1	0
Between smoke past first room and filling housing unit	Other room	0.92-1.92	2.57	2.57

The simplifying assumptions up to this point are a mix of conservative and non-conservative assumptions. The simplified location assignments will mean more people are assigned locations in a bedroom or living room when a fire starts there than will be there on average, while fewer people are assigned locations near a fire starting anywhere else. The simplified assignments by time of day will indicate more evening exposure of busy people with outside activities than will actually occur, but they miss many of the reasons why people may stay home during the day, as well as the exposure of guests. The simplified maximum limit on household size is entirely conservative, as it will underestimate exposure. The ranges linking exposure to smoke extent will overestimate some exposures, *e.g.*, where people in the room where a fire begins are able to escape with no exposure at all, but underestimate some other exposures, *e.g.*, where people's activities (rescuing, fire fighting, investigating, or escaping by some routes) take them toward the fire rather than away from it. In the end, the authors believe that no major net overestimation or underestimation occurs with these assumptions.

Table 12 provides statistics from recent U.S. fire loss data regarding the number of reported home fires and associated civilian deaths and injuries, by area of fire origin, time of day, and final extent of smoke damage. The numbers of fires can be used with the entries of Table 11 to estimate the range of exposure. The numbers of deaths and non-fatal injuries provide contrasting numbers on the number of exposed people suffering recognized health effects.

Table 12 uses a more detailed breakdown on the final extent of smoke damage, in order to permit additional ranges of effect in the estimation. Fires with smoke damage confined to room of origin are subdivided into fires with smoke damage confined to area of origin (meaning the immediate area around the point of origin but beyond the single object of origin) vs. fires with smoke damage beyond the area of origin but still confined to the room of origin. The former are less likely to expose people in the room of origin; the latter are more likely to cause such exposure. Similarly, fires with smoke damage beyond room of origin are subdivided into fires with smoke damage confined to floor of origin vs. fires with smoke damage beyond floor of origin. The former are less likely to expose people somewhere in the building other than the room of fire origin, while the latter are more likely to do so.

Table 12. Numbers of Reported Fires, Deaths, and Injuries by Area of Fire Origin, Time of Day, and Extent of Smoke Damage Annual Average of 1993-97 Home Structure Fires Reported to Municipal Fire Departments

[Area of Fire Origin: Kitchen; Bedroom; Living room, family room, den or associated chimney; Other room.

Time of day: Day (7 am – 6 pm), Evening (6 pm – 11 pm), or Night (11 pm – 7 am)

Extent of smoke damage: None or confined to Object or area of fire origin; beyond area of origin, but confined to Room of origin; beyond room of origin, but confined to Floor of origin; Beyond floor of origin.]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Fires	Civilian Deaths	Civilian Injuries
K	D	O	27,156	26	645
K	D	R	12,522	11	493
K	D	F	12,597	25	647
K	D	B	22,352	146	1,334
K	E	O	13,765	8	341
K	E	R	6,352	3	262
K	E	F	6,759	8	375
K	E	B	10,944	66	683
K	N	O	5,148	11	141
K	N	R	2,604	3	101
K	N	F	3,378	14	222
K	N	B	7,211	222	695
B	D	O	4,637	13	158
B	D	R	3,565	16	179
B	D	F	5,194	57	482

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Fires	Civilian Deaths	Civilian Injuries
B	D	B	14,984	280	1,544
B	E	O	2,702	5	107
B	E	R	1,961	7	99
B	E	F	2,664	18	212
B	E	B	6,990	130	590
B	N	O	2,228	18	109
B	N	R	1,672	10	99
B	N	F	2,470	52	322
B	N	B	8,120	382	1,087
L	D	O	4,000	16	101
L	D	R	1,632	6	69
L	D	F	1,560	28	150
L	D	B	8,324	313	875
L	E	O	2,713	4	53
L	E	R	1,037	3	45
L	E	F	953	19	75
L	E	B	4,542	157	358
L	N	O	1,882	17	73
L	N	R	924	6	50
L	N	F	1,089	37	157
L	N	B	6,440	567	958
O	D	O	43,179	16	370
O	D	R	10,738	7	189
O	D	F	7,300	15	228
O	D	B	38,367	245	1,573
O	E	O	25,983	10	205
O	E	R	5,772	0	103
O	E	F	3,980	6	110
O	E	B	19,535	121	729
O	N	O	15,243	27	133
O	N	R	4,050	7	84
O	N	F	3,362	19	131
O	N	B	23,350	445	1,417

Table 13 translates all the other tables into estimates of exposed people, by time of day, area of fire origin, and final extent of smoke damage. The several ranges introduced at various points have been reduced to three estimates, called “lowest,” “low,” and “high.” The “lowest” estimate uses the lower numbers for people located at or near the fire and the upper ends of the ranges on how much smoke extent is required to expose people away from the fire (*i.e.*, smoke beyond area of origin is required to expose people in room of fire origin; smoke beyond floor of origin is required to expose people outside room of fire origin). The “low” estimate also uses the lower numbers for people located at or near the fire but uses the lower ends of the ranges of smoke extent needed to expose people. The “high” estimate uses the higher numbers for people located at or near the fire and the lower ends of the ranges of smoke extent needed to expose people.

Table 13. Estimated Number of People Exposed to Smoke in Home Fires by Area of Fire Origin, Time of Day, and Extent of Smoke Damage

[Area of Fire Origin: Kitchen; Bedroom; Living room, family room, den or associated chimney; Other room.

Time of day: Day (7 am – 6 pm), Evening (6 pm – 11 pm), or Night (11 pm – 7 am)

Extent of smoke damage: None or confined to Object or area of fire origin; beyond area of origin, but confined to Room of origin; beyond room of origin, but confined to Floor of origin; Beyond floor of origin.]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Lowest	Low	High
K	D	O	0	0	27,156
K	D	R	0	0	12,522
K	D	F	0	11,589	24,186
K	D	B	20,564	20,564	42,915
K	E	O	0	0	13,765
K	E	R	0	0	6,352
K	E	F	0	17,372	17,372
K	E	B	28,126	28,126	28,126
K	N	O	0	0	0
K	N	R	0	0	0
K	N	F	0	8,682	8,682
K	N	B	18,533	18,533	18,533
B	D	O	0	0	4,637
B	D	R	0	0	3,565
B	D	F	0	4,779	9,973
B	D	B	13,786	13,786	28,770
B	E	O	0	0	2,702
B	E	R	0	0	1,961
B	E	F	0	6,846	6,846
B	E	B	17,964	17,964	17,964
B	N	O	0	2,228	4,456
B	N	R	1,672	1,672	3,344
B	N	F	2,470	6,347	6,347
B	N	B	20,867	20,867	20,867
L	D	O	0	3,680	3,680
L	D	R	1,502	1,502	1,502
L	D	F	1,435	1,435	1,435
L	D	B	7,658	7,658	7,658
L	E	O	0	6,375	6,375
L	E	R	2,438	2,438	2,438
L	E	F	2,239	2,449	2,449
L	E	B	11,672	11,672	11,672
L	N	O	0	0	0
L	N	R	0	0	0
L	N	F	0	2,799	2,799

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Lowest	Low	High
L	N	B	16,550	16,550	16,550
O	D	O	0	0	43,179
O	D	R	0	0	10,738
O	D	F	0	6,716	14,016
O	D	B	35,297	35,297	73,664
O	E	O	0	0	25,983
O	E	R	0	0	5,772
O	E	F	0	10,230	10,230
O	E	B	50,204	50,204	50,204
O	N	O	0	0	0
O	N	R	0	0	0
O	N	F	0	8,640	8,640
O	N	B	60,009	60,009	60,009

Table 14 compares the range of estimates of people exposed to toxic fire smoke to the reported 1993-97 annual average civilian fire deaths and injuries, by area of fire origin, time of day, and final extent of smoke damage. Tables 15-18 present summary statistics from Table 14, showing the grand total as well as breakdowns by one or two of the three variables at a time. Again, the "lowest" estimate uses lower number of people by location and upper range of smoke extent (*i.e.*, smoke beyond area of origin to expose people in room of fire origin; smoke beyond floor of origin to expose people outside room of fire origin). "Low" estimate uses lower number of people by location but lower range of smoke extent needed to expose people. "High" estimate uses higher number of people by location and lower range of smoke extent needed to expose people.

Table 14. Range of Estimated Number of People Exposed to Smoke in Home Fires vs. 1993-97 Average Reported Civilian Fire Deaths and Non-Fatal Injuries, by Area of Fire Origin, Time of Day, and Extent of Smoke Damage

[Area of Fire Origin: Kitchen; Bedroom; Living room, family room, den or associated chimney; Other room.

Time of day: Day (7 am – 6 pm), Evening (6 pm – 11 pm), or Night (11 pm – 7 am)

Extent of smoke damage: None or confined to Object or area of fire origin; beyond area of origin, but confined to Room of origin; beyond room of origin, but confined to Floor of origin; Beyond floor of origin.]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Exposed People	Civilian Deaths	Civilian Injuries
K	D	O	0 – 27,156	26	645
K	D	R	0 – 12,522	11	493
K	D	F	0 – 24,186	25	647
K	D	B	20,564 – 42,915	146	1,334
K	E	O	0 – 13,765	8	341
K	E	R	0 – 6,352	3	262
K	E	F	0 – 17,372	8	375
K	E	B	28,126	66	683
K	N	O	0	11	141
K	N	R	0	3	101
K	N	F	0 – 8,682	14	222
K	N	B	18,533	222	695
B	D	O	0 – 4,637	13	158
B	D	R	0 – 3,565	16	179
B	D	F	0 – 9,973	57	482
B	D	B	13,786 – 28,770	280	1,544
B	E	O	0 – 2,702	5	107
B	E	R	0 – 1,961	7	99
B	E	F	0 – 6,846	18	212
B	E	B	17,964	130	590
B	N	O	0 – 4,456	18	109
B	N	R	1,672 – 3,344	10	99
B	N	F	2,470 – 6,347	52	322
B	N	B	20,867	382	1,087
L	D	O	0 – 3,680	16	101
L	D	R	1,502	6	69
L	D	F	1,435	28	150
L	D	B	7,658	313	875
L	E	O	0 – 6,375	4	53
L	E	R	2,438	3	45
L	E	F	2,239 – 2,449	19	75
L	E	B	11,672	157	358
L	N	O	0	17	73
L	N	R	0	6	50

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Exposed People	Civilian Deaths	Civilian Injuries
L	N	F	0 – 2,799	37	157
L	N	B	16,550	567	958
O	D	O	0 – 43,179	16	370
O	D	R	0 – 10,738	7	189
O	D	F	0 – 14,016	15	228
O	D	B	35,297 – 73,664	245	1,573
O	E	O	0 – 25,983	10	205
O	E	R	0 – 5,772	0	103
O	E	F	0 – 10,230	6	110
O	E	B	50,204	121	729
O	N	O	0	27	133
O	N	R	0	7	84
O	N	F	0 – 8,640	19	131
O	N	B	60,009	445	1,417

Table 15. Range of Estimated Number of People Exposed to Smoke in Home Fires vs. 1993-97 Average Reported Civilian Fire Deaths and Non-Fatal Injuries, by Area of Fire Origin and Time of Day

[Area of Fire Origin: Kitchen; Bedroom; Living room, family room, den or associated chimney; Other room.

Time of day: Day (7 am – 6 pm), Evening (6 pm – 11 pm), or Night (11 pm – 7 am)]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Exposed People	Civilian Deaths	Civilian Injuries
K	D	All	20,564 – 106,779	207	3,120
K	E	All	28,126 – 65,615	86	1,660
K	N	All	18,533 – 27,215	249	1,159
B	D	All	13,786 – 46,945	365	2,363
B	E	All	17,964 – 29,474	161	1,008
B	N	All	25,009 – 35,014	462	1,617
L	D	All	10,594 – 14,274	363	1,195
L	E	All	16,349 – 22,934	184	531
L	N	All	16,550 – 19,349	627	1,238
O	D	All	35,297 – 141,597	283	2,360
O	E	All	50,204 – 92,189	138	1,148
O	N	All	60,009 – 68,649	498	1,765

Table 16. Range of Estimated Number of People Exposed to Smoke in Home Fires vs. 1993-97 Average Reported Civilian Fire Deaths and Non-Fatal Injuries, by Area of Fire Origin and Extent of Smoke Damage

[Area of Fire Origin: Kitchen; Bedroom; Living room, family room, den or associated chimney; Other room.

Extent of smoke damage: None or confined to Object or area of fire origin; beyond area of origin, but confined to Room of origin; beyond room of origin, but confined to Floor of origin; Beyond floor of origin.]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Exposed People	Civilian Deaths	Civilian Injuries
K	All	O	0 – 40,921	44	1,126
K	All	R	0 – 18,874	17	856
K	All	F	0 – 50,240	47	1,244
K	All	B	67,223 – 89,574	435	2,712
B	All	O	0 – 11,796	36	374
B	All	R	1,672 – 8,870	33	377
B	All	F	2,470 – 23,166	126	1,017
B	All	B	52,617 – 67,601	792	3,221
L	All	O	0 – 10,055	37	227
L	All	R	3,939	15	164
L	All	F	3,674 – 6,683	84	383
L	All	B	35,880	1,037	2,191
O	All	O	0 – 69,161	53	708
O	All	R	0 – 16,511	15	375
O	All	F	0 – 32,885	41	469
O	All	B	145,510 – 183,877	811	3,720

Table 17. Range of Estimated Number of People Exposed to Smoke in Home Fires vs. 1993-97 Average Reported Civilian Fire Deaths and Non-Fatal Injuries, by Time of Day and Extent of Smoke Damage

[Time of day: Day (7 am – 6 pm), Evening (6 pm – 11 pm), or Night (11 pm – 7 am)

Extent of smoke damage: None or confined to Object or area of fire origin; beyond area of origin, but confined to Room of origin; beyond room of origin, but confined to Floor of origin; Beyond floor of origin.]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Exposed People	Civilian Deaths	Civilian Injuries
All	D	O	0 – 78,652	70	1,274
All	D	R	1,502 – 28,326	40	929
All	D	F	1,435 – 49,610	124	1,507
All	D	B	77,304 – 153,007	984	5,327
All	E	O	0 – 48,825	28	705
All	E	R	2,438 – 16,524	14	509
All	E	F	2,239 – 36,896	52	773
All	E	B	107,966	474	2,360
All	N	O	0 – 4,456	72	455
All	N	R	1,672 – 3,344	25	334
All	N	F	2,470 – 26,468	122	832
All	N	B	115,959	1,616	4,157

Table 18. Range of Estimated Number of People Exposed to Smoke in Home Fires vs. 1993-97 Average Reported Civilian Fire Deaths and Non-Fatal Injuries, by Area of Fire Origin, Time of Day, or Extent of Smoke Damage

[Area of Fire Origin: Kitchen; Bedroom; Living room, family room, den or associated chimney; Other room.

Time of day: Day (7 am – 6 pm), Evening (6 pm – 11 pm), or Night (11 pm – 7 am).

Extent of smoke damage: None or confined to Object or area of fire origin; beyond area of origin, but confined to Room of origin; beyond room of origin, but confined to Floor of origin; Beyond floor of origin.]

Area of Fire Origin	Time of Day	Extent of Smoke Damage	Exposed People	Civilian Deaths	Civilian Injuries
K	All	All	67,223 – 199,609	542	5,939
B	All	All	56,758 – 111,433	988	4,988
L	All	All	43,494 – 56,557	1,174	2,964
O	All	All	145,510 – 302,434	919	5,272
All	D	All	80,241 – 309,595	1,218	9,038
All	E	All	112,643 – 210,211	568	4,347
All	N	All	120,101 – 150,227	1,836	5,778
All	All	O	0 – 131,933	170	2,434
All	All	R	5,611 – 48,194	79	1,772
All	All	F	6,144 – 112,974	298	3,112
All	All	B	301,230 – 376,933	3,075	11,844
All	**All**	**All**	**312,984 – 670,034**	**3,623**	**19,163**

The grand total row (bold) shows a range of annually exposed people in the range of 310,000 to 670,000 people per year. This compares to 3,623 civilian fire deaths reported per year, 19,163 civilian fire injuries reported per year, and a combined 22,786 civilian fire fatal or non-fatal injuries reported per year.[11] [Deviations from published figures are due to rounding errors.] This translates into a range of 14 to 29 people exposed to toxic fire smoke per year for every one with a reported civilian fire injury.

The ratios would be even more dramatic if the deaths and injuries were limited to those involving smoke inhalation, in part or in whole. In 1993-97 home civilian fire deaths and injuries involving smoke inhalation, alone or in combination with burns, averaged 3,318 deaths and 11,505 injuries per year, for a total of 14,823 civilian fire fatal or non-fatal injuries per year.[11] This translates into a range of 21 to 45 people exposed to toxic fire smoke per year for every one with a reported civilian fire injury involving smoke inhalation.

It is important to consider the potential sources of the enormous difference between these estimates of numbers of people exposed to fire smoke, which very low thresholds would estimate should produce an injury in nearly every case, and the much lower numbers of actual reported injuries and deaths:

- It is unlikely that the injuries from smoke inhalation in reported fires are numerous enough to change substantially this huge gap between estimated exposed people and estimated injured people. Even if one includes injuries in unreported fires, the number of recognized (by the victim) smoke inhalation injuries falls well short of these estimates. The last study of unreported home fire injuries produced an estimate of total fire injuries above the high estimate for people exposed to toxic fire smoke, but most of those injuries were burns from small cooking fires, not from smoke inhalation. These were injuries recalled by people, based on extrapolation from a 3-month recall period and some prompting from the telephone interviewers regarding examples of what is included in the category of fire injuries.[12] Were numerous and significant aftereffects of smoke inhalation still being felt, these injuries would have been more evident in the study.
- There is the possibility of a very large number of unreported, unrecognized fire injuries due to fire smoke inhalation. These *single* exposures (except in the case of fire fighters) would result in injuries less severe than those from ordinary *chronic* exposures to carbon monoxide, such as second-hand cigarette smoke, use of fireplaces, and exposures to operating motor vehicles in partially confined spaces such as garages and bus tunnels. [Such injuries would seem to fall short of the type of serious and lasting health effects contemplated by those who set the goals in national codes and regulations or even those cited by advocates of the more sweeping goals cited in justifying more stringent thresholds.]
- Most of the potential exposures in the low-end estimate above occurred in larger fires, where smoke spread beyond the floor of origin and the victims were outside the room of origin. The smoke will have been diluted as it typically expands well beyond the zone of burning in such large fires (see Section III.C), and this will have reduced the occupants' exposure to levels below, often well below, those near the fire. In addition, most of the exposures added to the low-end estimate to produce the high-end estimate involve smaller fires (within the two categories of fires with smoke confined to or not confined to room of origin). Transport effects will apply to these victims as well, even though they tend to be closer to the point of fire origin.
- By definition, most exposed occupants are not unusually vulnerable to smoke.

While these figures and this analysis are for home fires only, the larger typical building size and much smaller fire incidence, death and injury rates in all other types of buildings will tend to mean that (a) the home fire numbers dominate the injury and death numbers for all buildings and (b) the ratio of estimated exposures to reported injuries and deaths is likely to be even higher for non-home buildings. For either reason, the qualitative conclusions would be unlikely to change if other occupancies were added to the analysis.

3. Estimating the Importance of Incapacitation as an Early Event Leading to Death and Value of Extra Time

From the thousands of single-fatality home fires reported to NFPA's FIDO database in the two years when all fatal fires were solicited, 127 were analyzed for this task. The incidents selected here, except as noted in the tables, were the first incidents coded (typically the earliest chronologically) into the system when all fatal fires were being sought. The patterns of interest from these were clear enough that it is unlikely additional data coding would have produced different results, but this remains an option for the future.

Tables 19-21 list the key data for fatal injuries, non-fatal injuries, and uninjured occupants, respectively. Here are some notes regarding the coding used in those tables:

- For non-fatal injuries and uninjured persons, there may be more than one per incident, in which case the identification code numbers the incident and then numbers the individuals from #1 up, (*e.g.,* #692-1).
- Under "Victim Location," "Intimate" means "Intimate with ignition," which means the victim was very close to the point of origin of the fire. Examples include clothing fires and ignitions of bedding near a person in bed.
- Under "Victim Condition at Ignition," "Impaired" means "Impaired by alcohol or other drugs," including legal medications. Physical conditions that might have made the victim more vulnerable to fire effects (*e.g.,* asthma) are shown, when reported, in brackets. A distinction is made between physical or mental "limits" of (old) age and more precisely defined physical or mental handicaps.
- Under "Victim Activity When Injured," details are provided, when reported, regarding exposure for people fatally injured while attempting rescue or fighting the fire. Details are grouped under four broad categories:
  - "Overcome" means the person was overcome/incapacitated by fire effects while engaged in the activity. A person overcome by fire can be rescued, in which case the injury suffered is non-fatal.
  - "Forced out" means the person sustained some exposure while engaged in the activity but had to break off the activity short of completion to flee what the victim perceived as intolerable fire effects.
  - "Forced back" means the person moved toward the fire or people needing rescue, but turned back at the edge of the fire exposure zone.
  - "Successful or stayed outside" means either the person was successful in the intended activity (rescuing or fire fighting) and so broke off the activity before being forced out or back by the fire OR the person stayed on the outer fringes of the fire-affected zone throughout the activity and so experienced very little if any exposure.

  Each of these categories is presumed to involve less quantity and duration of exposure to fire effects than the one before it, although that is not as clear for the last category.

- Under "Condition Preventing Escape," the term "incapacitated" is the term used in coding to mean an inability to move prior to fire exposure, such as the situation for a bedridden victim. It does NOT mean early incapacitation by the fire.

  This is the column where information is shown, when reported, to indicate the nature of the "irrational activity" recorded under "Victim Activity." "Irrational activity" always involves positive actions that increase risk for no good reason, usually a decision to seek refuge inside the home (*e.g.*, a child fleeing to his or her own bedroom, choosing familiar surroundings over a safe refuge). This column also records information, when reported, that provides more detail on severity and duration of exposure or, more often, on how close the victim was to successful escape.

Entries were made for 115 fatally injured individuals, with the last five recorded under a revised protocol where only individuals involved in rescuing or fire fighting when injured were recorded. Entries were made for 42 incidents involving non-fatal injuries, with a total of 65 non-fatally injured individuals documented. Of the 42 incidents, 16 (or nearly two-fifths) had reports on more than one non-fatally injured individual. Entries were made for 22 incidents involving documentation on uninjured individuals, with a total of 38 uninjured individuals documented. (One of those individuals was actually a family of unreported size, all of whose members escaped together from a separate apartment unit than the point of fire origin.) Of the 22 incidents, 11 (or half) had reports on more than one uninjured individual.

All of the non-fatally injured or uninjured people who were not engaged in attempting rescue, fighting the fire, or attempting to escape when injured were themselves rescued by someone else (except for a couple cases where the relevant information was unknown or unreported).

Table 19. Special FIDO Study – Fatal Victims

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
651	Same room	Impaired	Unable to act	Blocked by fire; incapacitated
680	Intimate	Impaired; physical handicap	Asleep	Incapacitated
681	Unknown	Physical handicap [partial paralysis]	Escaping	Moved too slow?
691	Unknown	Unknown [asthma]	Unknown	Unknown
692	Same room	Too young to act	Irrational activity	None
693	Another room	Impaired (very)	Asleep	Incapacitated
698	Intimate	Asleep	Asleep	None
716	Same room; close to fire but not intimate	Impaired	Escaping	Chose wrong path – to bedroom not direct to outside
720	Unknown	Physical handicap	Escaping	Moved too slow?, reached carport, close to escape

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
734	Unknown	Unknown	Unknown	None
743	Another floor	Physical handicap due to age	Escaping	Moved too slowly; incapacitated after 20' of walking slowly in smoke-filled hall
745	Another room?	Impaired	Asleep?	Incapacitated
752	Intimate	Awake	Irrational activity, maybe even suicide	None
756	Intimate	Awake	Irrational activity	Chose wrong refuge – familiar bedroom
757	Same room	Unknown	Unknown	Unknown
759	Unknown	Unknown	Escaping	None
764	Another room	Asleep	Escaping, rescuing – just by yelling alert	Blocked by fire, *i.e.*, trapped
765	Same room	Unknown	Irrational activity	Chose wrong refuge – bathroom
766	Intimate or same room	Physical handicap, age-related limits	Unable to act	Incapacitated
779	Intimate or same room	Awake	Irrational activity	Chose wrong refuge – own bedroom
781	Same room	Unknown [emphysema]	Irrational activity	Returned from outside – to get rifle
806	Another room	Physical handicap	Unknown	Unknown
813	Another room	Unknown [diabetic]	Escaping	Unknown
821	Another room	Too young to act	Unable to act (9 months old)	Unknown
912	Another room	Asleep	Rescuing (cats) – overcome by fire	None – Fire was confined to room of origin but flashed over enclosed room
917	Another room	Asleep	Escaping	Blocked by fire, chose wrong path – primary path
922	Same room	Awake?	Unable to act – knocked down or fell	Incapacitated – but unknown how
1005	Intimate	Physical handicap	Asleep or unable to act	Incapacitated?
1009	Unknown – but found in a different room	Physical limits of age	Unknown	Unknown
1013	Unknown	Impaired; also beaten unconscious	Unable to act	Incapacitated
1021	Intimate	Too young to act [2 years old]	Unable to act	Moved too slow, fire setter
1022	Same room	Physical handicap, also	Unknown – didn't	Incapacitated or

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
		limits of age	move	moved too slow?
1024	Intimate – smoked while on oxygen	Physical handicap – on oxygen [emphysema]	Unable to act – removed by rescuer	Blocked by fire
1034	Intimate	Physical limits of age	Unable to act	None
1036	Intimate	Impaired	Unable to act	Clothing on fire; fire blocked exit
1201	Same room	Too young to act (10 months)	Unable to act	Moved too slow
1208	Another room	Unknown	Unknown	Unknown
1210	Intimate	Mental handicap (schizophrenia)	Asleep or unable to act	Unknown
1228	Same room	Awake	Fire fighting – overcome by fire	None
1230	Unknown	Impaired	Escaping	None
1232	Another room	Asleep	Rescuing – overcome by fire	Re-entered building
1235	Intimate	Physical limits of age [used a walker]	Escaping or fire fighting – overcome by fire while moving away, to water	Moved too slowly
1236	Same room, fire setter	Impaired, mental handicap	Irrational activity	Chose wrong refuge – fled to bathroom
1239	Intimate	Asleep	Fire fighting – overcome by fire	None
1241	Intimate	Impaired	Escaping	Blocked by fire
1244	Intimate	Bedridden by physical handicap	Unable to act	None
1249	Same room	Unknown	Unknown	None
1250	Another floor	Unknown	Unknown	Blocked by fire
1254	Another floor	Unknown	Sleeping?	Unknown
1257	Another room	Unknown	Escaping	None
1260	Another room	Awake	Fire fighting – became disoriented, so fled to wrong refuge	Chose wrong refuge – bathroom tub
1262	Another room	Impaired	Escaping	None
1265	Another floor	Asleep [also sick with flu]	Sleeping	Blocked by fire
1274	Another room	Unknown	Unable to act – afraid to jump	Blocked by fire
1275	Same room	Unknown	Unknown	Unknown
1279	Same room	Impaired	Unknown	Unknown
1284	Another room	Physical handicap [on breathing machine]	Unable to act	Incapacitated
1295	Intimate	Physical handicap [stroke, blind in one eye]	Escaping	Door nailed shut

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
1303	Another room	Asleep	Escaping	None
1313	Unknown	Physical limits of age	Unknown	None
1315	Unknown	Unknown	Escaping	None
1319	Intimate	Physical handicap, mental limits of age	Unable to act	Incapacitated – in restraints
1320	Unknown	Physical limits of age [used a walker]	Escaping	Unknown – was 4-5' from front door when overcome by fire
1337	Another room	Impaired	Escaping	None
1339	Intimate	Physical handicap [legally blind], physical limits of age	Escaping	Chose wrong path – into closet, because blind and disoriented
1340	Another room	Bedridden by physical handicap	Unable to act	Incapacitated
1433	Intimate	Impaired [also liver disease]	Sleeping	None
1436	Another room	Physical limits of age [used a walker]	Unknown	None
1446	Same room	Bedridden by physical handicap	Unable to act	Incapacitated
1448	Same room	Unknown	Unknown	Unknown
1456	Another room	Unknown	Unknown	Unknown
1479	Another floor	Unknown	Unknown	Unknown
1482	Intimate	Physical handicap [stroke 2 days earlier]	Escaping	Unknown
1486	Another room	Asleep	Escaping	Chose wrong path, primary path to front door went toward fire
1490	Intimate	Asleep [had terminal cancer]	Escaping	None
1497	Another room	Asleep	Escaping	None – overcome by fire in room next to room of origin
1498	Same room	Unknown	Unknown	Unknown
1499	Same room	Asleep	Sleeping	Unknown
1502	Intimate	Awake	Fire fighting – overcome by fire on self while moving to water	Clothing on fire; ran to bathroom
1504	Another room	Physical limits of age	Escaping – had cardiac arrest while investigating fire	Unknown
1521	Intimate	Mental limits of age	Escaping, fire fighting – overcome	Clothing on fire; went to bathroom

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
			by fire on self while moving to water	
1522	Intimate	Impaired	Escaping	None
1527	Another floor	Asleep	Escaping	Unknown
1535	Unknown	Impaired	Escaping	None
1537	Another room or floor	Unknown	Escaping	None – Almost got through front door
1541	Unknown	Unknown	Unable to act – mother carried him to window but he would not jump	None
1543	Another room	Unknown	Unknown	None
1545	Another room	Physical limits of age [arthritis; used walker]	Escaping	None
1548	Same room	Awake	Escaping	Locked door
1549	Unknown	Impaired	Unknown	Unknown
1551	Another room	Too young to act [10 months]	Escaping	Blocked by fire
1552	Same room	Physical handicap	Unable to act	Incapacitated; blocked by fire
1646	Unknown	Impaired	Unknown	Unknown
1648	Another room or floor	Asleep	Sleeping	Unknown
1650	Another room	Asleep	Escaping	Blocked by fire
1655	Same room	Unknown	Escaping	Blocked by fire
1659	Another room	Unknown	Unknown	Unknown
1661	Unknown	Impaired	Unknown	Unknown
1663	Another room?	Impaired	Escaping	Unknown
1672	Intimate	Impaired	Irrational activity	Chose wrong refuge – went to bedroom after setting fire
1725	Another room	Too young to act [1 year old]	Unable to act	None
1745	Intimate	Physical limits of age	Unknown	Unknown
1746	Intimate	Impaired, physical handicap	Sleeping or unable to act	Incapacitated – rescued by neighbor
1748	Intimate	Impaired	Escaping	None
1750	Same room	Bedridden due to physical handicap	Unknown – but moved to dining room	Unknown
1752	Same room	Unknown	Escaping	None – made it to “near” back door
1760	Another room	Asleep	Sleeping	None
1764	Intimate	Physical handicap [wheelchair]	Unable to act	Blocked by fire
1765	Same room	Awake	Unable to act?	Unknown – child stayed in bed after

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
				setting fire there
1768	Same room	Unknown	Escaping	Chose wrong refuge – adult went to a bedroom closet
After #1768, no fatal cases recorded except when victim activity included attempting rescue or fire fighting				
1840	Same room	Impaired [insulin for diabetes]	Fire fighting – overcome by fire on second trip to bathroom for water to fight fire	
1875	Another room	Asleep	Fire fighting – overcome by fire while escaping after breaking off fire fighting	None
2511	Same room	Asleep	Rescuing, escaping – overcome during escape after rescue attempt	Chose wrong path – during escape, went to room of fire origin to call 911
2514	Same room	Impaired	Fire fighting – overcome while moving away from fire toward water in kitchen	None
2515	Intimate	Physical limits of age	Fire fighting, escaping – overcome by fire on self while moving to water in kitchen	Clothing on fire

Table 20. Special FIDO Study – Non-fatal Injury Victims

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
651-1	Intimate or same room	Awake	Escaping	None
651-2	Another room	Asleep	Escaping	Blocked by fire – dove out window
692	Another room	Asleep	Rescuing – Overcome by fire and rescued by firefighters	None
743	Another floor	Asleep	Escaping	None – walked into heat/smoke zone, became disoriented, not sure how escaped
766	Another room	Physical handicap, also limits of age	Fire fighting, rescuing – Forced out, possibly by heavy smoke	None – tried to rescue wife, who needed wheel-chair, from fire room
781	Same room	Asleep	Escaping	None – some initial exposure
912	Another room	Asleep	Escaping	None – fatality died rescuing cats while this one escaped with same initial conditions
1013-1	Intimate	Awake	Setting the fire, then escaping	None
1013-2	Unknown	Unknown	Escaping	Unknown
1021	Another floor	Unknown	Rescuing – Forced out by heat and smoke	None
1022	Another room	Physical handicap	Rescuing – Had to be rescued himself, possibly partially overcome	None
1201-1	Another room	Asleep	Rescuing, escaping – Forced back by flames	Blocked by fire, so jumped out window
1201-2	Same room	Too young to act [2 years old]	Unable to act – rescued by passerby	None
1228	Another room	Unknown	Unknown – rescued by firefighters and had not moved	Unknown
1232-1	Another room	Asleep	Rescuing – partial success, spent time in fire zone	Reentered building

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
1232-2	Another room	Asleep	Sleeping	None – rescued by parent
1232-3	Another room	Asleep	Sleeping	None – rescued by parent
1249	Same room	Unknown	Rescuing – Forced out by smoke	None
1265	Outside building	Awake	Rescuing – Forced back by flames	None
1275	Same room	Unknown	Rescuing – Successful, but removed victim later died	None
1303-1	Another room	Asleep	Rescuing, escaping – Forced back by heat and smoke	Blocked by fire
1303-2	Another room?	Asleep	Escaping	None
1303-3	Another floor?	Asleep	Unknown	None – rescued by firefighters from unreported location
1337-1	Unknown	Impaired	Escaping	None
1337-2	Unknown	Impaired	Rescuing, escaping – Forced out by smoke	Unknown
1340	Intimate	Impaired	Escaping	None
1448	Another room or floor	Unknown	Unknown	Unknown
1499-1	Same room	Asleep	Unknown	Unknown – rescued by parent
1499-2	Unknown	Unknown	Rescuing – successful, spent time in fire zone	Unknown
1541-1	Unknown	Unknown	Rescuing, escaping – spent time in fire zone, then fell out window	None
1541-2	Unknown	Unknown	Escaping	None
1541-3	Unknown	Unknown	Escaping	None
1545	Unknown	Mental handicap	Fire fighting, rescuing, escaping – Forced out by smoke	None
1551	Same room	Too young to act [2 years old]	Irrational activity	Chose wrong refuge (bedroom), rescued by neighbor
1552	Another room	Asleep	Escaping, rescuing – Forced out and then overcome by fire	None – Rescued after incapacitation by fire-fighters and survived; found 10’

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
				from front door
1648-1	Another room or floor	Asleep	Rescuing, escaping – partially successful, time in fire zone	None
1648-2	Another room or floor	Asleep	Sleeping – rescued by parent	Unknown
1672	Another room	Unknown	Unknown	Blocked by fire
1764	Another room	Asleep	Escaping	Blocked by fire
1771-1	Another room	Asleep	Escaping – via window	Blocked by fire
1771-2	Another room	Asleep	Escaping – via window	Blocked by fire
1786	Another floor	Asleep	Escaping – wife died under same circumstances	None
1810	Outside building	Awake	Rescuing – Partial success, stayed outside at fringe of fire effects zone	None
1830-1	Same room	Mental handicap	Escaping	Blocked by fire
1830-2	Another room	Asleep	Rescuing – Forced out by firefighters, based on heavy smoke	None
1830-3	Another room	Asleep	Fire fighting – Forced out by fire size	None
1866	Same room	Asleep	Escaping	None
1874-1	Same room	Impaired	Fire fighting, rescuing, escaping – Forced out due to fire size	None
1874-2	Another floor	Asleep	Escaping	None
1874-3	Another floor	Asleep	Escaping	None
2098	Another room	Impaired	Escaping	Overcome by fire but rescued by firefighters
2144-1	Same room	Awake	Escaping – rescued via window	Blocked by fire
2144-2	Another room	Unknown	Escaping	Blocked by fire – jumped from window
2163-1	Unknown	Unknown	Unknown	Blocked by fire, rescued by firefighters
2163-2	Unknown	Unknown	Unknown	Blocked by fire,

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
				rescued by firefighters
2163-3	Unknown	Unknown	Unknown	Blocked by fire, rescued by firefighters
2175-1	Unknown	Asleep	Escaping	None
2175-2	Unknown	Asleep	Escaping	None
2189-1	Intimate	Awake	Escaping	None
2189-2	Another floor	Awake	Escaping	None
2189-3	Another floor	Awake	Escaping	None
2208	Unknown	Asleep	Escaping	Unknown
2249	Outside building	Awake	Escaping, rescuing – Forced back	None
2281	Another floor	Asleep	Escaping	None – rescued after being incapacitated
2323	Another room	Asleep	Escaping, rescuing – Successful, repeated exposure to fire effects zone for 3 rescues	None

Table 21. Special FIDO Study – Uninjured Occupants

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
691-1	Another floor	Unknown	Unable to act	Blocked by fire but rescued, in smoke zone till rescued
691-2	Another floor	Unknown	Unable to act	Blocked by fire but rescued, in smoke zone till rescued
691-3	Another floor	Unknown	Unable to act	Blocked by fire but rescued, in smoke zone till rescued
692-1	Intimate or same room	Too young to act [3 years old]	Escaping – led to safety	Moved too slowly – possible initial exposure
692-2	Another room	Asleep	Rescuing – did not have to enter fire effects zone	No exposure
692-3	Another room	Unknown	Escaping	No exposure
692-4	Another room	Unknown	Escaping	No exposure
716-1	Another room	Awake	Rescuing – in fire effects zone, and exposed crawling out	None
716-2 more than one person	Another floor – a family of unreported size	Unknown	Escaping	No exposure
720	Another room	Awake?	Rescuing – Forced back by fire	Some exposure
1021-1	Another floor	Unknown	Escaping, rescuing – Avoided fire effects zone	None
1021-2	Another floor	Unknown	Escaping	None
1021-3	Another floor	Too young to act	Unable to act – rescued	Moved too slowly but never in fire effects zone
1022	Another building	Awake	Rescuing – Successful, some time in fire effects zone	None
1024	Another room	Awake	Rescuing – Successful even though victim later died, some time in fire effects zone	None
1228	Another floor	Asleep	Escaping	None

ID #	Fatal Victim Location	Victim Condition at Ignition	Victim Activity when Injured	Condition Preventing Escape
1284	Another floor	Physical limits of age	Rescuing, escaping– Forced back by smoke and heat	Unknown
1497-1	Another room	Asleep	Escaping	None
1497-2	Another room	Asleep	Escaping	None
1527-1	Another floor	Impaired	Escaping	None
1527-2	Another floor	Asleep	Escaping	None
1527-3	Another floor	Impaired	Escaping	None
1548	Same room	Awake	Escaping	None
1655-1	Another room	Asleep	Escaping, rescuing – Forced back by fire	Unknown
1655-2	Same room	Awake	Escaping	None
1746	Outside building	Unknown	Rescuing – Removed victim from burning bed, but victim later died	None
1752-1	Outside building	Awake	Fire fighting, rescuing – Removed victim from floor but victim died	None
1752-2	Outside building	Awake	Fire fighting, rescuing – Removed victim from floor but victim died	None
1810	Same room	Awake	Escaping – from fire he set	None
1866	Another room	Asleep	Escaping	None
2103-1	Another floor	Asleep	Escaping	None
2103-2	Another floor	Asleep	Escaping	None
2118-1	Outside building	Awake	Rescuing – Forced out by heat	None
2118-2	Outside building	Awake	Fire fighting – Forced out by flames	None
2149-1	Another apartment unit on same floor	Awake	Fire fighting – Forced back or out by fire	None
2149-2	Another apartment unit on same floor	Awake	Fire fighting – Forced back or out by fire	None
2175	Unknown	Asleep	Escaping	None
2511	Another room	Asleep	Escaping	None

Table 22 compares the fraction of victims involved in various activities for reported deaths and injuries in home fires to the corresponding fractions from the FIDO study. For deaths, the FIDO study differs from the reported fire deaths particularly with regard to sleeping and escaping. It is possible that our coding gave credit to people for attempting to escape based on less evidence or less success than the typical fire officer would use. The differences are much larger for non-fatal injuries, but this reflects the fact that the FIDO study only examined injuries suffered in fires where one person died. For all statistics, proportional allocation has been done for cases where activity at time of injury was unknown. For FIDO study statistics, when two or more activities were noted for a single injury, a fractional value was assigned to each.

Table 22. Activity at Time of Injury – Special FIDO Study vs. 1993-97 Reported Home Fire Civilian Deaths and Injuries[11]

Activity at Time of Injury	Reported Deaths	FIDO Study – Deaths	Reported Injuries	FIDO Study – Injuries
Sleeping	41.3 %	14.0 %	17.3 %	5.3 %
Escaping	27.2 %	42.4 %	23.8 %	62.6 %
Unable to act	13.7 %	25.6 %	4.8 %	1.8 %
Irrational action	6.4 %	9.3 %	5.0 %	1.8 %
Rescuing	3.1 %	2.9 %	7.4 %	24.9 %
Fire fighting	2.9 %	5.8 %	31.9 %	3.8 %
Other known activity	5.4 %	0.0 %	9.8 %	0.0 %

The purpose of the FIDO study was to obtain additional insight into the risk consequences of certain behaviors. Table 23 provides a summary description of what inferences might be reasonably drawn from a combination of coded descriptions about a fatally or non-fatally injured victim.

Activity is the most important of these descriptors. An individual coded as "unable to act" or "acting irrationally" is very unlikely to benefit from additional time, as they will need someone else to rescue them. Incapacitation by fire is irrelevant in that these individuals are already incapacitated by other conditions. For example, there were 22 fatally injured victims coded as "unable to act" compared to only 1 non-fatally injured victim and three uninjured occupants so coded. The latter were primarily children who required only direction for successful rescue. The fatally injured victims who were "unable to act" included a number of adults who were either physically or mentally unable to assist in their own rescue and would have posed a severe challenge even with more time.

Table 23. Estimated Value of Delayed Time to Incapacitation, Based on Victim Activity at Time of Injury, Condition at Time of Ignition, Location at Time of Ignition, and on Other Condition Preventing Escape

Activity of Victim at Time of Injury	**Condition Preventing Escape**	**Condition of Victim at Time of Ignition**	**Location of Victim at Time of Ignition**	**Would Delayed Incapacitation Have Provided Useful Time?**
Escaping (1)	Any	Any	Any	Very probably yes
Irrational activity (8)	Any	Any	Any	No, unless irrational act is due to incapacitation by fire, which is rarely true. In FIDO study, these victims usually sought refuge in unsafe place or re-entered building for no good reason
Unable to act (7)	Any	Any	Any	No
Fire fighting (3-5)	Any	Any	Any	Possibly, if delayed growth allowed successful completion of task before escape became impossible
Attempting rescue (2)	Any	Any	Any	Possibly, if delayed growth allowed successful completion of task before escape became impossible
Sleeping, unclassified, or unknown (6,9,0)	Fire grew too fast, fire between victim and exit, victim moved too slowly, unclassified or unknown (Not 3-5 or 7)	Awake or asleep (1,8)	Intimate with ignition (1)	Unlikely; there are serious problems that won't disappear with more time
Sleeping, unclassified, or unknown (6,9,0)	Fire grew too fast, fire between victim and exit, victim moved too slowly, unclassified or unknown (Not 3-5 or 7)	Awake or asleep (1,8)	Not intimate (2-7)	Possible; these problems might be manageable with more time, especially if there is earlier detection, too
Sleeping, unclassified, or unknown (6,9,0)	Any combination of codes other than those in the two rows above			Unlikely or uncertain; there are no favorable victim characteristics to encourage optimism

At the other end of the spectrum, an individual coded as "escaping" is very likely to benefit from additional time. Incapacitation stops the escape attempt and is of critical importance in the timeline leading to death. A substantial majority of individuals in the FIDO study who were coded as "escaping" emerged without fatal injury. For reported deaths and injuries, this pattern is even more dramatic, bearing in mind that the overall totals are about 5-to-1 non-fatal to fatal injuries and the percentages of each coded as "escaping" are quite similar.

Some victims (*e.g.*, those coded as impaired by drugs or alcohol, or having physical or mental handicaps or limits associated with age) might benefit less from a given increment of escape time than victims without such limitations, but all should benefit to some degree. However, the other characteristics of victims who were attempting to escape rarely show problems that would reduce their ability to benefit from extra time. For example, only 9.7 % of these deaths and 7.6 % of these injuries involve victims who began their escape after being intimately involved with ignition. Only 7.4 % of these deaths but 20.4 % of these injuries involve victims with reported handicaps, impairments, or limitations.

An individual coded as "sleeping" will need some help to benefit from any delay in the timeline of developing fire hazard. Absent the introduction of some form of alerting that did not occur in the fire as it happened, the individual is likely to continue sleeping and simply be fatally injured later. Incapacitation is irrelevant to what happened to them, but might not have been irrelevant if they had been alerted to the fire earlier. Some victim conditions (*e.g.*, impaired by drugs or alcohol, or having physical or mental handicaps or limits associated with age; victim located in same room as fire) and some fire conditions (*e.g.*, fire blocked escape path to exit, fire moved too quickly and left no time to escape) would indicate less potential for the individual to benefit from extra time.

An individual coded as "unclassified" or "unknown" with regard to activity is like an individual coded as "sleeping" in that time might help or might not help, and the difference is likely to depend on factors captured by other victim characteristics or by factors not recorded.

An individual coded as "rescuing" or "fire fighting" poses a very interesting situation. Clearly, incapacitation is important because it terminates the activity and probably does so with the victim exposed to severe fire danger. At the same time, both activities involve voluntary assumption of risk by the individuals for a rational purpose. If the risk of incapacitation takes longer to develop, the individual may continue to attempt rescue or fire control during that time.

We do not know how often that extra time will lead to sufficient success to allow the individual to save himself or herself. We do not know what cues individuals use to decide to stop these activities and save themselves. Therefore, it is quite possible that extra time until incapacitating conditions develop would not help these individuals.

Because the stakes are higher for rescue than for fire fighting, we might speculate that rescuers are more likely to persist in their attempts than fire fighting occupants. And it may be noted that there are 58.8 non-fatal injuries suffered while fire fighting for every fatal injury suffered during that activity, compared to only 12.6 non-fatal injuries suffered while rescuing for every fatal injury suffered during that activity. This argues for the greater persistence, even unto death, for the would-be rescuers, while the even lower ratios (only 3.4) for all other activities argues for the fact that both rescuing and fire fighting involve voluntary risk that can be broken off if the individual feels too much at risk. Persistence for sleepers or those unable to act or acting irrationally is not something they choose – or choose to stop.

Table 24 shows how very different the fatal injuries, non-fatal injuries, and no-injury cases are in terms of the kind of exposure associated with each group's approach to attempting rescue or fire control:

Table 24. Reason for Termination of Rescue or Fire Fighting Activity, by Severity of Harm to Person Engaged in Activity

How Did Activity Terminate?	FIDO study – Fatal injuries	FIDO study – Non-fatal injuries	FIDO study – Uninjured people
Person overcome by fire (and, if not fatally injured, was then rescued)	79 %	14 %	0 %
Person forced out (*i.e.*, had to leave the fire zone)	21 %	41 %	13 %
Person forced back (*i.e.*, prevented from entering the fire zone)	0 %	18 %	33 %
Person successful in activity and/or stayed outside fire zone	0 %	27 %	53 %
Total cases	14	22	15

In both of the injury columns, fatal and non-fatal, we do not know whether any changes delaying the time to an incapacitating dose would in fact lead to a reduced dose received because:

- we do not know the cues leading people to break off the activity short of success and
- we do not know how close the unsuccessful people were to success (although the narratives uniformly suggest that they were not that close).

It appears more likely that the person would have simply extended his or her activity time, taking advantage of the reduced strain from the fire.

Table 25 indicates the numbers and shares of deaths and injuries associated with each of the categories in Table 23. It also includes a letter grade (A to F) intended to provide an estimate of the degree to which extra time until incapacitation is likely to lead to a different, more favorable outcome. The "escaping" victims account for 16.5 % of deaths and 18.6 % of injuries; they are the ones most likely to benefit and have grade "A." The "rescuing" and "fire fighting" victims account for 3.8 % of deaths and 32.4 % of injuries; they are next most likely to benefit and have grade "B." Four-fifths of the deaths and roughly half of the injuries fall in the remaining categories, where the value of extra time is less certain or less favorable. The "unable to act" and “acting irrationally” victims account for 12.4 % of deaths and 7.6 % of injuries; they are the least likely to benefit and have grade “F.” The other victims (67.4 % of deaths, 41.4 % of injuries) were sleeping or had activity unclassified or unknown, with most having no other known characteristics of victim or fire to indicate that they would or would not have benefited from extra time to incapacitation. They were given grades from C to D, with higher grades reserved for those victims who did have other known characteristics pointing to a better chance of using extra time effectively.

Table 25. Number and Share of Reported Home Fire Deaths and Injuries, Based on Victim Activity at Time of Injury, Condition at Time of Ignition, Location at Time of Ignition, and on Other Condition Preventing Escape

Activity of Victim at Time of Injury	Condition Preventing Escape	Condition of Victim at Time of Ignition	Location of Victim at Time of Ignition	Number/Percent of Deaths and Injuries (Letter Grade is for ‘Would Time Help?’)
Escaping (1)	Any	Any	Any	594 deaths (16.5 %) 3,571 injuries (18.6 %) (A – Extra time most likely to help)
Irrational activity (8)	Any	Any	Any	139 deaths (3.9 %) 747 injuries (3.9 %) (F – Extra time won’t help)
Unable to act (7)	Any	Any	Any	307 deaths (8.5 %) 701 injuries (3.7 %) (F – Extra time won’t help)
Fire fighting (3-5)	Any	Any	Any	73 deaths (2.0 %) 5,053 injuries (26.4 %) (B)
Attempting rescue (2)	Any	Any	Any	66 deaths (1.8 %) 1,154 injuries (6.0 %) (B)
Sleeping, unclassified, or unknown (6,9,0)	Fire grew too fast, fire between victim and exit, victim moved too slowly, unclassified or unknown (Not 3-5 or 7)	Awake or asleep (1,8)	Intimate with ignition (1)	78 deaths (2.2 %) 227 injuries (1.2 %) (D+)
Sleeping, unclassified, or unknown (6,9,0)	Fire grew too fast, fire between victim and exit, victim moved too slowly, unclassified or unknown (Not 3-5 or 7)	Awake or asleep (1,8)	Not intimate (2-7)	732 deaths (20.3 %) 2,172 injuries (11.3 %) (C-)
Sleeping, unclassified, or unknown (6,9,0)	Any combination of codes other than those in the two rows above			1,620 deaths (44.9 %) 5,525 injuries (28.9 %) (D)

This analysis suggests that roughly half of the deaths and roughly two-thirds of the injuries could be prevented were the times to incapacitating exposures lengthened sufficiently to result in a more favorable outcome. This summation, based on the content of Table 25, assumes that:

- all of the A and B deaths and injuries could be prevented,
- none of the grade F deaths and injuries could be so affected, and
- half the grade C deaths and injuries and one-third of the grade D deaths and injuries could be so prevented

4. Summary

Estimates from analysis of epidemiological data indicate that:

- Approximately one half million people are exposed to fire smoke each year. This is 21 to 45 times the number of reported civilian fire injuries involving smoke inhalation. It is likely that this disparity results from most of the exposures being of short duration and/or to low smoke concentrations.
- Roughly half of the deaths and roughly two-thirds of the injuries could be prevented were the times to incapacitating exposures lengthened sufficiently to result in a more favorable outcome.

Thus, it can be inferred that sublethal effects from smoke exposure can play a substantive role in preventing safe escape from a fire, but lead to noticeable consequences in only a small fraction of the people exposed.

5. Future Work

The single most useful addition to the knowledge upon which the foregoing analyses are based would be enhanced information on the subsequent health of people exposed to fires.

C. CHARACTERISTICS OF FIRE SCENARIOS IN WHICH SUBLETHAL EFFECTS OF SMOKE ARE IMPORTANT

A second approach led to further guidance in identifying a lesser number of fire scenarios in which consequential sublethal exposures to fire smoke might occur. This was accomplished using:

- an analysis of the published literature on the fire size, duration, and toxicant yields for fires important in U.S. fire statistics, and
- computer modeling of the resulting conditions in compartments near to and away from the fire source. In these simulations, the relative importance of toxic potency and thermal effects was monitored.

The criteria used for identifying classes of fire scenarios in which sublethal effects of smoke were important were:

- smoke exposures ranged from one third of the lethal level (taken to be the incapacitating exposure) to one percent of the lethal exposure (taken to be a conservative value for a non-harmful exposure), and
- harm from thermal effects did not occur before a harmful toxic exposure was accumulated.

1. Categorization of Fire Scenarios

The primary descriptor of a fire is its *size*. Fire incidence reports group fires in *categories*:

- *Fire confined to the initial combustible, or spread beyond that combustible, but confined to the room of fire origin.* These are generally pre-flashover fires of limited duration and spatial extent. In the U.S., injuries and deaths in the room of fire origin from these fires are most often caused by intimate contact with the fire, *e.g.*, inhalation of nearly undiluted smoke from a smoldering chair or burns from flaming clothing. Prior indications are that outside the room of fire origin, lethal or incapacitating exposures to heat or smoke are unlikely.
- *Fire extended beyond the room of origin.* These are generally regarded as post-flashover fires. They generally continue until actively suppressed or until all the accessible fuel is consumed. Prior analysis indicated that within the room of fire origin, heat most often reaches a life-threatening level before toxic effects occur. Outside the room of fire origin, both thermal and toxic potency effects can be important. In the U.S., most fire fatalities involving smoke inhalation, either as the sole cause or as a contributing cause, occurred outside the room of fire origin and from fires that had spread beyond the room of origin.

When treating fires *quantitatively*, the proper measure of fire size is the heat release rate (HRR). It is this released heat (enthalpy) that raises the temperature of the surroundings, imposing radiative and convective flux on the occupants. The result is an accelerating, perhaps exponentially growing rate of consumption of the mass of the fuel items. This is why HRR is both the single most important indicator of real-scale fire performance of a material or construction and of the consequent fire hazard.[13] The report of the recent European program on Fire Safety of Upholstered Furniture (CBUF) is consistent with this view, ranking the performance of materials by the HRR of the product and the resulting height of the hot smoke gas layer.[14] Heat release rates can range from a few kilowatts for a smoldering fire to several megawatts for a post-flashover fire.

Fires are also characterized by their growth rate, which in the absence of specific data is usually represented as quadratic with time. Typically, four categories are used, where the characteristic time is that at which the fire reaches 1 MW:

Ultra fast	< 75 s
Fast	75 s - 150 s
Medium	150 s - 400 s
Slow	> 400 seconds.

Variation in other fire characteristics has far lesser effect on the development of fire hazard. For flaming fires, the details of the ignition process have little import since it is the rapid rise of the rate of heat release that leads to hazardous conditions. For smoldering fires, the growth rate is very slow, and the smoldering time tends to be very long compared to the initial ignition transient.

The concentration of toxic gases and aerosols depends on the mass of products that is consumed in the fire, as well as dilution during transport to additional spaces and forced or natural ventilation. As shown in Section III.D, there is a range of toxic potency values that can be significant. Thus, the source term of the concentration of toxic smoke from burning products needs to be carefully determined.

2. Published Test Data

While there have been numerous real-scale room tests of burning products, relatively few have included the information needed for input to predictive computations to compare thermal effects and toxic potency:

- fire size,
- gas temperatures and radiant fluxes to which occupants may be exposed,
- yields of important fire gas species and resulting concentrations in compartments of representative occupancies.

A sampling of available data is summarized below and in Table 26.

Särdqvist [15] reports heat release rate, smoke production, and CO concentrations for a number of different products from other literature sources. For typical construction products, peak HRR values range from about 200 kW to more than 3000 kW. For most of the products, only a CO production rate is available, without an accompanying mass loss rate. For products where data are available, CO yields range from 0.02 kg/kg to 0.08 kg/kg.

Kokkala, Göransson, and Söderbom[16] report heat release rates and CO yields for a range of wall surface linings tested in the ISO 9705 room/corner test. All of the tests resulted in high HRR values. They note $[CO]/[CO_2]$concentration ratios below 0.1 for HRR values up to 1000 kW and close to 0.25 for HRR values above 1000 kW.

Sundström[14] reports on upholstered chairs and mattresses tested for the European CBUF program. In tests of single items of upholstered furniture, they report HRR values ranging from 300 to 1500 kW. CO yields range from 0.01 kg/kg to 0.13 kg/kg and HCN yields range from 0.0002 kg/kg to 0.004 kg/kg. Most, but not all, of these furniture items would lead to fires below a level that would cause flashover in their test facility. They note that gas yields increase and times to untenable conditions decrease within the fire room as ventilation openings decrease.

Ohlemiller *et al.*[17] report on a series of tests to study the fire behavior of bed assemblies, including a mattress, foundation, and bedclothes. Table 26 shows some of the test results for a mattress assembly. The peak heat release rate was 990 kW. The $[CO]/[CO_2]$ ratio varied during the test, ranging from 0.33 just after ignition to 0.006 during active burning.

Purser[18,19] has reported a number of tests that include measurement and analysis of tenability during building fires. Data on CO, CO_2, and HCN yields are included. Yields of CO and HCN are seen to vary inversely with ventilation, with somewhat higher yields at lower ventilation conditions. CO yields range from 0.01 kg/kg to 0.08 kg/kg; HCN yields range from 0.009 kg/kg to 0.09 kg/kg. Times to incapacitation for occupants in an upstairs bedroom of the test structure were estimated to be 2 min to 2.5 min with the fire room door open and more than 20 min with the fire room door closed.

Purser[20] reviewed a range of available test data comparing gas yields from small- and large-scale tests. Table 26 includes some of the large-scale test results. Yields of CO and HCN were somewhat higher for tests where flaming combustion was preceded by a period of smoldering. CO yields range from 0.04 kg/kg to 0.13 kg/kg and HCN yields range from 0.0006 kg/kg to 0.007 kg/kg.

Morikawa and Yanai [21] and Morikawa *et al.*[22] present the results of a series of fully furnished room fires in a two-story house. In all fires, the ignition source and fuel load were large enough to lead to rapid flashover in the burn room. The major fire gases were measured in the burn room and on the upper floor after flashover. Gas temperatures in excess of 700 °C were reported in the burn room; upper floor temperatures were not reported. CO and HCN levels reached more than 4 % volume fraction (40,000 ppm by volume) and 0.1 % volume fraction (1000 ppm by volume), respectively, in the upper floor within some of the ten minute tests. Although no yields for the important gases are reported, the authors conclude that HCN production increases when the [CO]/[CO_2] ratio is greater than 0.1.

Denize[23] reports on a series of furniture calorimeter tests on upholstered chairs. Similar burning behavior is seen for all the chairs. A representative sample is included in Table 27. He notes two regimes for the [CO]/[CO_2]ratio. Lower values, in the range of 0.005 to 0.01 are seen during the growth phase of the fire and higher values around 0.01 to 0.03 as the burning decreased. T-squared fire growth curves are seen to be a good representation of design fires for upholstered furniture fires.

Babrauskas *et al.*[24] report on a series of room tests conducted to compare a range of furnishing materials both with and without added fire retardants. They include bench-, furniture, and full-scale test results, including HRR, gas species, and animal exposures. For fires with HRR as high as 639 kW, CO yields ranged from 0.18 kg/kg to 0.23 kg/kg and average [CO]/[CO_2] ratios ranged from 0.02 to 0.19. They conclude that available escape time for occupants of a room with fire-retardant furnishings is more than 15-fold greater than for occupants of an equivalent room with non-fire-retardant furnishings.

Braun *et al.*[25] and Babrauskas *et al.*[26] report on large-scale tests conducted to compare to bench-scale toxicity measurements. Braun used different combustion modes: smoldering ignition initiated by a cigarette, flaming combustion initiated by a small gas burner, and smolder-to-flaming transition combustion initiated by a cigarette and forced into flaming after a prolonged period of smoldering. Yields of CO, CO_2, and HCN were included. CO yields ranged from 0.08 kg/kg to 0.15 kg/kg and average [CO]/[CO_2] ratios ranged from 0.01 to 0.2. HCN yields ranged form 0.0002 kg/kg to 0.01 kg/kg. Babrauskas used three different materials in a post-flashover fire with Douglas fir, a rigid polyurethane foam, or PVC lining the walls of the burn room. Yields of CO, CO_2, and HCN were included. CO yields ranged from 0.07 kg/kg to 0.5 kg/kg and average [CO]/[CO_2] ratios ranged from 0.01 to 0.2. HCN yields ranged form 0.0002 kg/kg to 0.01 kg/kg.

Tsuchiya [27] reports mainly [CO]/[CO_2] ratios for a series of fires. The ratios are seen to depend upon fuel type and fire conditions. He notes three burning regimes: pre-flaming smoldering, flaming growth or steady burning, and glowing as the fire decreases. Typical values of the [CO]/[CO_2] ratio include 0.14 during smoldering, from 0.005 to 0.025 for the flaming fires, and as high as 0.4 to 0.5 for post-flashover fires.

The data in Table 26 provide guidance for model simulations to estimate temperatures and gas concentrations in a variety of occupancies and fire conditions. For a wide range of fire sizes in open burning, likely equivalent to pre-flashover conditions, the [CO]/[CO_2] ratios are typically less than 0.1 and as low as 0.005. For the larger fires within rooms, most likely vitiated, the values are higher, with values in the reviewed data up to 0.4. It is noteworthy that experiments with wood-lined enclosures show much higher CO levels under vitiated conditions, with [CO]/[CO_2] ratios near unity.[28] While these conditions are seen most often in lethal scenarios, sub-lethal effects may be of note far removed from the room of fire origin.

HCN yields show less variation, with only one value greater than 0.02 kg/kg fuel. More typically, values in the order of 0.001 kg/kg to 0.007 kg/kg are evident, with several values less than 0.001 kg/kg.

Irritant gas yield data from full-scale tests are extremely rare. For example, the CBUF report[14] includes HCl yields that range from 0.0001 kg/ kg fuel to 0.03 kg per kg fuel. HBr concentrations were below 10^{-5} volume fraction and were not quantified further. Concentrations of other irritant gases were not measured.

Table 26. Heat Release Rate and Gas Yields for Selected Products Taken from Selected Literature Sources

Source	Combustible	Test Type	CO yield (kg/kg fuel)	$[CO]/[CO_2]$ mass ratio	HCN yield (kg/kg fuel)	HRR (kW)
Särdqvist	Easy chairs, tests Y5.3/10-14[a]	Furniture calorimeter	0.02 – 0.08	Not reported (n.r.)	n.r.	240 to 2100
	Sofas, Y5.4/10-23	Furniture calorimeter	n.r.	n.r.	n.r.	200 to 3000
	Wall linings, O4/10-11,20-24	Room/corner test	n.r.	~0.1	n.r.	1500 to >3000
	Curtains, Y7/10-14	Room calorimeter	n.r.	n.r.	n.r.	400 to 1500
Kokkala, et. al.	Wall coverings over gypsum wallboard	Room/corner test	n.r.	0.09 to 0.24	n.r.	1300 to 3400
Sundström	Upholstered chairs, 1:2, 1:4, 1:6, 1:8	Furniture calorimeter	0.01 to 0.02	n.r.	0.0002 to 0.004	780 to 1500
	Mattress, 1:21, 1:22	Furniture calorimeter	0.03 to 0.13	n.r.	0.003	300 to 870
Ohlemiller	Mattress, 21a	Furniture calorimeter	n.r.	0.006 to 0.33	n.r.	990
Purser	Armchair, CDT 10 to CDT 13	Open burning	0.07 to 0.12	0.007 to 0.12	0.009 to 0.013 [b]	n.r.
	Armchair, CDT 17 to CDT 23	Enclosed house, open fire room	0.01 to 0.17	0.09 to 0.15	0.01 to 0.02 [b]	n.r.
	Armchair, CDT 16	Enclosed house, closed fire room	0.18	0.25	0.09 [b]	n.r.
	Polyurethane seating foam	Furniture calorimeter and room corridor, flaming	0.04 to 0.09	0.012 to 0.047	0.0006 to 0.002	n.r.
	Polyurethane seating foam	Furniture calorimeter and room corridor, smoldering then flaming	0.06 to 0.13	0.03 to 0.07	0.001 to 0.007	n.r.
Denize	Chair, G-22-S2-1	Furniture calorimeter	n.r.	0.005 to 0.025	n.r.	750
Babrauskas	Various, all	Room calorimeter	0.18 to 0.23	0.02 to 0.19	n.r.	69 to 639
Braun	Foam and fabric, 1-10	Room, Room corridor	0.08 to 0.15	0.01 to 0.2	0.002 to 0.01	n.r.
Babrauskas	Wall linings, all	Room corridor	0.07 to 0.5	0.04 to 0.4	0.005 to 0.01	
Tsuchiya	Various	Various	n.r.	0.005 to 0.5	n.r.	n.r.

[a] Identification of test specimen from original work is included to provide reference to details of material and construction
[b] HCN yield is expressed as kg of HCN per kg of nitrogen-containing fuel

3. Computer Modeling Design

A number of simulations were performed using the CFAST (version 3.1) zone fire model.[29] This computer program predicts the environment in a structure that results from a specified fire. The CFAST model is widely used throughout the world, and has been subjected to extensive evaluations to study the accuracy of the model.

The simulations produced time-varying profiles of smoke concentration and temperature distributions. Since the main output was to be the relative times at which these two fire products produced incapacitation, and for simplicity of modeling operation, the people remained stationary as the environment around them evolved.

Three facility geometries were selected for the simulations. They contain features that capture the essence of many of the fixed facilities in Table 2 from Section II.A (single- or multiple-family residences, hospitals, nursing homes, board and care buildings, office buildings, day care facilities, schools, and detention/correctional buildings). The ranch house geometry is a typical single-family residence with multiple rooms on a single floor. The hotel geometry includes a single long corridor connecting two guest rooms. The long hallway would allow increased heat losses to the surroundings compared to the ranch house. The office geometry is a far larger structure with higher ceilings and a larger, more open floor plan than either of the other two geometries.

In any given year, very few people are exposed to fires in the largest, high-ceiling facilities (stadiums, large recreational buildings, warehouses, high hazard industrial buildings, and stores), and they are not included for that reason. The simulations of the various rooms of fire origin provide insight into the relative hazard from thermal or toxicological effects in single-compartment transportation vehicles (automobiles, trucks, buses, trains, urban mass transit vehicles, and aircraft). The principal difference between spacecraft and any of the above is the nominal absence of gravity in the former. Fires in spacecraft require different simulations than the ones performed here.

The selected combustibles are representative of the most common fires in which people are exposed to smoke. The design properties of these fires were varied, thus making these combustibles surrogates for almost any type of burning products. Table 27 summaries the simulations.

Table 27. Conditions in Computer Simulations

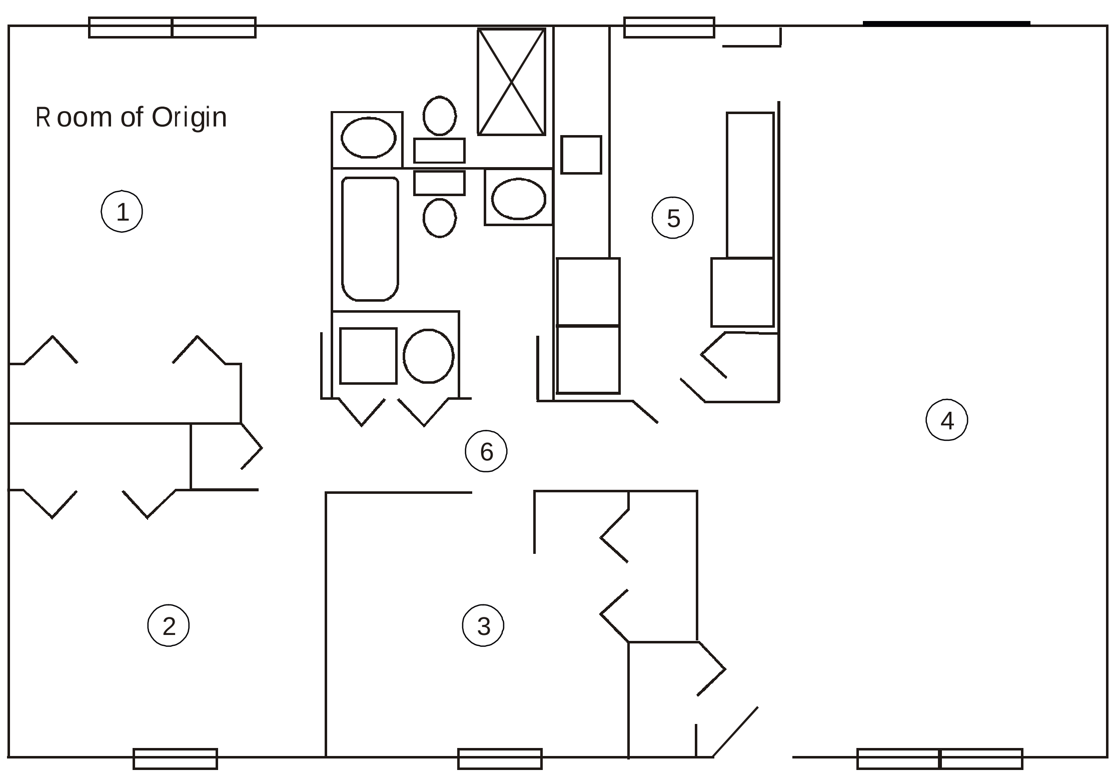
Facility	Combustibles
Single-level (ranch) house	Mattress and bedding
Business occupancy	Cooking materials
Hotel occupancy	Upholstered furniture
	Interior wall coverings

a. Ranch house. This configuration is intended to be a generic residential floor plan. The layout consists of three bedrooms, a central hallway, a combined living room and dining room, and a kitchen. The geometry is described in Table 28; the layout is shown in Figure 1.

Table 28. Geometry of the Ranch House

Room Number	Description	Floor Area (m^2)	Ceiling Height (m)	Door to:	Fire
1	Master Bedroom	13.68	2.4	6	Yes
2	Bedroom #2	10.80	2.4	6	No
3	Bedroom #3	10.20	2.4	6	No
4	Living & Dining Rooms	36.45	2.4	5, 6	No
5	Kitchen	10.26	2.4	4	No
6	Hallway	16.88	2.4	1, 2, 3, 4	No

Figure 1. Schematic of the Ranch House

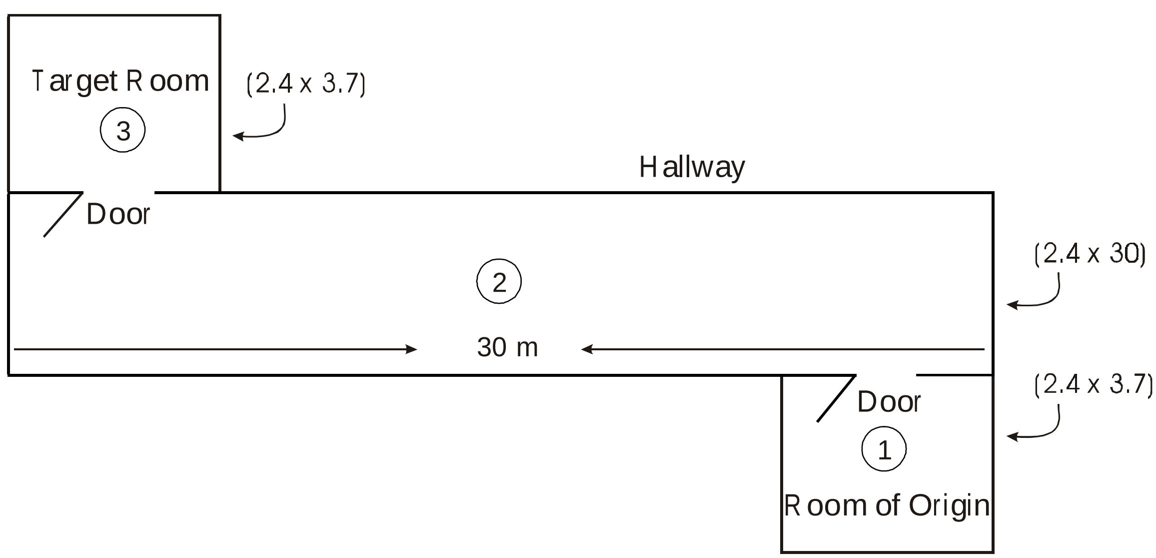


b. Hotel. This configuration consists of two sleeping rooms and a connecting hallway. The hallway is 30 m long, thus the separation between the rooms is quite significant. The geometry is summarized in Table 29 and the layout in Figure 2.

Table 29. Geometry of the Hotel Scenario

Room Number	Description	Floor Area (m^2)	Ceiling Height (m)	Door to:	Fire
1	Hotel Room	8.93	2.4	2	Yes
2	Hallway	73.20	2.4	1 , 3	No
3	Hotel Room	8.93	2.4	2	No

Figure 2. Schematic of the Hotel

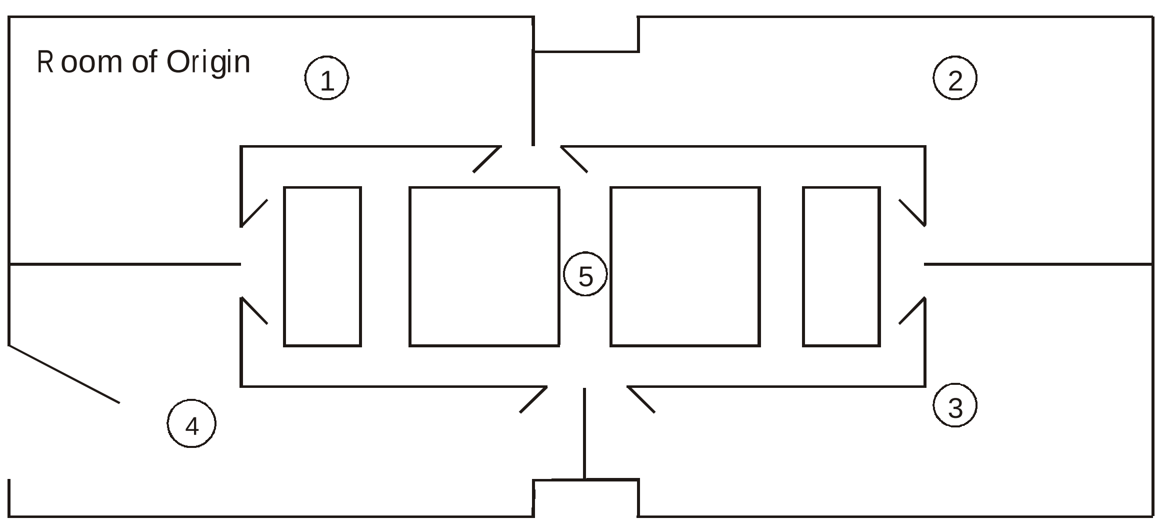


c. Office. This configuration consists of 4 equally sized office spaces enclosing a hallway and elevator lobby. Each office has two doors connecting to the hallway. The office layout is assumed to be an open floor plan with desks and/or cubicles. The geometry of the office is summarized in Table 30. The layout is also shown in Figure 3.

Table 30. Geometry of the Office Scenario

Room Number	Description	Floor Area (m^2)	Ceiling Height (m)	Door to:	Fire
1	Office 1	625	3	5	Yes
2	Office 2	625	3	5	No
3	Office 3	625	3	5	No
4	Office 4	625	3	5	No
5	Hallway and Elevators	1000	3	1, 2, 3, 4	No

Figure 3. Schematic of the Office



d. Design Fires. Previous analysis had shown that fires that proceeded beyond flashover could and did produce lethal environments outside the room of fire origin.[30] These results suggest that sublethal exposures to smoke are also readily possible for post-flashover fires. This paper also cited U.S. fire incidence data showing that about one fifth of the smoke inhalation deaths arose from fires that had not proceeded beyond the room of origin, suggesting that some types of these fires could result in people experiencing sublethal smoke exposures.

Accordingly, the design fires in this study were chosen to reflect a broad spectrum of fire behavior from smoldering fires to near-flashover fires in each of the three facilities.

- The smoldering fire was approximated with a steady 10 kW heat release rate. The thermal effects on people from a smoldering fire are generally negligible relative to the effects of the toxic species.
- Three geometry-dependent fires were selected to represent low, medium, and high levels of flaming combustion. The fires are geometry-dependent due to the fact that the maximum HRR is determined by calculating the minimum fire size that would result in flashover in the room of fire origin, using Thomas' flashover correlation.

Thomas' flashover correlation[31] is the result of simplifications applied to an energy balance of a compartment fire. The simplifications resulted in the following equation that has a term representing heat loss to the total internal surface area of the compartment and a term representing enthalpy flow out of the vent:

$$\dot{Q} = 7.8A_T + 378A\sqrt{h} \qquad (1)$$

Q is the minimum HRR required for room flashover (kW), A_T is the total surface area of the room (m^2), A is the area of the vent (m^2), and h is the height of the vent (m). The constants represent values correlated to experiments producing flashover.

The fire sizes for each scenario were chosen to range from 0.05 to 0.9 times the minimum flashover HRR calculated for the specific geometry. Thus, the absolute magnitude of the fire is higher for the office scenario (with its larger room size) than the hotel and ranch scenarios.

Finally, fires from experimental measurement of actual products prevalent in fire statistics were used to provide representative fires from the fire test data reviewed earlier. An upholstered chair fire and a mattress fire were included to place the generic design fires in context when compared to conditions generated from actual fire test data. Table 31 summarizes the design fires chosen for each scenario.

Gas species yields for these design fires were taken from the literature data reviewed earlier. For the flaming fires, the [CO]/[CO_2] ratio was set at a constant value of 0.03 and the HCN yield was set to 0.0003 kg/kg fuel from the literature data reviewed above. For the smoldering fires, higher yields were used, increasing the [CO]/[CO_2] ratio by an order of magnitude and the HCN yield by a factor of 2. For the upholstered chair and mattress fires, experimental data from the tests were used.

Table 31. Selected Design Fire Scenario Characteristics

Geometry	Fire Descriptor	Maximum HRR (kW)	Growth Characteristics
Ranch	Smoldering	10	Steady
	0.05 • Flashover	87	Linear
	0.1 • Flashover	174	Linear
	0.5 • Flashover	869	Linear
	0.9 • Flashover	1,564	Linear
	Upholstered Chair	1490	$\sim t^2$
	Mattress	990	$\sim t^2$
Hotel	Smoldering	10	Steady
	0.5 • Flashover	713	Linear
	0.9 • Flashover	1,283	Linear
Office	Smoldering	10	Steady
	0.5 • Flashover	5974	Linear
	0.9 • Flashover	10,752	Linear

e. Tenability Criteria. The following are the criteria used for the two potential effects on people. As in all zone model calculations, the hot gases are presumed to be uniformly mixed in an upper layer and not present in a lower layer in each room. The effects of concentrated smoke or high temperatures near the fire itself are not included.

Heat exposure: The current version of ISO document 13571[32] includes equations for calculating incapacitation from skin exposure to radiant heating and from exposure to convected heat resulting form elevated gas temperatures. Combining the two, a dimensionless Fractional Effective Dose (FED) for heat exposure is given as:

$$\mathrm{FED}_{\mathrm{HEAT}} = \sum_{t_1}^{t_2} \frac{q^{1.33}}{1.33} \Delta t + \sum_{t_1}^{t_2} \frac{T^{3.4}}{5 \times 10^{7}} \Delta t \qquad \textbf{(2)}$$

where q is in kW/m^2 and T is in °C.

Gas Concentration: The FED equation for the incapacitating effects of asphyxiant gases, derived from the current version of ISO document 13571 is:

$$FED_{GASES} = \sum_{t_1}^{t_2} \frac{CO}{35000} \Delta t + \sum_{t_1}^{t_2} \frac{\exp(HCN/43) - 1}{220} \Delta t \qquad (3)$$

The HCN term has been modified slightly from $\exp(HCN/43)/220$ to eliminate the artifact of a zero HCN concentration resulting in lethality at very long exposures. CO and HCN are the average concentrations of these gases (in the conventional ppm by volume) over the time increment Δt. The person "receives" incremental doses of smoke until an incapacitating value of FED is reached.

The ISO document also includes an equation for incapacitation from irritant gases. Few sets of large-scale test experimental include yields of irritant gases. In addition, current fire modeling capabilities do not typically include the ability to track the generation and transport of multiple irritant gases. Thus, an irritant gas (HCl) was only included in our analysis for one scenario where such data were available. For the other calculations, we assumed that the asphyxiant gases accounted for all or half of the overall tenability due to gas inhalation.

The Fractional Effective Concentration (FEC) equation for the incapacitating effect of irritant gases in the current version of ISO document 13571 is:

$$FEC = \frac{[HCl]}{1000} + \frac{[HBr]}{1000} + \frac{[HF]}{500} + \frac{[SO_2]}{150} + \frac{[NO_2]}{250} +$$

$$\frac{[acrolein]}{30} + \frac{[formaldehyde]}{250} + \sum \frac{[Irritant]_i}{C_i}$$

For our analysis, two FED or FEC values were used:

- FED or FEC = 0.3, indicating incapacitation of the susceptible population. This limit was used for both heat and gas tenability.
- FED or FEC = 0.01 (1 % of the lethal FED value for the susceptible population), a value well below a level at which a significant sublethal effect would occur. This limit was used only for the gas tenability.

The following hazard calculations were based on the assumption that occupants would breathe the relatively clean lower layer gases when possible. Specifically, if the layer height were above 1.5 m, lower layer values were used, since occupants could breathe lower layer gases while standing. If the layer height were between 1 m and 1.5 m, the upper layer values were used if the upper layer temperature was below 50 °C; otherwise, the lower layer values were used. This presumes that occupants would breathe upper layer gases if the gas were not to hot; otherwise they would bend over and breathe lower layer gases. If the layer height were below 1 m, the upper layer values were used, since occupants could not bend far enough if the gases sufficiently filled the room. While some occupants might crawl, this cannot be presumed, and the upper layer assumption is conservative. FEC calculations were based solely on upper layer values since the FEC is based on an instantaneous exposure.

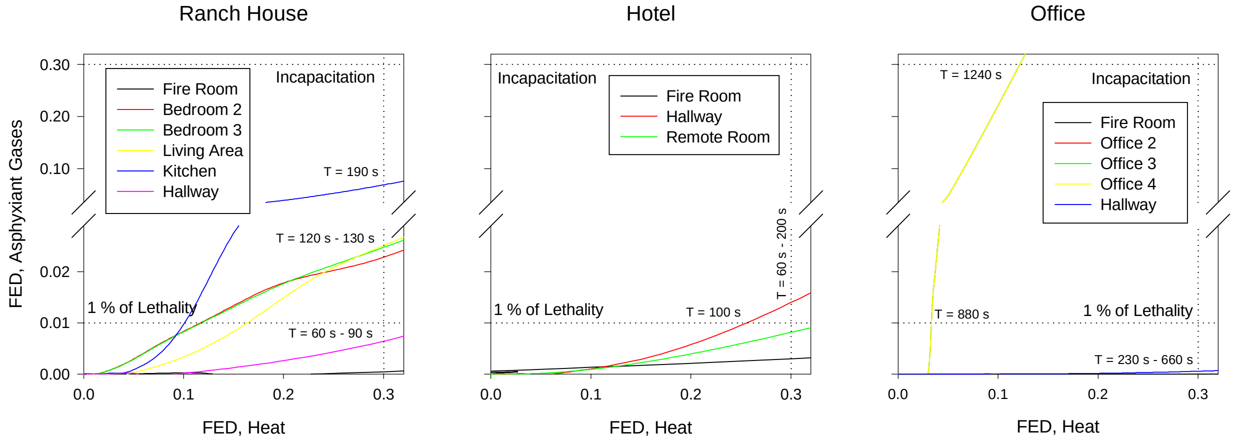
4. COMPUTER MODELING RESULTS

a. Baseline Results. A baseline scenario was conducted for each of the three geometries. The door to the room of fire origin was fully open and the fire had a linearly increasing HRR (increasing by 10 kW/s) until a maximum HRR of 90 % of the minimum HRR necessary for room flashover, as determined by Thomas' flashover correlation.

Figure 4 shows the relative importance of the thermal FED criterion *vs.* the gas FED criterion at incapacitation and at 1 % of the lethal concentration levels.

- *Ranch house configuration.* The occupants of rooms 1 and 6 were overcome by heat before any sublethal effects were noted (the 1 % of lethality criterion). For rooms 2 through 5 (bedrooms, living/dining room, and kitchen) the criterion for incapacitation by heat was achieved between 120 s and 190 s, soon after the conservative threshold for any sublethal effect was passed - between 90 s and 140 s, and well before smoke inhalation was incapacitating. Even in the kitchen, the room farthest from the fire, incapacitation from heat occurred well before incapacitation from smoke inhalation, but at times when lesser smoke effects might be felt. Thus, in all cases, incapacitation from thermal exposure occurs before incapacitation from gas inhalation, but sublethal smoke effects might occur remote from the fire room.
- *Hotel configuration.* Thermal effects significantly preceded any toxicity effects in all rooms.
- *Office configuration.* The volume of the office occupancy is large due to the higher ceilings (relative to the other two scenarios) and the large square footage of the office and hallway spaces. This doubles the effective volume above the height where occupants would be exposed. Thermal effects dominate in the office of fire origin, as well as in the hallway outside that office, resulting in heat criterion achievement in 230 s and 660 s, respectively. People in the remaining offices crossed the 1 % of the lethal gas FED threshold at 880 s, while becoming incapacitated from smoke inhalation at 1240 s. Incapacitation from heat occurred at 1570 s. However, for this scenario the occupants are estimated to be evacuated from the fire floor within 370 s [33], well before incapacitation and even before the potential onset of sublethal effects in some areas. Causality for the differing scenario results is investigated below.

Figure 4. Comparison of Thermal Effects and Narcotic Gas Effects for Several Different Geometries



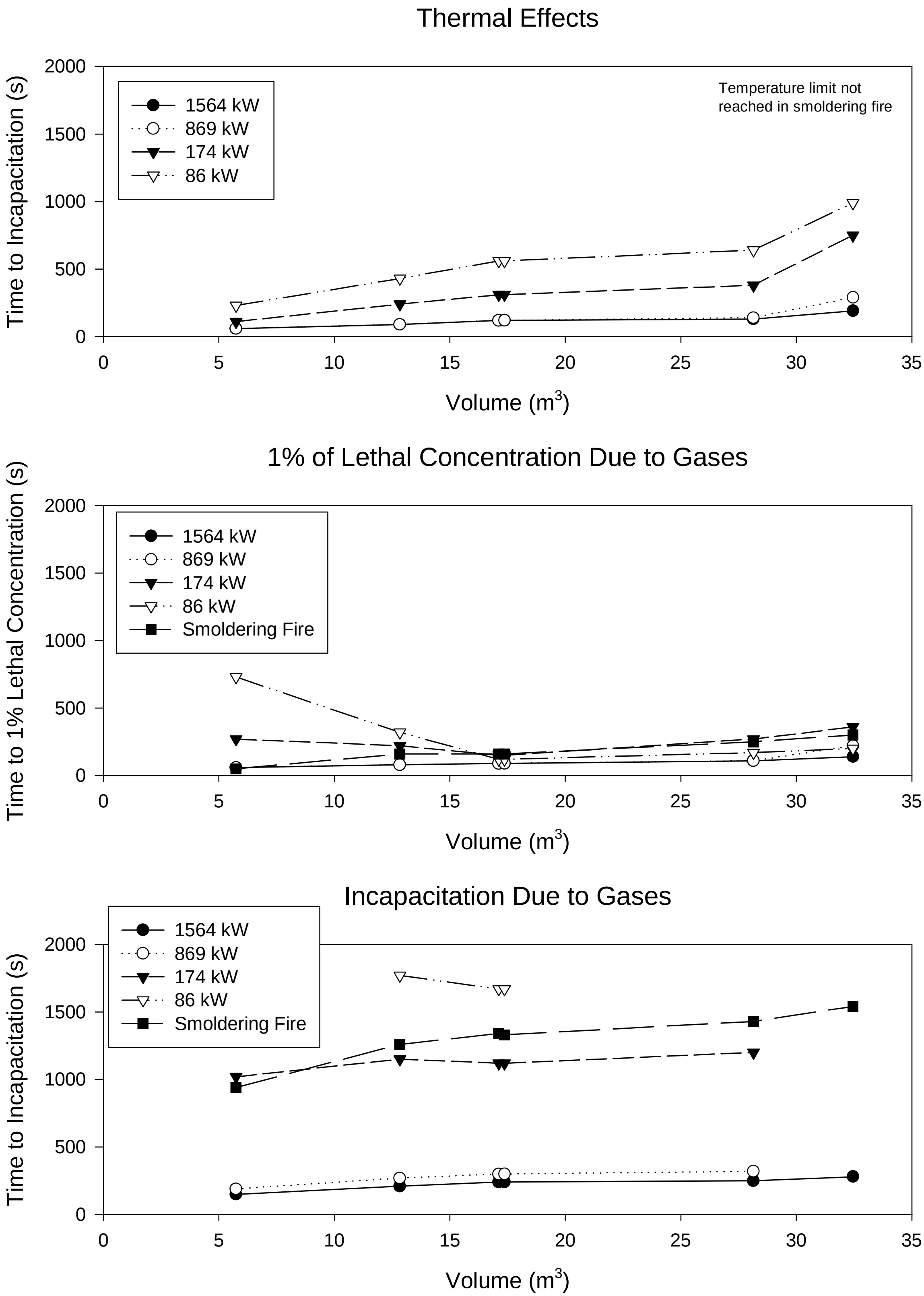
b. Effect of Fire Size Variation. Since the magnitude of a fire in a room will affect, in different ways, the rates of temperature rise and mass of toxic gases, simulations were performed in which the fire size was systematically varied. Five different fire sizes were simulated in the ranch house scenario (only), ranging from smoldering (10 kW) to 0.9 times the HRR for flashover (1564 kW). Figure 5 shows the results in times to effect for different fire sizes as a function of a fill volume. As the fire grows, the smoke must fill the top of the room (the floor area times the distance between the ceiling and top of a door) before the fire effluent can spread to subsequent rooms. Each time the smoke spills into another space, the additional room results in a step increase in this fill volume.

Incapacitation from thermal effects.

- For the largest HRR fires (1564 kW and 869 kW), the thermal criterion was rapidly exceeded in all rooms.
- For the 10 % of flashover fire level (174 kW), the effects of volume separation were significant. Incapacitating exposures in the rooms intimate with the fire (room of origin and hallway) were reached in less than 250 s, while the subsequent rooms (bedrooms 2 and 3, living room, and kitchen) remained tenable for 310 s to 750 s.
- For the small, 86 kW fire, an incapacitating exposure was reached in the room of fire origin in 230 s, but not in the kitchen until 990 s.
- For the smoldering fire, the thermal criterion was never exceeded in any of the rooms.

Thus, large fires resulted in rapid thermal effects throughout the ranch house. A critical intermediate fire size exists for which thermal tenability limits may or may not be achieved based upon proximity to the fire (intervening volume). Very small fires do not realize significant thermal impact on people beyond the room of fire origin.

Figure 5. Effect of Fire Size on Time to Incapacitation due to Thermal Effects and Narcotic Gases for Fires in a Ranch House.



Incapacitation from narcotic gases.

- For the largest fire (1564 kW), the criterion for incapacitation by smoke inhalation was rapidly exceeded in all rooms. The same is true of the 869 kW fire, with the exception of the kitchen, from which people could escape for 3180 s, almost an hour.
- For the 174 kW fire, the time to incapacitation was far longer, greater than 1000 s for all rooms. People could still escape from the kitchen after 7200 s (which is beyond the time interval over which the FED equation is valid).
- People would not be incapacitated by smoke from the smallest flaming fire (86 kW) except after long times in the hallway (1770 s) and the two bedrooms (1670 s). The room of fire origin does not become untenable due to a vent to the outside.
- For the smoldering fire, the incapacitation criterion was exceeded, but at long exposure times, in all rooms. This is because the toxic species yields were taken to be significantly higher (10 times the CO and twice the HCN) for smoldering fires than flaming fires.

Thus, large fires can rapidly generate incapacitating exposures throughout the facility. Logically, smaller fires take disproportionately longer to do so. Smoldering fires can lead to shorter times to incapacitation than small flaming fires due to higher narcotic gas yields. In all cases, unlike for thermal effects, the intervening volume (remoteness from the fire) has a minimal effect upon times to incapacitation by smoke inhalation, as shown by the shallow curve slopes in Figure 5. By the time toxic gases become important, the entire volume of the house is filled below the door lintels. Thus, the structure resembles a single large volume more than a series of smaller spaces.

"No effect" criterion.

For all the fires, this sub-threshold exposure is exceeded within five minutes in all rooms, and thus some secondary effects of smoke are possible if evacuation or rescue is delayed. Similar to the incapacitation results, there is little dependence on the intervening volume at all fire sizes. Again, the structure resembles a single large volume more than a series of smaller spaces.

In general for these pre-flashover flaming fires with all open vents, the time to incapacitation from thermal effects is comparable to or shorter than the time to incapacitation from inhalation of asphyxiant gases. For the smoldering fire, thermal effects are, of course, not important, while incapacitation from smoke inhalation can occur.

c. Effect of Variation in the Fire Room Doorway (Vent) Opening. The results of simulations of the impact of ventilation between the room of fire origin and the rest of the ranch house scenario are shown in Figure 6. The HRR of the fire is 1564 kW, or 90 % of the HRR that would lead to flashover with the door fully open. Based on Thomas' flashover correlation, the scenarios with the door partially closed would result in fire room flashover.

The effect of decreasing the door opening was to decrease the available ventilation to the fire room. An oxygen-limited fire may result, thus decreasing the prescribed HRR of the fire. Additionally, flow is reduced between the room of origin and the rest of the structure. The average flow from the room of fire origin to the connecting hallway with the doorway 10 % open was roughly one fifth of the flow when the vent was fully opened.

Incapacitation from thermal effects. Changing the vent opening had a significant impact on the time to thermal incapacitation. When the door to the room of fire origin was completely open, the exposure criterion was exceeded for all rooms in less than 190 s. Reducing the door opening by half resulted in a significant difference only in the kitchen, the room farthest from the fire, where the time to incapacitation increased from 190 s to over 350 s. The differences for all other rooms were less than 30 s. Closing the door to 10 % open resulted in times to incapacitation 3 to 5 times longer than if the door were 100 % open for all rooms except for the room of fire origin. The kitchen did not exceed the thermal criterion in 500 s.

Incapacitation from narcotic gases. Incapacitation from smoke inhalation occurred in all rooms between 150 s and 280 s with the door fully or half open. Having only 10 % of the original door opening resulted in toxicity incapacitation times between 400 s and 470 s for all rooms except the room of fire origin. [The fact that the kitchen did not become untenable when the door was 50 % open was a function of the assumptions made in the analysis of which layer (upper or lower) the occupant was breathing. Since the upper layer was warm (greater than 50 °C) but greater than 1 m off the floor, the occupant was assumed to breathe the lower layer (low toxic gas concentrations, relative to the upper layer). In the door 10 % open scenario, the upper layer temperature in the kitchen was less than 50 °C, and the layer height was between 1 m and 1.5 m. Therefore the occupant was assumed to breathe air from the upper layer.]

"No effect" criterion. Generally, within about two minutes, there was a hypothetical potential for sublethal effects throughout the house. This took a bit longer in the kitchen when the door is half open. Interestingly, when the door was open only 10 %, the flow from the hallway (to the two bedrooms and the dining/living room) exceeded the flow to the hallway from the room of fire origin, extending the tenability somewhat. With larger door openings, the flow to the hallway dominated.

Severely restricting the opening between the fire room and the rest of the structure limits the flow of gases out of the fire room. This results in longer times both to thermal effects and to effects from combustion products.

Figure 7 shows a comparison of the thermal and gas concentration effects for two single-item fires taken from the literature reviewed above. In the ranch house, both the upholstered chair and the mattress fire resulted in occupants being overcome by thermal effects at or before the time gas concentrations reached 1 % of lethal values. Temperatures reached 100 °C in rooms outside the room of fire origin within 130 s for the chair fire and 260 s for the mattress fire. (For the mattress fire, the kitchen never reached 100 °C.) Gas concentrations reached 1 % of lethal values within 110 s to 190 s for the chair and mattress fire, respectively. Incapacitation occurred far later, with values ranging from 460 s to 650 s for the chair fire and from 560 s to 920 s for the mattress fire.

In all but the smallest fires, times to incapacitation are greater than or competitive with the time occupants would be overcome by thermal effects resulting from the fire. In some cases, notably larger fires with open vents near the room of fire origin, incapacitation due to thermal effects occurs prior to any sublethal effects.

Figure 6. Effect of Fire Compartment Vent Opening on Time to Incapacitation due to Thermal and Narcotic Gas Effects for Several Rooms in a Ranch House

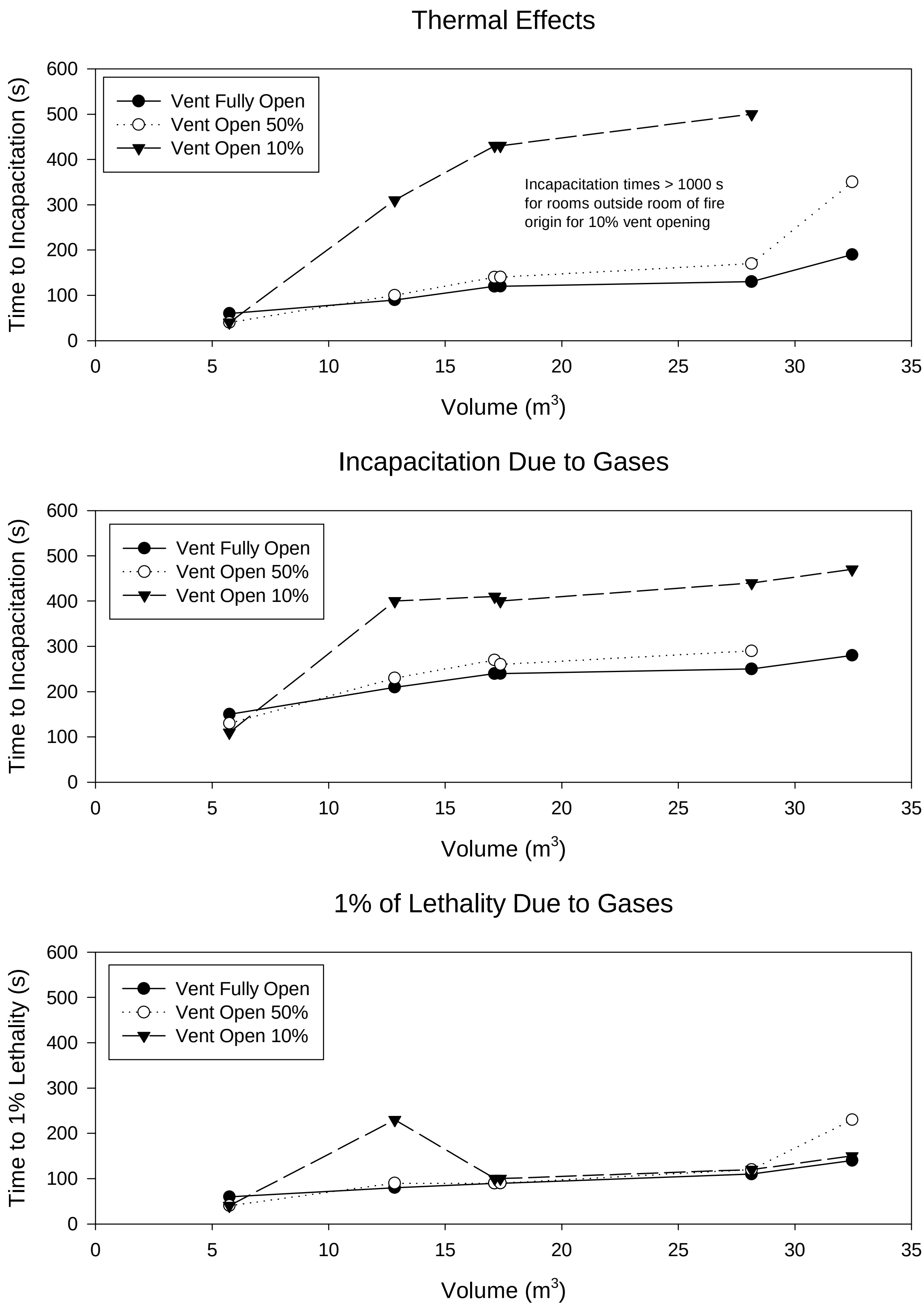
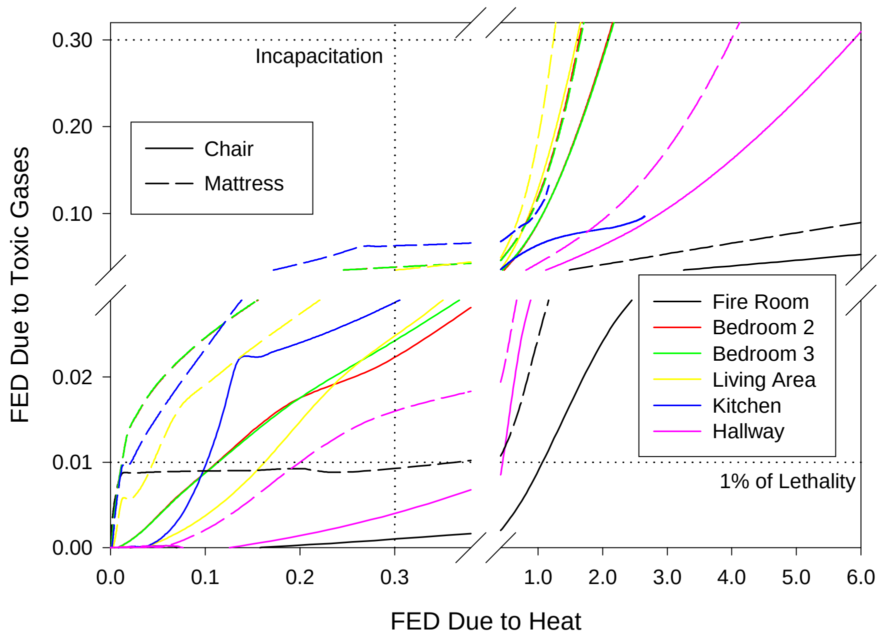


Figure 7. Comparison of Incapacitation from Thermal Effects and Narcotic Gas Effects for Two Single Item Fires in a Ranch House



d. Sublethal Effects from Irritant Gases. There are numerous accounts of people "suffering from smoke inhalation" as they evacuate a building. Many of these are presumably from exposures of the order of a few minutes or less. Based on the above simulations, these effects are not likely to be from narcotic gases. It is more probable that the cause is irritant gases, exposure to which causes upper respiratory effects very quickly, especially at the incapacitating level.[32] As stated earlier, there is a dearth of irritant gas yield data from room-scale tests and so they were not studied in detail for this analysis.

For one of the single-item fires, an upholstered chair, yield data for HCl were available. For this scenario, FEC values for exposure to HCl were calculated along with FED values for asphyxiant gases and heat. FEC values never reached incapacitating levels in any of the rooms of the ranch house. Irritant gases reached 1 % of lethal conditions at times roughly comparable to those for narcotic gases. Typical values of the FEC for HCl exposure at incapacitation times due to heat or narcotic gases were approximately 0.03 and 0.06, respectively. The HCl yield for this item was only 0.002 kg/kg fuel; it would have to be 5 to 10 times higher for incapacitation from HCl to occur at times comparable to heat or asphyxiant gases.

5. SUMMARY: FIRE SCENARIOS FOR WHICH SUBLETHAL EFFECTS COULD LEAD TO SIGNIFICANT HARM.

It had previously been shown for *post-flashover* fires that thermal conditions are the first to make the room of fire origin untenable and that lethal or incapacitating exposures could precede intolerable thermal conditions in rooms remote from the fire room.[30]

From the computer modeling in Section III.C, we now project that for *pre-flashover* fires:

- In the room of fire origin, incapacitation from thermal effects generally will occur before narcotic gas concentrations reach even 1 % of lethal conditions. The exception to this involves smoldering fires that generate little heat and, with little buoyancy to drive mixing throughout the space, can readily generate incapacitating exposures, especially for occupants intimate to the smoldering item.
- Outside the room of fire origin, in buildings with large rooms, smoke is diluted rapidly, and the exposure threshold for significant smoke inhalation effects will occur well after incapacitation from heat.
- Outside the room of fire origin, in residential buildings and other buildings with ordinary-size rooms, incapacitation from smoke inhalation will rarely occur before incapacitation from heat and thermal radiation or escape or rescue. These occurrences of incapacitation from smoke would take place remote from the room of fire origin at times long after ignition. In remote rooms, the exposure threshold for significant sublethal effects may well be exceeded from fires that stay below flashover.
- Under certain ventilation conditions, fires in concealed spaces (from which cooled but noxious smoke could escape into adjacent areas) in any occupancy could produce harmful smoke environments.

There are few data sets from room-size fires that include the yields of irritant gases. Depending on those yields, the time to incapacitation from irritant gases could be comparable to the time to incapacitation from narcotic gases.

These projections, which would benefit from experimental confirmation, are consistent with analyses of U.S. fire incidence data.[30] 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.

This knowledge suggests that occupancies in which sublethal effects from open fires could affect escape and survival include:

- multi-room residences,
- medical facilities,
- schools, and
- correctional facilities.

In addition, fires originating in concealed spaces in any occupancy pose such a threat.

In the following occupancies sublethal smoke effects of smoke are not likely to be of prime concern:

- Open fires in single- or two-compartment occupancies (*e.g.*, small apartments and transportation vehicles) themselves; however, sublethal effects may be important in adjacent spaces;

- Buildings with high ceilings and large rooms (*e.g.*, warehouses, mercantile); and

- Occupancies in which fires will be detected promptly and from which escape or rescue will occur within a few minutes.

6. Future Work

Time-dependent yield data for typical fire-generated gases, especially irritant gases, from room-scale fires are almost non-existent and are needed before firm conclusions can be drawn.

D. TOXIC POTENCY VALUES FOR PRODUCTS AND MATERIALS

To be able to perform the toxicity component of a fire hazard or risk analysis, the practitioner needs to know how much smoke it takes to produce undesirable effects on people. Over the past 30 years, scientists have developed numerous methods and extensive data for a variety of single component materials and commercial products. Nearly all of the studies involved combusting a small sample in a laboratory apparatus intended to simulate some type of fire; exposing laboratory animals, generally rodents, to the smoke; and characterizing the result. The typical measurement is an EC_{50}, the **c**oncentration of smoke (*e.g.*, in g/m^3) needed to produce an **e**ffect in half (**50** %) of the animals in a given exposure time. Nearly all of the material and product data are for lethality (LC_{50}) or incapacitation (IC_{50}).

This section of the report examines that wealth of data, sorts it by the combustion conditions (related to a type of fire) producing the smoke, the specimens tested, and the animal effect measured. We use the best available information to extrapolate from data for the median rodent to values for a susceptible person and then update the generic values to use in fire hazard analysis when the composition of the mix of combustibles is unknown. This is valuable in both building design and fire reconstruction. A key component of this evaluation is the assignment of an uncertainty range to the derived toxic potency values.

There exists related literature on the toxicological effects of the individual and combined gases in smoke on animals and people. An assessment of those data is to be the subject of another study.

1. Compilation of Toxicological Data

The search for lethal and sublethal toxic potency data for materials and products involved on-line library searches for pertinent books, journal articles, proceedings, and technical reports. The primary on-line database used for this literature search was the Fire Research Information Services (FRIS) maintained by the Building and Fire Research Laboratory at NIST. Other on-line library searches were performed using TOXLINE and MEDLINE (maintained by the National Institutes of Health) and the Office of Pollution Prevention and Toxic Substance Library (maintained by the Environmental Protection Agency). In addition, technical experts involved in the project were asked for unpublished data and other published data that were not readily available otherwise. Table 32 presents a summary of the literature search, including the number of citations found. A complete list of references obtained is presented as a separate list in Appendix A to this report.

2. Data Organization

The literature review identified different types of toxicity test methods ranging from laboratory small-scale tests to full-scale tests. To enable analysis of the full set of toxic potency data, the results from the various test methods were categorized by:

- Combustion/pyrolysis condition
- Material/product examined
- Type of test animal
- Toxicological endpoint

Table 32. Sources of Toxic Potency Data

Source	Number of Citations
Annual Review of Pharmacology and Toxicology	1
ASTM/ISO Publications	4
Environmental Health Perspectives	2
Journal of American Industrial Hygiene Association	2
Journal of Archives of Environmental Health	3
Journal of Combustion Science and Technology	1
Journal of Combustion Toxicology	39
Journal of Consumer Product Flammability	1
Journal of Fire and Flammability	1
Journal of Fire and Materials	18
Journal of Fire Safety	2
Journal of Fire Sciences	23
Journal of Fire Technology	4
Journal of Forensic Materials and Pathology	1
Journal of Fundamental and Applied Toxicology	3
Journal of Industrial Hygiene and Occupational Medicine	1
Journal of Macromolecular Science-Chemistry	1
Journal of Medical Science and Law	1
Journal of Science	2
Journal of Testing and Evaluation	1
Journal of the American College of Toxicology	2
Journal of Toxicology	1
Journal of Toxicology and Applied Pharmacology	3
Journal Zeitschrift Fur Rechtsmedizin	1
NIST Publication, Technical Notes, and Report	23
Proceedings	38
Other Reports	25
Toxicology Letters	1

a. Combustion/Pyrolysis Conditions. As shown in Table 5 (Section III.A) there is a small number of types of combustion in fires:

- oxidative pyrolysis (non-flaming), typical of products being heated without bursting into flames themselves;
- well-ventilated flaming combustion, typical of pre-flashover fires;
- ventilation-limited combustion, typical of post-flashover fires or fires in nominally airtight spaces; and
- smoldering, or self-sustaining, non-flaming combustion.

The purpose of a small-scale toxic potency measurement is to obtain data from a small material or product sample that is germane to some particular set of realistic fires. In this section, we assess the combustion conditions in the 12 small-scale apparatus for which data are available. Each apparatus will then be aligned with one or more of these realistic fire conditions.

As shown in Table 33, the combustors in the small-scale apparatus fall into three types: cup furnace, radiant heater, and tube furnace. While measurements of combustion gases have been made in a number of other small-scale devices, these 12 are the only ones for which animal exposure data have been reported.

In the cup furnace methods, the sample is placed in an open-top quartz beaker that is set in a furnace. The bottom and lower portions of the beaker are heated to a pre-set *temperature*, which is generally picked to be above or below the autoignition temperature (AIT) of the pyrolysis vapors. The pyrolysis or combustion vapors rise and flow out the top of the beaker into the box in which the animals are exposed. The box is closed, so the test animals experience the accumulated combustion products. Combustion tests have shown that the lethal toxic potency of pyrolysis smoke is at a maximum at furnace temperatures near the AIT. Thus, in most non-flaming cup furnace tests, the furnace temperatures are kept at approximately 25 ºC below the predetermined AIT to ensure conservative toxic potency values. For flaming tests, the oxygen concentration remains high enough that the vitiation does not obscure the toxicity of the smoke. Natural buoyancy tends to draw sufficient “fresh” air to the sample so that the combustion product profile for flaming samples is indicative of fuel-limited combustion. Thus, cup furnace data are typically used to represent well-ventilated flaming combustion and oxidative pyrolysis.

In the radiant heat devices, the sample is exposed to a defined *heat flux*. The irradiance is generally sufficiently high (*e.g.*, 50 kW/m^2) and abetted by an ignition device to ensure flaming for all but the most resistive products or low enough (*e.g.*, 25 kW/m^2) to preclude flaming of all but the most readily ignitable smoke. The combustion products remain in a closed compartment, and the animals are exposed to the time-integrated accumulation of smoke. The smoke is indicative of well-ventilated burning. [It has also been shown that the data can be used to calculate the toxic potency of smoke from post-flashover burning by enhancing the carbon monoxide yield to that level observed in post-flashover fires.[34]]

Table 33. Small-Scale Toxicity Test Methods

Method Group	Individual Test
Cup Furnace Methods	NBS Cup Furnace
	Dow Chemical Company Method
	University of Utah Method
Radiant Heat Methods	Weyerhaeuser Method
	NIST/SwRI Method
Tube Furnace Methods	UPITT Method
	DIN 53 426 Method
	Federal Aviation Administration Method
	University of San Francisco Method
	University of Michigan Method
	University of Tennessee Method
	NASA/JSC Method

Like the cup furnaces, the combustion environment in tube furnaces is defined by *temperature*. This can be uniform, a fixed value, or a time-variant (ramped) range. The sample lies within a long horizontal tube, much of which lies inside the furnace. In some devices the sample is stationary, in others it is moved through the heated zone of the tube, replenishing the supply of fresh fuel. In the tube furnace experiments reviewed there is no mention of the ignition of smoke in the combustion device. Tube furnaces are open systems, with the air flowing to the sample and through the combustion zone. The animals are thus exposed to a time-varying smoke composition. Depending on the particular apparatus and operating procedures, it was difficult to determine discrete fire conditions represented by the tube furnace combustion.

None of these devices can accurately replicate a 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 bench-scale devices.

In most of the cited literature, the combustion conditions represented in a test were either vague or completely undefined. Thus, in order to make use of as large a fraction of the accumulated data as possible, we attempted our own assignments. This was achieved as follows:

- For those tests in which the sample flamed, the ratio of the concentrations or yields of carbon dioxide (CO_2) and carbon monoxide (CO) was reported, and the [CO_2]/[CO] ratio was eight or greater, the combustion mode was considered well-ventilated. For tests in which the [CO_2]/[CO] ratio was less than 8, the combustion mode was considered ventilation-limited. In cases of flaming combustion where the concentrations or yields were not reported, the toxicity data were most often set aside.

- In some flaming experiments, the nature of the sample being burned had a strong influence on the ventilation. For example, in cup furnace experiments with low-density samples (with a corresponding large size relative to the beaker), oxygen access to the burning site is expected to be impeded, and the combustion would tend toward ventilation-limited. In experiments with high-density samples (with a corresponding small size relative to the beaker), oxygen levels are expected to be higher.

- In many of the tube furnace tests, it was not reported whether the sample flamed and, if so, for what portion of the test. To determine retroactively whether flaming was likely, we compared the reported furnace temperature with an AIT for the material being tested. [The source of these temperatures was the cup furnace literature, in which the AIT of the test material was measured in order to assure flaming or non-flaming combustion. Knowing that, *e.g.*, all polystyrenes do not have the same AIT, we nonetheless used the cup furnace AIT value as indicative, for lack of better information.] If the furnace temperature was at least 25 ºC above the AIT, we considered the combustion to be flaming. Where the furnace temperature was at least 25 ºC below the AIT, the combustion was labeled non-flaming. When the furnace temperature was within 10 ºC or so of the AIT, the data were set aside. In some cases, CO and CO_2 concentration or yield data were reported. This information was also used to make the determination of combustion conditions.

Reports on many of the tube furnace articles (specifically, the descriptions for the combustion oven experiments at the University of Pittsburgh, University of Michigan, University of Tennessee, and NASA/Johnson Space Center) did not provide sufficient information to establish the fire conditions being represented. Furthermore, in some of the tests spontaneous flaming occurred in otherwise non-flaming experiments. In either of these cases, the data generated from these experiments were set aside since they could not be directly related to one of the three combustion conditions. Table 34 summarizes the relationships we found between toxicity methods and fire conditions.

Table 34. Fire Conditions Replicated by Principal Toxicity Test Methods

Method Type	Fire Conditions			
	Well-ventilated Flaming	Ventilation-limited Flaming	Oxidative Pyrolysis	Mixed or Unknown
Cup Furnace	X	X	X	
Radiant Furnace	X	X		
Tube Furnace		X		X

b. Materials and Products Examined. The citations included toxic potency data for a wide range of single component materials and for a limited number of products. Very few references provided the detailed composition of the test specimens. Typically, the sources provided the generic polymer and whether or not the material or product was fire retarded. The type or formulation of the retardant(s) was often lacking. Given the vagueness of such details, we grouped the tested items into generic classes of materials and products, which are presented in Table 35.

Table 35. Material and Product Groupings

Acrylic fibers	Polyesters
Acrylonitrile butadiene styrenes	Polyester fabric/polyurethane foam
Bismaleimide	Polyethylenes
Carpet (modacrylic/acrylic)	Polyphenylene oxides
Carpet foam (with nylon)	Polyphenylene sulfides
Carpet jute backing (with nylon)	Polyphenylsulfones
Chlorofluoropolymers	Polystyrenes
Epoxy	Polyurethanes, Flexible
Fabric, vinyl	Polyurethanes, Rigid
Fluoropolymers (data set A)	Polyvinyl chlorides, Plasticized
Fluoropolymers (data set B)	Polyvinyl chloride, Resin
Modacrylics	Urea formaldehydes
Phenolic resins	Wire insulation, NFR cross-linked EVA
Polyacrylonitriles	Wire, PTFE coaxial
Polyamides	Wire, THHN with nylon-PVC jacket
Polycarbonates	

The fluoropolymers were separated into two distinct sets (A and B) because, as will be seen below, the lethality values fell into two groups that were two orders of magnitude apart. Fluoropolymer data set B is shown only for completeness. Real-scale experiments have shown that these very high toxic potencies are not realized when hydrogen-containing combustibles are also involved in the fire.[35] Thus, this set of values has not been used in the analyses that follow. The fluoropolymers were the only product group for which the data warranted this separation.

c. Test Animals. The test subjects used in all the listed toxicity test reports were rats and mice. As noted above, the data from the two methods that used mice (University of Pittsburgh and University of San Francisco devices) were not used in this analysis because of the indeterminate flame conditions in those apparatus. Thus, the data evaluated in this compilation are based solely on rats as the test subject. We do not differentiate among strains of rats used in the experiments.

The number of test subjects and their exposure to the smoke also varied among the tests. In the cup furnace and radiant heat methods, individual rats were positioned such that only their heads were exposed to the smoke. In the tube furnace methods, rats or mice were exposed as either individuals in a head-only position or as groups in whole-body positions. For the purposes of this study, the toxicity data are evaluated only in terms of the species used, not the number or position of the subject.

d. Toxicological Endpoint. The toxicological effects encountered during the literature review were lethality and incapacitation. There were no data found on other sublethal effects. Table 36 presents a matrix of the reported lethality endpoints, grouped by the toxicity methods.

Table 36. Toxicological Effects Measured Using Principal Test Methods

	Toxicological Effect			
Method Type	**LC_{50}**	**LL_{50}**	**IC_{50}**	**Other**
Cup Furnace	X		X	
Radiant Heat	X			
Tube Furnace	X	X		

Smoke lethality was expressed as either a lethal concentration or lethal loading. The lethal concentration, which is expressed as an LC_{50} value, is the mass loading or mass combusted of a specimen per unit chamber volume (smoke concentration, in g/m^3 or mg/l) that kills 50 % of the test animals during a fixed exposure time and perhaps a post-exposure observation period. The lethal loading, which is expressed as an LL_{50} value, is defined as the mass loading in the furnace that kills 50 % of the test animals as a result of a fixed exposure time (mass of material, g). Unless the latter could be converted to a concentration, the data from the tests could not be use in hazard analyses.

Sublethal endpoints are typically expressed as either an effect concentration or a time-to-effect. Time-to-effect measurements provide information on the rapidity of toxic action rather than on toxic potency. Since the purpose of this study is to generate dose-response information, the time-to-effect endpoints are not included in this evaluation. Thus, the data compiled here are incapacitating concentrations (expressed as an IC_{50} value), which are defined as the mass loading or mass combusted per unit chamber volume (smoke concentration, in g/m^3 or mg/l) that causes incapacitation of 50 % of the test animals during a fixed exposure time and perhaps a post-exposure observation period. While a variety of pure gas exposure studies have used various techniques for measuring incapacitation, all the articles collected for this project used the hind-leg flexion conditioned avoidance response test.[36]

Among the large number of methods and laboratories, there was variation in the length of time the animals were exposed to the smoke. Table 37 presents a summary of the different exposure times reported for the toxicity test methods reviewed.   Most of the data are for an exposure time of 30 min with a post-exposure observation period ranging from 10 min to 14 days. In some experiments, there were no post-exposure observation periods. For the tube furnace methods (specifically the combustion oven devices including the University of Pittsburgh, University of Michigan, University of Tennessee, and NASA/JSC methods), the exposure times were (10, 30, 60, 140, or 240) min, with post-exposure observation periods of 5 min or 10 min, or 7 days or 14 days. However, since as noted above, the data from these devices did not meet other criteria, all the LC_{50} and IC_{50} values in the following discussions and analyses are for 30 min exposures.

Table 37. Exposure Times for Principle Test Methods Reviewed

Method Type	Exposure Time (min)				
	10	**30**	**60**	**140**	**240**
Cup Furnace		X			
Radiant Heat		X			
Tube Furnace	X	X	X	X	X

For the evaluation in this report, we used only toxic potency data developed from tests that included a post-exposure period. In the reported tests, incapacitation (from a combination of narcotic and irritant effects) typically occurred during an animal's exposure to fire smoke. Lethality, on the other hand, occurred either during the exposure to smoke or during the post-exposure period. The relationship between these post-exposure effects in rats and the effects on people during a fire remains to be assessed. However, we felt it more appropriate to use the more conservative toxic potency values (*i.e.*, those that include a post-exposure period) for the current purpose. Alternative analyses can be performed as desired using the information assembled in Appendix A.

3. Evaluation of Toxicological Data

The usable sets of LC_{50} and IC_{50} data are shown in Tables 38 and 39, respectively. As noted earlier, all data are for rats exposed to the smoke for 30 min and then observed for some post-exposure period. Each cell contains a median value for the experimental determinations and 95 % confidence limits; the number of determinations is shown in italics.

a. Estimation of Confidence Intervals. The original toxic potency data, compiled in Appendix A, is of varying quality. Some LC_{50} and IC_{50} values have corresponding 95 % confidence intervals and some do not. In addition, the numbers of individual experiments (sample sizes) used to calculate these confidence intervals are not always available. This varying quality of the individual data presents some challenge to appraising the aggregated set of toxicological values, a principal objective of the SEFS project.

To estimate the 95 % confidence intervals for each combination of material, combustion condition, and toxicological endpoint, the available information was grouped into three cases:

1. For some combinations, each of the (one or more) reported toxic potency values includes a 95 % confidence interval. The standard uncertainties were derived from the confidence intervals. A hierarchical Bayesian model[37], implemented with the BUGS software[38], was then used to obtain a consensus LC_{50} or IC_{50} value and its 95 % confidence interval. These results are indicated in the cells of Tables 38 and 39.

2. For other such combinations, some of the reported toxic potency values include 95 % confidence intervals and some do not. To estimate 95 % confidence intervals for the latter, we assumed that their accuracy is similar to that of the former. We determined a representative standard error of results for studies of the same material and combustion mode. The now-complete set of data were then fed into the same model used in case 1. These cells in Tables 38 and 39 are marked with a double asterisk.

3. For the third group of such combinations, there are no studies with reported confidence intervals, but confidence intervals are available for the same generic material under a different combustion method. We assumed the accuracy of results is similar across combustion methods and used an approach analogous to that described for set 2. These cells in Tables 38 and 39 are marked with a single asterisk.

It appears that, although the data were reported in the source articles to as many as three significant figures, the repeatability of these results is probably not better than ± 30 %.

It is important to note, however, that the gas yields and toxic potency data from only one of these 12 bench-scale devices (the radiant furnace now used in NFPA 269 and ASTM E1678) has been validated against room-scale experiments.[34] Thus, the accuracy of the other bench-scale data is undetermined.

b. Generic Toxic Potency Values. A quick scan of Tables 38 and 39 shows a wide range of toxic potencies. A hazard or risk analysis for a known set of combustibles should use toxic potency values appropriate to those products, the expected combustion conditions, and the proper toxicological effect.

In many cases, however, there is a mix of combustibles whose composition and time of entry into the fire are not well known. In those instances, generic values of toxic potency are desirable, ones that can be held constant throughout the analysis.

The last two rows of Tables 38 and 39 contain estimated mean LC_{50} or IC_{50} values for each of the combustion conditions and the estimated 95 % confidence interval for the median value obtained using the following Monte Carlo method. For each combustion condition (column), a random sample of size 1500 was drawn from the materials in that column. At each draw, each material present in the column for that combustion condition had an equal probability of being selected. Then, for that draw a random value was picked from a presumed normal distribution with mean and standard deviation given by the entry for that material and combustion condition. For example, suppose that for well-ventilated combustion the first draw chose "epoxy." The random value would then be from a normal distribution with mean 7.6 and standard deviation of 4.1. These 1500 points were then averaged to obtain an estimated overall mean LC_{50} or IC_{50} value. The 95 % confidence interval was determined assuming that the 1500 points represented a normal distribution.

Table 38. Average LC_{50} Values (g/m^3) (confidence limits, g/m^3) (*sample size*)

Material	Well-ventilated Combustion	Ventilation-limited Combustion	Oxidative Pyrolysis
Acrylonitrile butadiene styrene	** 26.4 (22.0,30.8) 4		** 32.3 (28.2,35.3) 4
Bismaleimide	14.9 (12.8,17.2) 1		41.9 (38.8,45.1) 1
Carpet foam (with nylon)	* 107.9 (46.6,138.5) 1		* 68.0 (36.0,81.1) 1
Carpet jute backing (with nylon)	* 57.0 (35.5,69.4) 1		* 89.9 (53.7,99.2) 1
Chlorofluoropolymers	** 17.8 (10.2,33.6) 2		** 24.6 (17.7,32.1) 2
Epoxy	7.6 (1.5,15.8) 1		11.0 (8.9,13.1) 1
Fabric, Vinyl	32.0 (28.0, 37.0) 1	19.0 (17.7, 20.9) 1	
Fluoropolymers (data set A)	** 27.4 (19.0,35.8) 4		** 25.4 (17.8,33.5) 4
Fluoropolymers (data set B)	** 0.12 (0.04, 0.93) 6		** 0.37 (0.10, 0.96) 4
Modacrylic	** 5.6 (4.0,7.2) 3		** 6.5 (4.6,8.3) 4
Phenolic resin	8.4 (7.3,9.5) 1		5.9 (4.8,7.0) 1
Polyacrylonitriles	** 40.2 (37.0,43.4) 2		
Polyester	** 35.6 (31.4,39.4) 4	** 38.2 (18.7,56.2) 1	** 37.8 (29.2,46.9) 3
Polyester fabric/polyurethane foam	* 41.9 (30.9,55.9) 1		* 29.9 (25.2,42.2) 1
Polyethylene	** 36.8 (30.1,43.0) 3		5.8 (3.5,8.9) 2
Polyphenylene oxide	* 31.0 (22.3,35.6) 1	* 24.0 (17.8,36.5) 1	
Polyphenylsulfone	** 27.2 (20.6,33.7) 4		** 18.0 (13.1,23.1) 4
Polystyrene	** 35.6 (33.4,37.9) 7		** 43.5 (41.1,45.6) 6
Polyurethane, Flexible	** 35.4(31.8,38.9) 18	** 20.4 (16.0,24.9) 4	** 29.9 (26.5,33.0) 15
Polyurethane, Rigid	** 13.0 (11.6,14.5) 12	** 25.9 (15.8,35.2) 1	** 29.5 (25.2,33.9) 10
Polyvinyl chloride, Plasticized	** 26.2 (20.1,33.2) 3	16.0 (13.7, 17.5) 1	** 22.9 (11.8,34.4) 3
Polyvinyl chloride, Resin	** 20.0 (16.8,23.2) 8		** 16.1 (13.2,19.3) 5
Strandboard			47.0 (37.7,57.3) 1
Tempered hardwood	58.1 (40.8,67.0) 1		86.5 (79.4,93.0) 1
Urea Formaldehyde	11.2 (10.4, 12.0) 1		1.20 (1.10,1.30) 1
Wire, PTFE coaxial wire	* 10.8 (5.7,25.7) 1		* 13.5 (8.00,25.2) 1
Wire, THHN wire w/ nylon-PVC	55.0 (44.0,66.0) 1		99.8 (88.6, 107.2) 1
Wire insulation, NFR crosslinked	51.0(40.8,61.2) 1		
Wire insulation, FR crosslinked EVA		25.2 (18.9,33.5) 1	
Wood	** 40.2 (34.8,45.1) 14		** 36.1 (30.8,41.0) 14
Estimated mean	30.4	25.8	27.8
95 % Confidence Interval	(5.4,58.4)	(16.9,41.3)	(1.6,78.4)

Table 39. Average IC_{50} Values (g/m^3) (confidence limits, g/m^3) (*sample size*)

Material	Well-ventilated Flaming	Oxidative Pyrolysis
Acrylonitrile butadiene styrene	** 11.2 (6.1,15.8) 3	** 15.4 (7.9,22.0) 3
Bismaleimide	6.8 (5.4,8.3) 1	20.1 (16.3,24.0) 1
Epoxy	6.2 (5.2,7.3) 1	4.1 (3.3,5.0) 1
Fluoropolymers (data set A)	** 14.8 (6.9,21.9) 2	** 14.5 (7.9,19.9) 2
Fluoropolymers (data set B)	** 0.55 (0.10,1.01) 2	** 0.68 (0.31,1.49) 1
Modacrylic	** 3.2 (0.7,6.0) 2	** 3.3 (0.2,6.7) 3
Phenolic resin	2.0 (1.6,2.4) 2	1.5 (1.2,1.8) 1
Polyphenylsulfone	** 15.3 (10.0,19.8) 3	** 11.6 (6.6,16.8) 3
Polystyrene	** 20.0 (15.0,24.9) 5	** 33.4 (22.4,39.8) 5
Polyurethane, Flexible	** 17.4 (10.1,25.2) 8	** 15.5 (7.6,22.7) 8
Polyurethane, Rigid	** 5.4 (4.0,6.8) 8	** 9.5 (5.3,14.00) 8
Polyvinyl chloride, Plasticized	** 7.1 (4.9,9.3) 1	** 3.4 (2.8,4.0) 1
Polyvinyl chloride, Resin	** 12.2 (8.6,16.3) 4	** 13.5 (6.1,20.4) 4
Urea Formaldehyde	7.4 (6.5,8.3) 1	0.7 (0.6,0.8) 1
Wood	** 21.4 (17.5,25.3) 10	** 15.3 (12.2,18.5) 12
Estimated mean	11.2	11.5
95 % Confidence Interval	(1.4,24.0)	(1.1,25.0)

c. Comparison among Combustion Conditions. Since the combustion conditions and the products on fire vary within a fire compartment and evolve as the fire grows and ebbs, it is useful to assess the accuracy of using a single toxic potency value in engineering calculations. The following examines lethality data for two pairs of fire conditions and incapacitation for one pair.

Lethality: well-ventilated flaming and ventilation-limited combustion. These data sets in Table 38 were compared in two ways:

- The first generalized approach was a comparison of the mean LC_{50} values for both conditions, including all materials (except fluoropolymers B) in the data set. There is a wide range of LC_{50} values and modest differences between the mean values for the two columns. The broad 95 % confidence limits around the two mean values suggest that any difference between the lethal toxic potencies of the smoke generated under these two sets of conditions is not resolvable.

  Examination of the data in the column labeled "Ventilation-limited Combustion" suggests that some of these numbers may be too high for use in evaluating post-flashover fires. Carbon monoxide yields from flaming fires are generally distinctly higher after flashover, so LC_{50} values should fall relative to the same products burning with ample ventilation. Further, the LC_{50} value for post-flashover smoke is about 25 g/m^3 if the only toxicants it contains are CO_2 and CO.[34] The presence of additional toxicants will reduce this. There are six materials with entries in these two columns. While the two chlorine-containing products and the flexible polyurethane foam appear to behave appropriately in both these aspects, the other two materials do not. The rigid polyurethane, which should produce some HCN as it burns, has an LC_{50} value near 25 g/m^3 and decreases in lethal toxic potency as the air supply decreases (the wrong direction). The underventilated LC_{50} value for the polyester sample is above 25 g/m^3. The LC_{50} value for the modacrylic carpet sample, which should produce HCN, is about the level for toxicity from CO_2 and CO only. However, even were all the "Ventilation-limited" data reflective of the two (above) guidelines for post-flashover fires, the mean value for this column would not likely be sufficiently lower that the two confidence intervals would not overlap.

- The second approach was a comparison of LC_{50} values on a material-by-material basis. For four of the six combustibles the 95 % confidence intervals overlap. In three of those cases, the ventilation-limited values are lower; in the fourth, the reverse is true. This does not constitute strong evidence for a fundamental difference between the data in the two columns.

Thus, while there is reason to expect that the lethal toxic potency of smoke from post-flashover fires would be higher than for pre-flashover fires of the same combustibles, the published data do not present sufficient evidence to resolve such a difference. This comparison is especially compromised by the small data set for ventilation-limited combustion and the inconsistencies in it.

Lethality: flaming combustion and oxidative pyrolysis. Comparison of the mean LC_{50} values and 95 % confidence intervals for the three combustion conditions reveals no statistical difference between them; the mean values are nearly identical and the confidence intervals for well-ventilated combustion and ventilation-limited combustion are fully contained within those for oxidative pyrolysis.

Incapacitation: well-ventilated flaming combustion and oxidative pyrolysis. Recall there were no reported IC_{50} values for ventilation-limited flaming conditions. The mean values of the two columns are nearly identical and the 95 % confidence intervals are essentially congruent. For about half the materials the individual confidence intervals show considerable overlap. The remaining half are split between the flaming value being higher and the reverse. Thus, any possible difference in incapacitating toxic potency between the smoke from these combustion modes is not discernible.

d. Comparison between Toxicological Effects. Kaplan and Hartzell[39] had reviewed the literature and found that for exposures to narcotic gases (CO or HCN), the concentrations that caused incapacitation (measured by a variety of devices) were one third to one half of those that resulted in the death of various animal species.

For the smoke data collected here, the mean value of the ratios of IC_{50} values to LC_{50} values and the standard deviation are 0.50 and 0.21, respectively. There is no significant difference between well-ventilated flaming combustion and oxidative pyrolysis.

These results are consistent with the Kaplan and Hartzell ratio, given the uncertainty in the measurements. In addition, since there is a broad set of expected toxic gases (*e.g.*, CO, halogen acid gases, HCN, partially-oxidized organics) in the smoke from this group of materials, it is not unreasonable to generalize that an incapacitating exposure is about half that of a lethal exposure.

e. Comparison among Materials and Products. As noted above, it would benefit engineering calculations if there were a single LC_{50} (and thus IC_{50}) value to be used when the mixture of combustibles in a fire is unknown. In HAZARD I, the suggested values are 30 g/m^3 and 10 g/m^3, respectively (for 30 min exposures of rats to smoke).

The wide range of toxic potency values in Tables 38 and 39 strongly suggests that any such generic value must be used with caution. However, should such a number be needed, a generic value for lethal toxic potency (30 minute rat exposure) in pre-flashover fires (even if much of the smoke were generated from pyrolysis rather than flaming) would be 30 $g/m^3 \pm 20$ g/m^3. For post-flashover fires, the situation is less clear. The data compiled here and the value calculated for CO and CO_2 only suggest an upper limit of 25 g/m^3. Data derived from the NFPA 269 radiant furnace[34] suggest a value of 15 $g/m^3 \pm 5$ g/m^3. [The uncertainty in the post-flashover value is much lower because the toxic potency is dominated by the large amount of CO produced during underventilated burning. This CO yield is controlled by the shortage of oxygen more than differences in the fuel chemistry.[3]]

For pre-flashover fires, a generic 30 minute IC_{50} value (for rats) would be 15 $g/m^3 \pm 10$ g/m^3. For post-flashover fires, the corresponding number would be 7 $g/m^3 \pm 2$ g/m^3.

In all cases, it is important to note that there are some materials with appreciably lower potency values, indicating higher smoke toxicity. If materials like these are expected to comprise a large fraction of the fuel load, a lower generic value can be used.

4. Extrapolation to People

The objective of fire hazard and risk analyses is to estimate conditions of safety for people, including those that are more sensitive to fire smoke than others. For this purpose, it is valuable to estimate the extrapolation of the above information (which addresses lethal and incapacitating exposures for the median rat) to incapacitation of the sensitive human. The information on which to base this extrapolation is far from definitive. The following analysis is directed at obtaining order-of-magnitude factors and estimated uncertainties at the current state of an imperfect art.

We rely heavily on the reviews and judgment of the team currently producing the Acute Exposure Guideline Levels (AEGLs) for Hazardous Substances.[40] We do note that the direct application of their effort is in a direction different from ours, and much of their analysis is not pertinent to calculations of the effects of exposure to fire smoke.

The AEGL team defines three levels of threat:

- AEGL-1 is the airborne concentration of a substance at or above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain subclinical, non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

- AEGL-2 is 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.

- AEGL-3 is the airborne concentration of a substance at or above which it is predicted that the general population, including susceptible individuals, could experience life-threatening effects or death.

Thus, for incapacitation in this project, we are interested in the analysis associated with AEGL-2 values.

a. Treatment of Toxic Potency of Materials and Products. The incapacitation results from a combination of narcotic and irritant gases. As noted above, the incapacitating exposure to fire smoke is about half the lethal exposure, and this factor of about two is similar whether dealing with pure narcotic gases or the complex mix of gases in the smoke from a burning product. Thus, we assume that the factor of two holds for irritant gases.

Next, we make the assumption that to extrapolate the toxic potency of the smoke from rats to the toxic potency for people, we can treat the toxic component of the smoke as behaving like the sum of a single narcotic gas and a single irritant gas. We choose CO and HCl, respectively, because of their prevalence and because of the existence of draft AEGL compilations for these two molecules.[41,42]

In two room-scale studies involving the burning of a halogenated combustible, the CO concentration is significantly larger than the halogen acid concentration:

- Sheets of non-plasticized PVC (43 % Cl mass fraction). The volume fraction of CO was about 1/6 that of CO_2; the [CO]:[HCl] ratio was about 3 (accounting for some HCl losses).[26]

- A fire-retarded TV cabinet (about 12 % bromine) produced comparable volume fractions of CO and CO_2. The volume fraction ratio of CO to HBr was about 10.[24]

Both of these items are toward the maximum of the halogen content for commercial products. Thus the ratio of CO to halogen acid concentration from combustion of such products will generally be higher than these numbers. In reality, serious fires result from the burning of multiple items, many of which (*e.g.*, wood items) are halogen-free. Thus, for the general fire that is capable of generating incapacitating smoke levels, a CO to halogen acid concentration ratio of 5 is a reasonable lower limit.

For those products containing no atoms that produce strong acids in the smoke, there will still be some production of organic irritants such as weak acids, aldehydes and ketones. There are no reported measurements of the yields of these gases in room-scale tests. For this estimation of incapacitating exposure, we assume that their contribution will be small relative to that of the halogen acids (which are included at the above [CO]:[HX] ratio of 5) as well as small compared to the CO contribution.

b. CO Toxicity

Rat Data and Human Levels. Rounded rat LC_{50} data assembled by the AEGL panel is compiled in Table 40:

Table 40. Lethal Volume Fractions of CO for Rats for Various Times of Exposure

Exposure time (min)	5	15	30	60	240
Volume fraction x 10^6 (ppm by volume)	12000	8600	5000	4200	1800

Children can be said to represent a smoke-sensitive but otherwise healthy sub-population. As such, they showed symptoms that would impair escape at about 25 % COHb.[43] Using the Peterson-Stewart curves[44] and the input values for a 5-year-old child,[41] this appears to result from, *e.g.*, a 5 min exposure to about 0.15 % volume fraction (1500 ppm by volume), or one-eighth of the 5 min lethal exposure for rats.

Another smoke-sensitive sub-population is people (adults) with coronary artery disease. Here, the AEGL summary indicates that exposures resulting in about 5 % COHb would lead to effects that would seriously compromise evacuation. A similar calculation to the one for children indicates that this COHb level could result from a 5 min exposure to about 0.1 % volume fraction (1000 ppm by volume), or about one twelfth the 5 min lethal exposure for rats.

Together, these estimates suggest using one tenth of the exposure lethal to rats in 5 minutes as the exposure that would incapacitate people in 5 min should provide protection for a large fraction of the smoke-sensitive human population.

Time Scaling of Exposure Data. Typically the interpolation/extrapolation from one set of exposure time data to other exposure times is done using an equation of the form: $C^n\, t =$ constant. A value of n = 2 produces a reasonable fit ($\pm$20 %) to the data in Table 40. A similar dependence had previously been found for lethality due to CO.[34] Thus, the 5 min IC_{sens} for people exposed to CO is about one fourth of the 30 min rat LC_{50}.

c. HCl Toxicity

Rat Data and Human Levels. Kaplan[45] exposed baboons, generally presumed to be a good surrogate for humans, to 0.019 % volume fraction to 1.7 % volume fraction (190 to 17000 ppm by volume) of HCl for 5 min. All were able to escape, despite significant trauma at the higher concentrations. [Note: The AEGL panel used rat data over the baboon data because the latter exposures are for very short exposure times minutes and they needed information on exposures up to 8 hours – a big extrapolation. For this application, the baboon exposures are appropriate.] In separate tests, exposure of anesthetized baboons to 0.5 % volume fraction and 1.0 % volume fraction (5,000 and 10,000 ppm by volume, respectively) for 15 min produced significant drops in arterial oxygen pressure.[46] [Such an effect was not observed in exposures to 0.05 % volume fraction.] Hartzell notes[47] that, if combined with exposure to CO, this drop could lead to incapacitation at modest COHb levels. Data on combined exposures were not developed. Since there are no data for exposures between 0.05 % volume fraction and 0.5 % volume (500 and 5000 ppm by volume) and since the 15 min exposures are three times longer than those from which none of the animals were incapacitated, we suggest that the HCl concentration that could lead to incapacitation in 5 min in the presence of CO is about 0.3 % volume fraction (3000 ppm by volume).

There are no citations for relating incapacitation of the median person to include the sensitive fraction of the human population. The AEGL draft report[42] uses a factor of 3 for this, saying that the irritation "is not expected to vary greatly between individuals." This leads to an estimate that the HCl concentration that could lead to incapacitation in 5 min of smoke-sensitive people in the presence of CO is about 0.1 % volume fraction (1000 ppm by volume).

As noted above, in a fire involving a chlorine-containing fuel, the HCl concentration is likely to be at least five times lower than the CO concentration. Thus, when the CO concentration is *ca.* 0.15 % volume fraction, the HCl concentration would be under about 0.03 % volume fraction (300 ppm by volume). This is well under the incapacitating concentration for smoke-sensitive people.

Time Scaling of Exposure Data. There do not appear to be reliable primate data to enable time scaling. The AEGL-2 summary indicates that n = 1. The toxicologists associated with ISO TC92 SC3 found the sensory irritancy was almost instantaneous and thus not time-dependent.

d. Summary

- For materials and products that do not generate strong acid gases, we can assume that CO (as a surrogate for asphyxiants) is the primary toxicant and use one fourth the 30 min rat LC_{50} as the 5 min human IC_{sens}.

- For materials and products that do generate strong acid gases, narcotic gases account for the majority of the combined incapacitating effect of narcotic and irritant gases. We suggest that one use one fifth of the 30 min rat LC_{50} as the 5 min human IC_{sens}.

- Since the narcotic component dominates the IC_{sens} values, the use of C^2t as a time scaling formula is preferred.

It is hard to affix an uncertainty to these conclusions given the (lack of uncertainty in the resources for) analysis of the AEGL information and the other assumptions stated above. An estimate is that they are accurate to within ± 50 %.

In Section II.D.2.e we estimated that, for an unknown mixture of combustibles, a generic value for the concentration of smoke that would incapacitate a rat of average smoke sensitivity in 30 min would be 30 g/m^3 ± 20 g/m^3 for a well-ventilated flaming fire and 15 g/m^3 ± 3 g/m^3 for a post-flashover fire. Incorporating the above analysis, we estimate that the corresponding values for the concentration of smoke that would incapacitate smoke-sensitive people in 5 min would be 6 g/m^3 for a well-ventilated fire and 3 g/m^3 for a post-flashover fire. The user of these values needs to be mindful of two key factors:

- There is a wide range of smoke toxic potency values reported for various materials. Some of these have significantly higher or lower values than these generic figures.

- These generic values are estimated with significant assumptions in their derivation. An estimated uncertainty is about a factor of two.

6. Future Work

As can be seen from the number of assumptions and approximations in the above analysis, considerable effort is needed to improve the reliability of the resulting estimates. In particular, one needs:

- Toxic potency data for rats for smoke from a wide range of materials and products obtained using a validated bench-scale apparatus.
- Gas yields, especially for irritant gases, from room-scale tests to improve the estimation of the extrapolation from animal lethality to human incapacitation.

We presume that documented human exposure data will be impossible to obtain and realize that even the data for laboratory animals will be difficult.

E. GENERATION AND TRANSPORT OF SMOKE COMPONENTS

Thus far, fire smoke has been treated as a bulk entity, *i.e.*, a mass of effluent generated during a fire. At the end of the prior Section, the toxic potency of the smoke was simplified as if it were composed of just two toxic components.

Smoke is, in fact, a mixture of gases and aerosols. The latter is defined as a suspension of solid and/or liquid particles. The nature of the aerosol component of smoke can play a profound role in the lethal and sublethal effects on people. This Section presents the state-of-the-art in the factors that could affect smoke toxicity: the amount of aerosols produced in fires and their characteristics, the changes in concentration that occur as the smoke moves away from the fire, and the potential for the aerosols to transport adsorbed or absorbed toxic gases.

1. Physical and Chemical Characteristics of Smoke Aerosol

Smoke particles include both micro-droplets formed from condensed organic vapors and highly carbonaceous agglomerated structures consisting of hundreds or thousands of nearly spherical primary particles (soot). A range of adverse health effects is associated with inhalation of these particles, 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. An assessment of conditions within the lungs must begin with information about the source of particulate matter: the fire itself.

Smoke particulates can be characterized in a number of ways, including shape, chemical composition, mass, size distribution, mass-to-charge ratio, and quantity. After a brief description of particle morphology, this Section reviews the data on smoke yield, aerodynamic diameter, and size distribution collected from the published literature.

a. Morphology. The composition of the smoke aerosol generated during flaming combustion is completely different in character from that generated during pyrolysis or smoldering. Chemical, electrical, and collisional processes in the flame environment result in smoke consisting largely of highly carbonaceous black soot.[48] Each soot particle is a complex chainlike agglomerate made up of hundreds up to a million roughly spherical primary particles, each typically on the order of 0.01 µm to 0.06 µm in diameter and close to monodisperse,[49,50,51] although primary particles up to 0.16 µm have been measured in a crude oil fire.[52] The largest primary diameters are associated with heavily sooting fuels, often with a high aromatic content.[50] The physical extent of a soot agglomerate is typically in the range of 0.5 µm to 5 µm, but may become as large as 200 µm.[53]

In contrast, the non-flaming processes of pyrolysis and smoldering result in a complex mixture of liquid and solid organic materials. Basic pyrolysis products may include fuel monomer, partially oxidized products, and polymer chains. Condensation of low vapor pressure organic constituents forms nearly spherical micro-droplets with a tarry consistency. The resulting smoke has a light-colored appearance.[48]

The surface area of a smoke particle and the chemical functionalities on that surface are of critical importance to the ability of that particle to adsorb water and toxic gases. Growth processes for smoke particles are discussed in Section E.2, and the topic of adsorption is covered in Section E.3 below.

b. Yield. Smoke yield, sometimes also referred to as the emission factor, is defined as the mass of smoke generated per mass of fuel burned. Values range from near zero to *ca.* 0.3 g_{smoke}/g_{fuel}, or 30 % of the fuel mass. Fuels such as methane and wood undergoing flaming combustion populate the low end of this scale, and the high end typically represents fuels with a highly aromatic chemical structure.

The amount of fuel converted into smoke particles in a specific fire is affected by a number of factors. Combustion mode (flaming or non-flaming), the fuel material itself, and the ventilation condition (well-ventilated or underventilated) are of primary importance. Other important influences involve the configuration of the fuel, including fuel bed size and geometry, and environmental conditions, *e.g.*, temperature and oxygen content. Tables 41 and 42 list smoke yields for a variety of materials under flaming and non-flaming conditions, respectively. To compare results under similar experimental conditions, the data in these two tables were collected from research performed using the same test bed, the ventilated Combustion Products Test Chamber at the Georgia Institute of Technology, between the years 1976 and 1991. All experiments reported in these tables were performed in air, with variations in ventilation airflow rate, radiant heating levels, and sample orientation. In all these cases the flames are well-ventilated. Materials are listed in order of smoke yield from largest to smallest in each table, with only factors that significantly affected the yield for a given material indicated under comments for clarity.

These two tables illustrate how strongly the amount of smoke generated is affected by the type of material being burned. Because cyclic ring structures are the basic component of both soot particles and waxlike tars, aromatic fuels such as polystyrene (PS) and fuels with a high aromatic component generate the highest smoke yields during both flaming and non-flaming combustion.[48,54,55,56] This accounts for the presence of polycarbonate (PC), asphalt, and rigid polyurethane (PU) foam near the top of both Tables 41 and 42. Cyclizing reactions taking place during degradation of polymers such as rubber and polyvinyl chloride (PVC) also enhance smoke production through the addition of aromatic molecules to the fire environment.[53] The mass of smoke produced by such fuels can exceed 10 % of the fuel mass during flaming combustion and 30 % during non-flaming combustion. Other chemical composition factors affecting smoke yield include molecular weight fraction and carbon content. A study on petroleum products by Patterson *et al.*[57] comparing smoke yields from kerosene, two type of diesel oil, and asphalt demonstrates that smoke yield increases with increasing molecular weight fraction. Increasing smoke yield also increases with increasing carbon content, as shown in a study of crude oils by Evans *et al.*[58] and a comparison of plain rubber with tire rubber containing a large amount of carbon black.[57] Note from Table 41 that smoke yields for flaming PVC measured by Patterson are considerably larger than those measured by Zinn, Bankston, and colleagues.[53,59] As shown in Table 42, smoke yields also vary widely for PVC undergoing non-flaming combustion, possibly indicating differences in the cyclizing reaction processes during degradation.

The smoke yields under non-flaming conditions considerably exceed those for flaming combustion for the vast majority of fuels, including wood, rubber, polycarbonate, rigid PVC, flexible PU foam, and expanded polystyrene (PS) foam.[57,60,61,62,63] For wood in particular, the near complete combustion in a flaming environment compared with high tar production during smoldering propels it from the bottom of Table 41 to near the top of Table 42. The difference in smoke yield between these two combustion modes has been attributed to the high chemical reactivity in the flame environment, which results in a larger breakdown of pyrolysis products to gaseous components than in non-flaming combustion.[53] A few exceptions to this trend are noted in the literature, however. Smoke yields from the two highly charring foams tested by Zinn *et al*.,[62] a rigid PU foam and a rigid trimer foam, were somewhat less for non-flaming than for flaming combustion, and PVC samples tested by Patterson *et al.*[57] produced significantly more smoke while flaming than during non-flaming combustion.

Fillers added to polymers to change their physical properties affect the smoke yield during burning, though the direction of the change depends on the specific additive. The addition of fillers to PVC and polypropylene (PP) was found to decrease smoke yield, sometimes significantly, although definite trends with amount of filler were not seen. Lowered smoke yield was accompanied by the conversion of a larger percentage of the original fuel mass to char.[53,61] Flame retardant additives decreased smoke yield for rigid trimer foam but significantly increased the smoke yield for flexible PU foam and expanded PS foam.[53] Mixing sand with polymeric fuels was found to increase smoke production in almost all cases.[60]

In general, smoke yield increases moderately with increasing fuel size. For a pool fire, increasing the diameter from 0.085 m to 2 m increased smoke production from 0.06 g to 0.13 g of smoke per gram of crude oil.[64] The smoke yield also increased with the depth of the fuel layer.[58] A comparison of large scale test results for sugar pine and rigid PU crib structures with those for cone calorimeter measurements of red oak and PMMA indicated that smoke yield was roughly equivalent for comparable specific burning rate.[65] Smoke production was found to be higher in bench-scale studies of whole wood and plywood than at medium scale, but the possible contribution of smoldering to the bench-scale tests could not be ruled out.[54]

Table 41. Smoke Yields for Flaming Combustion in Air

Material	Smoke Yield (g_{smoke}/g_{fuel})	Comments	References
PVC	0.185	9.6 l/s airflow	Patterson et al., 1990[57]
PVC	0.094, 0.144	4.8 l/s airflow	Patterson et al., 1991[60]
Asphalt	0.119	9.6 l/s airflow, 80 kW/m^2	Patterson et al., 1991[60]
PC	0.102, 0.104		Patterson et al., 1990[57]
Asphalt	0.097	9.6 l/s airflow, 50 kW/m^2	Patterson et al., 1991[60]
Rigid PU foam	0.085, 0.091		Zinn et al., 1979[62], Bankston et al., 1981[59]
Tire rubber	0.082, 0.089	9.6 l/s airflow	Patterson et al., 1990[57]
Expanded PS foam	0.085		Zinn et al., 1979[62], Bankston et al., 1981[59]
#5 Diesel oil	0.071	9.6 l/s airflow	Patterson et al., 1991[60]
Asphalt	0.061	5 l/s airflow, 50 kW/m^2	Patterson et al., 1991[60]
Rigid trimer foam	0.060		Zinn et al., 1979[62], Bankston et al., 1981[59]
#5 Diesel oil	0.045, 0.053	4.8 l/s airflow	Patterson et al., 1991[60]
Plain rubber	0.045	4.8 l/s airflow	Patterson et al., 1990[57]
PP	0.042		Patterson et al., 1990[57]
PS	0.032, 0.041		Zinn et al., 1978[53], Bankston et al., 1981[59], Patterson et al., 1990[57]
#2 Diesel Oil	0.023, 0.035, 0.045		Patterson et al., 1991[60]
Kerosene	0.027, 0.031		Patterson et al., 1991[60]
HDPE	0.028		Patterson et al., 1990[57]
Flexible PVC	0.028		Zinn et al., 1978[53], Bankston et al., 1981[59]
Rigid PVC	0.025		Zinn et al., 1978[53], Bankston et al., 1981[59]
Wood	0.025	25 kW/m^2	Bankston et al., 1981[59]
PP	0.018		Zinn et al., 1978[53], Bankston et al., 1981[59]
Rigid PVC	0.012		Bankston et al., 1978[61], Bankston et al., 1981[59]
MDPE	0.012		Zinn et al., 1978[53], Bankston et al., 1981[59]
PMMA	0.008-0.018		Zinn et al., 1978[53], Bankston et al., 1981[59], Patterson et al., 1990[57]
Flexible PU foam	< 0.01		Bankston et al., 1978[61], Bankston et al., 1981[59]
Wood	0.0026, 0.0041, <0.01	80, 50 kW/m^2	Patterson et al., 1990[57], Bankston et al., 1981[59]

Table 42. Smoke Yields for Non-flaming Combustion in Air with 50 kW/m^2 Radiant Heating

Material	Smoke Yield (g_{smoke}/g_{fuel})	Comments	References
PC	0.32		Patterson et al., 1990[57]
Asphalt	0.288		Patterson et al., 1990[57]
Wood	0.154	Vertical	Bankston et al., 1976[66], Bankston et al., 1981[59]
Flexible PU foam	0.146	Vertical	Bankston et al., 1978[61], Bankston et al., 1981[59]
Tire rubber	0.136	9.6 l/s airflow, high heat flux	Patterson et al., 1990[57]
Flexible PVC	0.123	Horizontal	Bankston et al., 1978[61], Bankston et al., 1981[59]
PP	0.121		Zinn et al., 1978[53], Bankston et al., 1981[59]
Plain rubber	0.12	4.8 l/s air flow	Patterson et al., 1990[57]
Expanded PS foam	0.114	Horizontal	Zinn et al., 1979[62], Bankston et al., 1981[59]
Wood	0.108	Horizontal	Bankston et al., 1976[66], Bankston et al., 1981[59]
Tire rubber	0.107	9.6 l/s air flow	Patterson et al., 1990[57]
Rigid PVC	0.093	Horizontal	Bankston et al., 1976[66], Bankston et al., 1981[59]
PS	0.084		Zinn et al., 1978[53], Bankston et al., 1981[59]
Rigid PU foam	0.082	Vertical	Bankston et al., 1976[66], Bankston et al., 1981[59]
Rigid PVC	0.070	Horizontal	Bankston et al., 1976[66], Bankston et al., 1981[59]
Rigid PU foam	0.070	Horizontal	Zinn et al., 1979[62], Bankston et al., 1981[59]
Flexible PU foam	0.064	Horizontal	Zinn et al., 1979[62], Bankston et al., 1981[59]
Rigid trimer foam	0.047		Zinn et al., 1979[62], Bankston et al., 1981[59]
PVC	0.037	9.6 l/s airflow	Patterson et al., 1990[57]
Rigid PVC	0.030	Vertical	Bankston et al., 1976[66], Bankston et al., 1981[59]
PVC	0.017	4.8 l/s airflow	Patterson et al., 1990[57]
PMMA	< 0.01		Zinn et al., 1978[53], Bankston et al., 1981[59]

As indicated by the comments in Table 42, the orientation of the fuel may have a significant effect on smoke yield for non-flaming combustion. The smoke produced by a vertically mounted sample of flexible PU foam was found to be over twice as much as that produced by a sample mounted horizontally, and smoke yields were also higher for vertical samples of wood and rigid PU foams.[66,61,62] An exception was noted for rigid PVC samples, for which a sample mounted vertically yielded less than half as much smoke as one mounted horizontally.[66]

Under most conditions for non-flaming combustion, an increase in radiant heating rate increases particulate mass concentration substantially.[66,57] For flaming combustion, increasing the external heat may either increase the smoke yield, as for asphalt,[57] or decrease it, as for flaming wood, for which any smoldering contribution raises the smoke yield considerably.[59]

Finally, the fire environment is an important factor. Underventilated fires usually result in more soot loading due to reduced oxidation. Measured smoke yields for wood cribs were an order of magnitude larger under underventilated conditions than when well ventilated.[54] However, testing by Patterson *et al.*[57] demonstrated lowered smoke yields with an oxygen-poor mixture of air and nitrogen for purely flaming PC, flaming PVC, and PC with a significant smoldering component. As indicated in Tables 41 and 42, higher airflow through the combusting environment increases smoke yield,[57] and the laminar or turbulent nature of the flow may also have an effect.[54]

For a listing of smoke yield data for a wider variety of fuels than shown here, see the chapter by Tewarson in *The SFPE Handbook of Fire Protection Engineering*.[67]

c. Aerodynamic diameters and particle shape. Soot particles produced in a fire are often reasonably well represented by a log-normal particle size distribution function.[68,69] In this type of size distribution, which provides certain mathematical advantages for particle size analysis,[70] the logarithm of the diameter, rather than the diameter itself, satisfies a Gaussian number distribution. If n_i is the number of particles with diameter d_i , the mean geometric diameter d_g is given by:

$$\log d_g = \frac{\sum n_i \log d_i}{\sum n_i} \tag{4}$$

and the geometric standard deviation σ_g is:

$$\log \sigma_g = \left[\frac{\sum n_i (\log d_g - \log d_i)^2}{\sum (n_i) - 1} \right]^{1/2} . \tag{5}$$

A plot of frequency vs. diameter for this size distribution is skewed toward the larger particle sizes, such that the number of smaller particles is much greater than the number of larger ones. Note that the value of σ_g is dimensionless; instead of adding or subtracting from the mean diameter, σ_g is a multiplicative factor, with one geometric standard deviation representing a range of particle sizes from (d_g/σ_g) to $(d_g \times \sigma_g)$ that contains 68.3 % of all particles.[48] For a perfectly monodisperse distribution, $\sigma_g = 1$.

The average size of particles described by a log-normal size distribution function may be quantified by any of a large number of median and weighted mean diameters. The wider the size distribution, as measured by the geometric standard deviation, the larger the difference between various measures of average diameter. Since smoke particle size distributions are typically quite broad, and since different experimental techniques measure different average diameters, it is critical to select the average diameter measure and measurement technique that best capture the information relevant to the specific problem at hand.

For the purpose of assessing health risk due to deposition in the respiratory tract, the most appropriate measure of size is the aerodynamic diameter. This is defined as the diameter of a unit density sphere (density = 1 g/cm^3) having the same aerodynamic properties as the particle in question. In other words, the settling velocity of a particle of any shape or density with a given aerodynamic diameter is equal to that of a spherical water droplet of the same diameter.[68,69] This choice enables direct comparison of the deposition behavior of the nearly spherical microdroplets generated in large quantities during pyrolysis and smoldering (non-flaming) processes with that of the complex agglomerates formed during flaming combustion. While the aerodynamic diameter is a good approximation to the actual diameter for a microdroplet, its relationship to the physical size of an agglomerate is not obvious and is best determined by experimental measurement. Cleary[71] found for soot generated by burning acetylene as a laminar diffusion flame that the aerodynamic diameter was a factor of 3 to 5 smaller than the overall agglomerate size.

A cascade impactor is the apparatus most frequently used to measure aerodynamic diameter. In this device, the aerosol whose size distribution is to be measured enters a compartment containing a series of collection platforms known as stages. Inertial forces transport particles in a direction perpendicular to the streamlines of the velocity field in this compartment with a rate dependent on flow field, size, and density, causing particles in successively smaller size ranges to impact on successive stages. The mass of particulate matter on each stage is then weighed. This information is combined with the particle size range for each stage, as previously determined by calibration, to plot the cumulative distribution function for this aerosol on log probability paper. The mass median aerodynamic diameter is the 50 % point on this curve, and the degree to which the size distribution is described by a log-normal distribution is established by how closely the curve represents a straight line. If the distribution is indeed log-normal, the geometric standard deviation is given by the particle size at the 50 % probability point divided by the size at 15.87 % probability.[71]

Size distribution data, including median aerodynamic diameter and standard deviations, are presented in Table 43 for smoke aerosols produced by flaming fuels and in Table 44 for those produced by non-flaming fuels. As a graphical illustration of their ranges, Figure 8 presents aerodynamic diameter plotted as a function of yield. In this plot, flaming data is marked by red asterisks and non-flaming (smoldering or pyrolysis) by blue open triangles. The range of median aerodynamic diameters for smoke aerosols as reported in the papers included in this literature search is from 0.05 μm for flaming wood to 10 μm for acetylene.

For smoke particulates produced during non-flaming combustion, geometric standard deviations are mostly in the range between 1.7 and 2.2, though values as large as 3 and 4 are reported (Table 44). Independent measurements by optical particle counters have provided consistent values of the size distribution. The flame generated smoke agglomerates show a much broader range of geometric standard deviations extending from 2 to 16 and even larger. Because of the complex shape of the agglomerates formed in the flame, there is a lack of an independent verification of the aerodynamic size distribution of these particles. Cleary[71] reported that the nature of the impactor collection substrate affects both the aerodynamic median diameter and the width of the distribution. A smooth surface such as aluminum foil, which was used in most of the studies reported in Tables 43 and 44, leads to “particle bounce” and a smaller apparent particle size compared to the results with a surface coated with a greasy material. There is a need for a better quantification of the aerodynamic properties of smoke agglomerates.

Table 43. Size Distribution and Yield of Smoke Aerosols Produced during Flaming Combustion

Fuel Type	Fuel Size (m^2 unless noted)	Smoke Yield (g_{smoke}/g_{fuel})	Mass Median Aero. Diam. (μm)	Geom. Stand. Dev.	Comments	References
Heptane	3.5 mm diam. cotton wick bundle	NA		1.5		Lee and Mulholland, 1977[72]
Acetylene	67.5 cc/min	0.062-0.088	6.4-9.6	No fit	Gas	Cleary, 1989[71]
	72 cc/min	0.064	5.8			Samson et al., 1987[73]
	59.0 cc/min	NA	2.4, 3.8	No fit		Cleary, 1989[71]
	51.0 cc/min	NA	0.72	No fit		
	43.3 cc/min	0.029-0.042	0.43-0.59	8.5-14		
	42 cc/min		0.48			Samson et al., 1987[73]
	39.5 cc/min	0.008-0.015	0.24-0.46	3.8-20		Cleary, 1989[71]
Kerosene	0.09	NA	3.2	12-13	Pool fire	Corlett and Cruz, 1975[74]
	0.36	NA	1.56, 0.57	11, 31		
Crude oil	113	0.12	1.0		Pool fire	Evans et al., 1992[64]
	1.13	0.080	2.5	3.1	Aged 150 min	Evans et al., 1989[58]
			1.1	2.4	Aged 90 min	
			0.8	2.7	Fresh	
	0.28	0.085	0.5	6.8	Pool fire	Evans et al., 1987[52]
	3.1	0.14	0.3			Evans et al., 1992[64]
Asphalt	2.27	0.024	0.34	8.5	Shingles, 30° angle	Dod et al., 1989[54]
Douglas fir	0.411 m^3	0.027	1.28	3.1	Wood crib, Undervent.	Dod et al., 1989[54]
	0.006	0.025	0.43	2.37	Vert., 2.5 W/cm^2, 4.8 l/s	Bankston et al., 1978[61]
	2.23	0.0014-0.0024	0.18	16	Plywood, Vert., Parallel plates	Dod et al., 1989[54]
	0.137 m^3	0.0009	0.056	46	Wood crib	

Birch wood	0.0225	0.0035	0.053	16	Vert., Parallel plates	Dod et al., 1985[63]
PMMA	0.006	0.015-0.018	1.1	9	Varied heating rate, airflow, %O_2	Patterson et al., 1990[57]
PS	0.006	0.041	1.0	4	Varied heating rate, airflow, %O_2	Patterson et al., 1990[57]
PVC	0.006	0.105-0.185	0.4-3	2.5-7	Varied heating rate, airflow, %O_2	Patterson et al., 1990[57]
Rigid PVC	0.006	0.012	0.44	2.02	Vert., 2.5 W/cm^2, 10 % O_2	Bankston et al., 1978[61]
		0.012	0.41	2.22	Same w/ air	
PP	0.006	0.042	0.6	11	Varied heating rate, airflow, %O_2	Patterson et al., 1990[57]
Rigid PU foam	0.006	0.091	0.48	1.90	Vert., 2.5 W/cm^2, 7.2 l/s	Bankston et al., 1978[61]
Flexible PU foam	0.0225	0.034	0.29	16	Horiz.	Dod et al., 1985[63]
HDPE	0.006	0.021-0.028	0.17-0.4	3.6	Varied heating rate, airflow	Patterson et al., 1990[57]

Table 44. Size Distribution and Yield of Smoke Aerosols Produced during Non-flaming Combustion

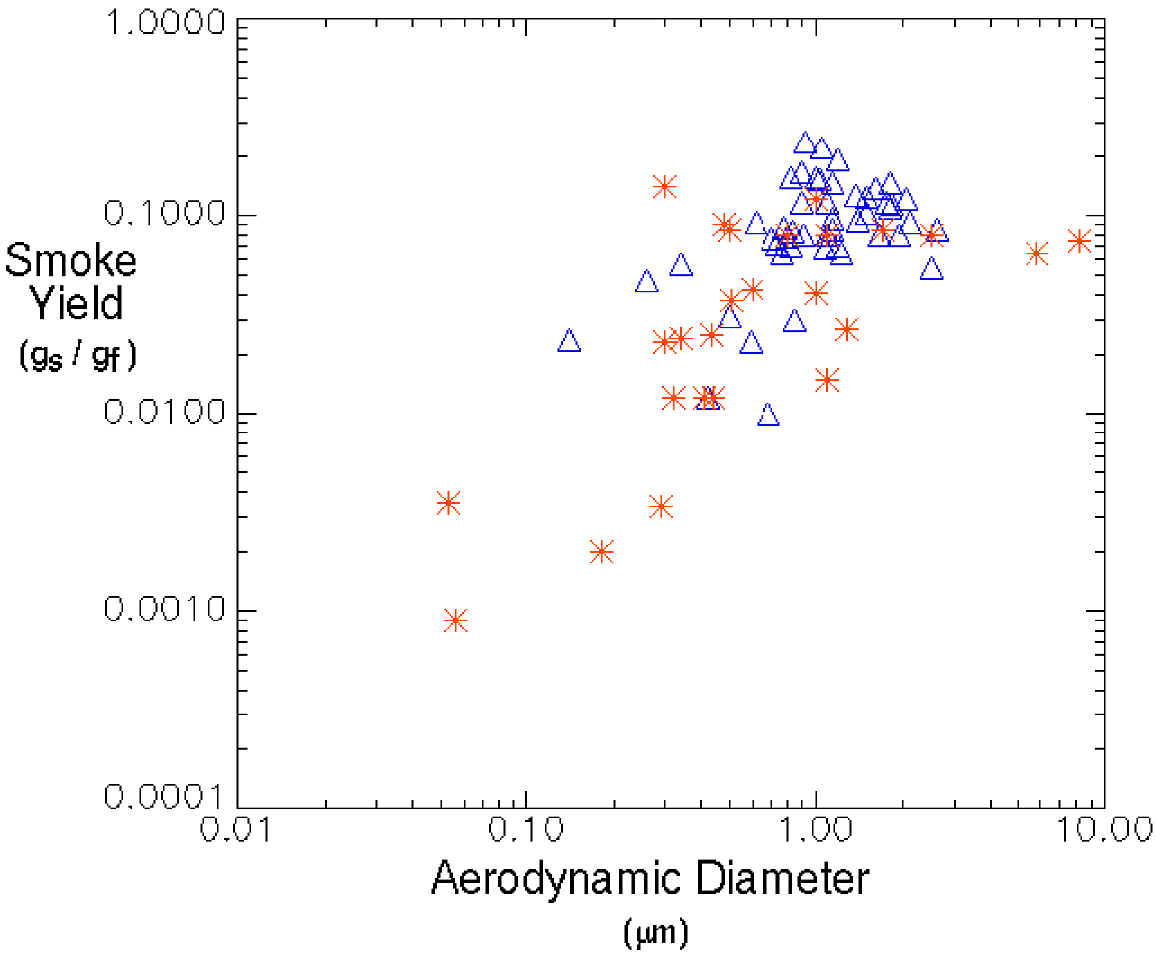
Fuel Type	**Fuel Size (m^2 unless noted)**	**Smoke Yield (g_{smoke}/g_{fuel})**	**Mass Median Aero. Diam. (μm)**	**Geom. Stand. Dev.**	**Comments**	**References**
Cellulosic insulation	0.021	0.055	2-3			Mulholland and Ohlemiller, 1982[75]
Cotton	4 cm x 2.2 cm cloth strip	NA		1.6-1.7	Horiz., Varying aerosol age	Lee and Mulholland, 1977[72]

Douglas fir	0.006	0.108	1.80	1.83	Horiz., 5 W/cm^2	Bankston et al., 1978[61]
		0.165, 0.221, 0.237	0.90, 1.05, 0.92	1.83, 1.93, 2.28	Vert., 6.2 W/cm^2, 17%,10%,5% O_2	
		0.154	0.82	1.98	Vert., 5 W/cm^2	
		0.031	0.5	1.86	Vert., 3.2 W/cm^2, low airflow	
	0.0225	0.0062	0.29	4.0	Flam./Smold. Plywood, Vert.,Parallel plates	Dod et al., 1985[63]
		0.0234	0.14	6.4	Same w/ Solid wood	
PS	0.006	0.084	2.60	1.84	Horiz., 5 W/cm^2	Zinn et al., 1978[53]
Expanded PS foam	0.005	0.114	1.84	2.17	Horiz., 5 W/cm^2	Zinn et al., 1979[62]
		0.147	1.15	2.08	Same w/ additives	
PP	0.006	0.121	2.05	1.77	Horiz., 5 W/cm^2	Zinn et al., 1978[53]
		0.092, 0.079, 0.115, 0.115	2.10, 1.95, 1.75, 1.10	1.85, 1.99, 1.74, 1.89	Same w/ additives	Bankston et al., 1978[61]
MDPE	0.006	NA	1.50	1.73	Horiz., 5 W/cm^2	Zinn et al., 1978[53]
Flexible PU foam	0.006	0.146, 0.102	1.80, 1.50	1.83, 1.60	Vert., 5, 10 W/cm^2	Bankston et al., 1978[61]
		0.137	1.60	2.22	Horiz., 5 W/cm^2, Additives	Zinn et al., 1979[62]
		0.064	1.23	2.56	Same, w/o additives	
		0.153, 0.080	1.04, 1.10	1.71, 1.82	Vert., Additives, 5,10 W/cm^2	Bankston et al., 1978[61]
		0.154, 0.68	1.01, 1.08	1.79, 2.08	Vert., Additives, 5,10 W/cm^2	
		0.116, 0.079	0.89, 1.66	1.88, 1.57	Vert., Additives, 5,10 W/cm^2	
Flexible PVC	0.006	0.123	1.49	1.61	Horiz., 5 W/cm^2	Zinn et al., 1978[53]
		0.123, 0.095, 0.085, 0.079	1.37, 1.15, 1.14, 0.91	1.61, 1.83, 1.78, 1.85	Same w/ additives	Bankston et al., 1978[61]

Rigid PVC	0.006	0.093	1.40	1.45	Horiz., 5 W/cm^2	Zinn et al., 1978[53]
		0.070	1.20	1.86	Horiz., 5 W/cm^2	Bankston et al., 1978[61]
		0.064-0.076	0.70-0.77	1.94-2.04	Vert., 6.2 W/cm^2, 17%,10%,5% O_2	
		0.030	0.85	1.79	Vert., 5 W/cm^2	
		0.012	0.42	1.90	Vert., 3.2 W/cm^2	
Rigid PU foam	0.006	0.191	1.20	2.10	Vert., 9.2 W/cm^2	Bankston et al., 1978[61]
		0.070	0.82	4.21	Horiz., 5 W/cm^2	Zinn et al., 1979[62]
		0.077	0.80	3.58	Same w/ additives	
		0.082, 0.086, 0.092	0.83, 0.78, 0.62	2.30, 2.38, 2.23	Vert., 6.2 W/cm^2, 17%,10%,5% O_2, low airflow	Bankston et al., 1978[61]
		0.057	0.34	3.10	Vert., 3.2 W/cm^2, low airflow	
PMMA	0.006	<0.01	0.68	1.87	Horiz., 5 W/cm^2	Zinn et al., 1978[53]
Rigid trimer foam	0.006	0.023	0.59	2.98	Horiz., 5 W/cm^2, Additives	Zinn et al., 1979[62]
		0.047	0.26	3.09	Same w/o additives	

As can be observed in Figure 8, particle sizes are generally smaller for flaming combustion than non-flaming. This was determined by Bankston *et al.*[61] to be the case for wood, rigid and flexible PU foams and rigid PVC, with mass median aerodynamic diameters nearly identical around 0.5 μm under flaming conditions and from 0.8 μm to 2.0 μm for non-flaming. The median aerodynamic diameter for flaming birch wood as measured by Dod *et al.*[63] was 0.0530 μm, as compared with 0.139 μm for smoldering Douglas fir. This is due to the more complete combustion that takes place during flaming.[72] From Tables 43 and 44, the particle size distribution may be considerably broader for smoke produced during flaming than during pyrolysis or smoldering.

Figure 8. Smoke Yield and Aerodynamic Data (red = flaming; blue = smoldering)



Median aerodynamic diameters for various materials are also listed in Tables 43 and 44. The processes of smoke particle formation and growth take place in the environment surrounding the burning material; therefore, although chemical composition plays a role, the size of a smoke particle is determined primarily by its thermal history, its residence time within regions of high concentrations of combustion products, and its residence time in the flame. Material composition is therefore of smaller importance, although some generalizations may be made. For the foams tested by Zinn *et al.*,[62] particle sizes are smallest for rigid trimer and rigid PU foams, both of which leave a considerable fraction of fuel mass as char after burning. A char-forming sample of PP was also found to produce particles with a substantially smaller particle size.[61,76] This may be due to lower concentrations of particles and combustion gases resulting from the reduced mass loss rate of charring materials. A relationship of the size of the primary particles within soot aggregates with fuel chemistry has been observed by Koylu and Faeth,[51] who note that the largest primary particle sizes are associated with aromatic fuels. The median aerodynamic diameter of smoke collected from smoldering cellulosic insulation was 2μm to 3 μm, much higher than the values obtained for smoldering Douglas fir.[75] The addition of fillers to polymeric materials may result in either an increase in smoke particle size, as for the trimer foam,[62] or a decrease as for PP, flexible PVC, flexible PU foam, and expanded PS foam.[62,61]

In most cases of flaming combustion, as shown in Table 43, the median aerodynamic size increases as the fuel size increases. This is to be expected since a larger fire tends to be hotter with a larger flame, providing a thermal environment conducive to particle growth An exception to this trend was observed by Corlett and Cruz[74] with kerosene pool fires, for which a quadrupling of the pan area resulted in a decrease of the median aerodynamic diameter. They qualify this finding with the comment that reproducibility deteriorates with decreasing particle size and that further work will be necessary. For non-flaming combustion, an increase in external heating rate increases the particle size as expected.

In non-flaming experiments by Bankston *et al.*,[66] particle size distribution for non-flaming combustion was not strongly affected by oxygen depletion, although for rigid PU foam the standard deviation decreased, with fewer very small and very large particles. For flaming wood cribs, particle sizes from an underventilated fire were considerably larger than those from a fire in an open environment, with median aerodynamic diameters of 1.3 μm and 0.06 μm respectively.[54] This is presumed to result from the lack of oxygen to convert soot precursors to CO_2 and water.

Increasing the flow velocity in the vicinity of smoldering material decreases particle size, since it decreases the residence time for particles to grow by coagulation.[72] Increasing ventilation gas temperature results in an increase in characteristic particle diameter,[53,62,61,77] presumably due to a higher concentration of pyrolysis products resulting from an increased mass loss rate.

2. Changes in Smoke Aerosol due to Particle Transport and Decay

A smoke aerosol is a dynamic entity in terms of its motion, the particle size distribution, and its chemical content. The gross motion of smoke is determined by the fluid mechanics of a buoyancy-driven flow within a building. To a large extent, the motion of the aerosol mimics that of the gas flow. However, there are smaller-scale transport processes affecting the concentration and size distribution of the particles. There are several processes leading to losses in the particle concentration including particle sedimentation, particle diffusion in the boundary layer region to the surface, and thermophoretic deposition from a hot smoke near a cooler surface. This Section describes each phenomenon, provides the formula defining the transport property, and gives estimates for the amount of smoke deposited as a result of each process.

The particle size distribution can also change as a result of individual particles coagulating, *i.e.*, particle collisions and sticking. The resulting increase in the average particle size will affect the aerodynamic diameter and thus the amount deposited in various portions of the respiratory tract. Estimates of these effects will be provided. There are other growth processes that are important for certain gaseous species. These include condensational growth and the adsorption of gases on the particle surfaces. These mechanisms will be treated in Section E.3.

a. Wall Loss. Should there be significant loss of smoke particles at surfaces, the tenability of the fire environment could increase. There are three processes that can lead to wall losses: thermophoresis, sedimentation and diffusion.

Thermophoresis. Small particles in the gas phase are driven from the high to low temperature. This becomes important in fires because the gas temperature as it impinges on the ceiling can be very high compared to the wall temperature. This is evident in fires by the black deposit on the ceiling directly above the fire with decreasing evidence for deposition as one goes out from the center. For particles much smaller than the mean free path of air, the thermophoretic velocity is independent of particle size and is given by the following equation:[78]

$$v_T = \frac{-0.55\eta}{\rho_g T}\frac{dT}{dx} \quad , \tag{6}$$

where dT/dx is the temperature gradient, η is the viscosity of air, and ρ_g is the density of air. In this limit the thermophoretic velocity in air for a temperature gradient of 100 K/cm is 0.03 cm/s. For particle sizes large compared to the mean free path, the thermophoretic velocity depends on the thermal conductivity of both the gas and the particle.[68] The velocity is lower in this limit by a factor of 3 to 10 depending on the thermal conductivity of the particle. In the transition region between the free molecular and continuum, the thermophoretic velocity is somewhere between the limiting values.

Sedimentation. The settling velocity of a particle is computed from the balance between the gravitational force and the drag force[68] leading to the equation:

$$v_S = \frac{\rho_p d^2 g C}{18\eta} \quad , \tag{7}$$

where d is the particle diameter, ρ_p is particle density, g is acceleration due to gravity, and the Cunningham slip correction C accounts for non-continuum effects through the following expression:

$$C(d) = 1 + K_n \left[A_1 + A_2 \exp(-A_3 / K_n)\right] \quad , \tag{8}$$

in which the Knudsen number is the mean free path of air divided by the particle radius ($K_n=2\lambda/d$), and constants are A_1=1.142, A_2=0.558, and A_3=0.999.[79]

Diffusion. Smoke particles undergo Brownian motion, manifested as irregular wiggling motions of the aerosol particles as a result of the random variations in the collisions of gas molecules with the particle. The Stokes-Einstein equation for the diffusion coefficient D is given by[68]

$$D = \frac{kTC}{3\pi\eta d} \quad , \tag{9}$$

where k is Boltzmann's constant and C is the Cunningham slip correction.

*Relative effects***.** Table 45 compares the magnitude of the wall loss effects for these three transport processes. We consider a uniformly distributed aerosol and a surface with a sticking boundary condition for the case of diffusion, aerosol settling on a surface for sedimentation deposition, and a fixed temperature gradient of 100 K/cm for the case of thermophoresis. In all cases, it is assumed that a particle touching the surface sticks. It is apparent that for the case of a 100 K/cm temperature gradient, thermophoresis results in a larger deposition rate than either of the other processes except for sedimentation of the largest particle sizes.

Table 45. Comparison of Calculated Particle Deposition Modes (particles sticking to a 1 cm^2 surface during a 100 s period for a suspended particle density of 10^6 particles/cm^3)

Particle Diameter, μm	Thermophoresis	Diffusion	Sedimentation
0.01	2.8×10^6	2.6×10^5	6.7×10^2
0.1	2.0×10^6	2.9×10^4	8.6×10^3
1.0	1.3×10^6	5.9×10^3	3.5×10^5
10.0	7.8×10^5	1.7×10^3	3.1×10^7

There are factors that impose significant limitations to this type of calculation:

- *Turbulent flow effects.* The results in Table 45 are for a static flow, while realistic fire-driven flows are buoyant and turbulent. The general approximation made in realistic calculations of particle deposition is that the particle concentration in the turbulent flow is uniform until one approaches the boundary layer, where the concentration decreases linearly to the surface. The diffusion velocity in this case is given by:

$$v_D = \frac{D}{\delta} \quad , \tag{10}$$

  where δ is the boundary layer thickness. The rate of deposition is much greater for turbulent buoyant flow compared to diffusion in still air because of the much larger gradient near the surface for the turbulent flow. The difficulty in applying this analysis is in the determination of the boundary layer thickness. The thermal gradient driving the thermophoretic deposition will also have a boundary layer thickness that is typically much greater than the particle concentration boundary layer thickness.

- *Soot agglomerate.* There is another serious difficulty in making a quantitative analysis for the case of flame generated soot. The particle deposition rates in Table 45 are for spherical particles. There are almost no quantitative data for the settling velocity, diffusion coefficient, or thermophoretic velocity for soot agglomerates. Fractal theory provides a framework for computing these properties, but there have been virtually no measurements of these properties for comparison with theory. Most comparisons are for the fractal dimension and the optical properties.

Experimental data. For room fires, there are no quantitative data on the soot deposited within the enclosure or in the connecting corridor and adjacent rooms. Lacking such information, we rely on a variety of studies providing deposition rate information for conditions simulating some of the features of smoke deposition in a room fire to provide an estimate of the magnitude of the action of the smoke deposited. In a study by Dobbins *et al.*,[80] smoke from burning crude oil was collected in a hood above the fire and drawn into a 1 m^3 aging chamber. The initial temperature of the soot was about 100 ^{o}C and it cooled to within a few degrees of the walls in a few minutes. The mass concentration of the smoke was monitored over a period of 90 min. There was about a 10 % decrease in the aerosol mass concentration in 15 min and about 25 % over a period of 90 min. The dominant particle deposition mechanisms in this case were sedimentation and diffusion with a small effect from thermophoresis when the smoke first entered the chamber. If the experiment were scaled up to the size of a realistic enclosure, the deposition via diffusion and sedimentation would be less because of the smaller surface area per unit volume.

Eventually, theoretical analysis of thermophoretic deposition may provide a simplification in predicting deposition for realistic conditions. For a flow of a particle-laden gas toward a cold isothermal surface, Batchelor and Shen[81] found for a range of flow conditions that the particle deposition is proportional to the heat flux to the boundary. The capability to compute the convective heat transport from a buoyant plume to the ceiling and walls of an enclosure for a 3-dimensional transient boundary layer is just now being developed by Baum and Rouson.[82] Combining this model with a suitable generalized Batchelor/Shen analysis would allow the computation of the thermophoretic deposition of the smoke to the walls and ceiling at the same time that the convective heat transport is computed.

A study by Mulholland *et al.*[83] provides a sense of the magnitude of the thermophoretic deposition. Smoke generated using the Cone Calorimeter apparatus was drawn through a 6.3 mm diameter stainless steel tube. The inlet temperature of the smoke, T_i, was in the range of 450 K to 625 K with an outlet temperature T_o of 300 K. It was found that the fraction of smoke deposited, f_T, was approximately proportional to the ratio of the temperature difference to the inlet temperature.

$$f_T = 0.5 \frac{T_i - T_o}{T_i} \quad . \tag{11}$$

Qualitatively, this expression suggests that the particle deposition is proportional to the heat loss even in the case where the wall temperature is not isothermal.

We can make an upper bound estimate of the thermophoretic deposition from a hot smoke layer by using equation (11) with the assumption that all of the temperature change of the gas is a result of convective heat exchange with the ceiling. We assume that the initial ceiling temperature is 1300 K and the temperature leaving the building is 300 K. For these assumptions, we compute $f_T = 0.38$.

A more realistic assumption is that only half of the heat transfer is to the ceiling while the other half is to the entrained flow beneath the ceiling layer. This results in a value of 0.19 for f_T.

The rough estimates given above suggest that about 10 % to 30 % of the smoke produced would be deposited over a period of 10 min to 30 min for a fire in a building. The value could be less than this if the fire were small or could be larger if the fuel produces very large soot agglomerates such as is the case with polystyrene. Of course, the deposition over a long period could also be larger if there is very little flow into the enclosure/building.

b. Smoke Coagulation/Agglomeration. Changes in the size of smoke particles affect their movement toward surfaces and their surface area, which in turn affects the mass of toxicants they can transport. Smoke aerosols are dynamic with respect to their size distribution function. Smoke particles or droplets undergoing Brownian motion collide and stick together. In the case of liquid particles, this results in the formation of larger droplets, while in the case of soot, which is made up of clusters of nearly spherical primary particles, this coagulation process leads to the formation of larger clusters which are called agglomerates. The coagulation equation expresses the rate of change in the concentration for a given particle size as a second order kinetic process involving gains due to collisions of smaller particles resulting in a particle of that size and losses resulting from a particle of the specified size colliding with any other particle size.[84] Integrating the coagulation equation over all particle sizes leads to an equation for the rate of change of the total number concentration, N, with coagulation coefficient, Γ:

$$\frac{dN}{dt} = -\Gamma N^2 \quad . \tag{12}$$

The value of the coagulation coefficient was estimated to be 4×10^{-10} for smolder generated smoke from incense sticks, 1.0×10^{-9} for smoke from flaming α-cellulose[85] and 1.5×10^{-9} for smoke produced by the burning of crude oil.[80] Integrating equation (12), we obtain an expression for the total number concentration as a function of time based on a homogeneously distributed aerosol with initial total number concentration N_0:

$$N = \frac{N_0}{1 + \Gamma N_0 t} \quad . \tag{13}$$

The total number concentration within a flame is on the order of 10^9 particles/cm^3 to 10^{10} particles/cm^3, and the coagulation coefficient is greater than the values given above because of the increased temperature. Assuming a number concentration of 10^{10} and a coagulation coefficient of 5×10^{-9}, one finds based on equation (13) that the number concentration has decreased by a factor of 26 after 0.5 s residence time in the flame. This suggests that there would be a significant amount of agglomeration within the flame. Agglomerates with as many as 100 spheres have been observed by transmission electron microscopy for soot sampled thermophoretically within the flame.

The equation above applies to a uniformly distributed smoke aerosol, while smoke produced by a fire is being continuously diluted by the entrainment of air. There is a lack of direct experimental data on the effect of the coagulation process on the size distribution of the smoke as the smoke travels from near the fire to a remote location where it might be inhaled by someone escaping the fire. If the smoke particle size increases by a large amount during this trip, this may mean that less of the smoke will penetrate deep into the respiratory system.

The smoke aging study carried out by Dobbins *et al.*[80] provides insight regarding the coagulation process. The smoke from a crude oil pool fire was collected in a hood about 2 m above the base of the fire and then sampled into a 1 m^3 aging chamber. The temperature (100 ^{o}C) and concentration (100 mg/m^3, 6×10^6 particles/cm^3) of the smoke entering the chamber are estimated to be similar to what the smoke properties would be for the plume as it reaches the ceiling of a room. Over a 90-minute period, it was found that the smoke number concentration decreased by a factor of 24 during which time the mass concentration decreased by only 25 %. From these concentrations and assuming a density of two for soot, we compute that the diameter of average mass increases from 0.25 μm to 0.72 μm. The aerodynamic mass median diameter increased from 0.8 μm to 1.1 μm during this same aging period, as shown in Table 42.[58] The reason for the relatively small change in the aerodynamic diameter is the broadness of the size distribution, resulting in a peak in the number distribution about a factor 4 lower than the peak in the mass distribution. Coagulation of small particles with each other has a large effect on the number concentration and on the count median size, but coagulation of a small particle or agglomerate with a large agglomerate has little effect on the mass of the large particle. The example given here is probably an overestimate for the effect of coagulation on the aerodynamic diameter, since in a more realistic scenario the smoke would be diluted by entrained air.

The above scenario suggests that there may not be a large change in the mass median aerodynamic diameter as a result of coagulation for an enclosure fire. Thus, if the initial size distribution indicates a large fraction of respirable particles, this will still be true for the aged particles. The coagulation process in many cases may, however, greatly reduce the concentration of very small particles in the range 10 nm to 40 nm. There is concern about the increased toxicity of such particles, despite their negligible mass.

While the above analysis suggests that coagulation may have only a small effect on the aerodynamic mass median diameter, this result is based on a limited data set for a single fuel burning at a fixed heat release rate. It would be valuable to measure the size distribution of smoke collected at various regions in a multi-room test facility for a range of burning materials and fire sizes to assess the effect of aging on the size distribution.

3. Adsorption and Desorption of Toxic Gases on Smoke Particles

Although much is known about the toxicological effects of fire gases on the respiratory tract, the potential for damage to the deep tissues of the lungs due to transport of toxic gases adsorbed on smoke particulates is as yet poorly understood. The preceding Sections considered the state of knowledge of characteristics of particles produced in a fire and their transport through the fire environment to a person ready to inhale. In this Section we consider the question of which toxic gases are likely to be carried and deposited in the lungs by looking at the mechanisms of adsorption and desorption for various gases and smoke particles.

Gas adsorption is a spontaneous process through which a system containing a gas and a condensed phase approaches thermodynamic equilibrium. In thermodynamic equilibrium for a specified gas adsorbed on a specified solid at a fixed temperature, the quantity of gas taken up by the surface is a function of its pressure, $n=f(p)$, or relative pressure, $n=f(p/p^0)$, where p^0 is the saturation vapor pressure of the adsorbate.[86] This relationship, known as an isotherm, has played a central role in the development of models for adsorption and the understanding of adsorption mechanisms.

During adsorption, unsaturated forces at the surface of a condensed phase material, the adsorbent, are at least partially saturated by interactions with gas-phase molecules, the adsorbate.[87] There are two types of adsorption, distinguished by the strength of the attractive forces:

- Chemisorption refers to the formation of a true chemical bond between the adsorbate molecule and the surface of the adsorbent. The process is strongly exothermic, releasing in excess of 0.5 eV per adsorbate molecule, but the energy barrier in breaking existing chemical bonds within the gas molecule or surface structure or both must first be overcome.
- In physisorption, the interaction between gas molecules and surface is controlled by weaker electrostatic or van der Waals forces, the same forces as those involved in condensation. Since no energy barrier exists, physisorption is reversible and occurs over a much more rapid time scale than chemisorption.

Desorption, the removal of the gas molecule from the condensed phase surface, is an endothermic process that occurs for physisorbed molecules only. The deposition of toxic gases in the lungs after transport by smoke molecules, therefore, depends on the partition of the available toxic gas molecules into those remaining in the gas phase, those chemisorbed onto the smoke particles, and those physisorbed. Only the physisorbed molecules are of interest for the lung deposition problem.

a. History and Recent Developments in the Field of Surface Adsorption. The book entitled *Equilibria and Dynamics of Gas Adsorption on Heterogeneous Solid Surfaces*[88] provides a good review of recent developments, especially in regard to modeling the gas surface interaction. The historical perspective presented in the Preface and the first chapter[87] begins with the "Pioneering Age" of adsorption theory, in which both the gaseous adsorbate and the solid adsorbent surface are highly idealized. These early models considered a gas molecule approaching a single adsorption site, represented as a local minimum in the gas-solid potential function (Langmuir in 1917), or a regular 2-D array of such sites (Onsager in 1944). The BET theory (Brunauer, Emmet, and Teller), still used today as the basis for the determination of surface area of adsorbents, extends the Langmuir model to account for secondary adsorption on a previously adsorbed layer. For adsorption on multiple layers of adsorbed material, the FHH isotherm (Frankel, Halsey, and Hill) models the adsorbate as a thin layer of liquid on a homogeneous flat solid. Time-dependent processes were handled with empirical equations, such as the Elovich equation developed in the late 1930's, and simple theoretical and experimental diffusion studies.

Key developments during the "Middle Age" of adsorption science, which started after the Second World War, were the consideration of the energy heterogeneity of real surfaces and the development of advanced analytic techniques for describing this heterogeneity along with interaction among adsorbed molecules. Approaches were sought for more complex problems, including the reverse problem, in which the adsorption energy distribution is sought from an experimental isotherm, and the treatment of gas mixtures in an equilibrium state. Absolute Rate Theory improved understanding of adsorption and desorption processes, and lattice gas theories explored surface self-diffusion for both physisorbed and chemisorbed species. For describing carbonaceous agglomerates such as soot, modifications of the Dubinin-Radushkevich (DR) isotherm proposed for microporous surfaces in 1947 are still being used with reasonable success.

The "Modern Era", beginning in the early 1990s, is marked by the application of greatly enhanced computer power to simulate complex adsorption and desorption events using computationally intensive tools such as Monte Carlo and Molecular Dynamics, combined with experimental techniques such as Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) to characterize in detail the molecular structure of real surfaces. For adsorption processes on carbonaceous particles, the techniques of FTIR spectroscopy, electron paramagnetic resonance (EPR), and microgravimetry enable the determination of the kinetics and mechanisms of some important heterogeneous reactions between the surface and the gas phase adsorbate.[89,90] Advances in theory have come with the use of fractal techniques to describe the soot surface. Adsorption isotherms derived from fractal theory represent an extension to the classical FHH isotherm model.[91]

b. Soot Surface Effects. Adsorption processes for soot have been the subject of considerable recent research because of concerns about the effects of man-made particulates on atmospheric chemistry and human health. Soot particle surfaces are highly complex due both to the wide variety of surface chemical functionalities and to their agglomerate physical structures, which result in large surface areas. Their strong affinity for gases of many kinds has long been noted; many industrial processes employ specially-designed "activated carbons" to remove impurities and act as reducing agents. The following are the features of the particle that affect the rate and extent of adsorption:

Surface functional groups. Carbonaceous aerosols formed by combustion processes vary widely in their surface properties depending on their origins, thermal history, and the composition of the surrounding environment as they form and develop. The range of responses of soot particles to hydration, for example, is due to differences in chemistry during development. If soot is produced under low temperature conditions, from 200 ^oC to 500 ^oC, oxygen is incorporated into the surface during formation. The surface oxides for this soot are acidic in nature, consisting of carboxylic, lactone, phenolic, and quinonoid functional groups. The resulting soot particles carry a negative surface charge and are hydrophilic. Hydrophobic, positively charged soot particles containing basic functional groups such as hydroxyl groups are created when soot lacking surface oxide groups, such as that produced at high temperatures (>1000 ^oC) in the presence of CO_2, is exposed to oxygen and hydrated at low temperatures.[92] Subsequent surface oxidation of a soot particle during aging increases the acidity and polarity of the carbonaceous surface, probably due to the formation of carboxylic acid groups, making the surface more hydrophilic with time. Physisorbed O_2 and incorporation of trace elements such as sulfur increase soot hydration as well.[89]

The chemical contents of soot may include elemental carbon (graphite), organic matter from incompletely-burned fuel, nitrogen, sulfur, and various other elements. The structure of soot is predominantly aromatic in nature and consists of randomly oriented graphitic microcrystallites, or platelets, each about 15 nm in area and 1 nm thick and separated by 2 nm to 5 nm. The most chemically reactive areas are likely to be at the edges of these platelets.[92] Along the edges, where aliphatic and aromatic chains are exposed, highly reactive sites may be found where carbon is not exerting its full valency and is attached to other atoms with only three bonds. Other chemical reaction opportunities are provided by the heterocyclic nature of many of the ringed structures at the platelet edges and by the surface functional groups containing oxygen. The presence of inorganic ash within the particle will also affect its adsorptivity properties. Only a percentage of the carbonaceous surface is active. For example, coverage of the surface by oxygen-containing functional groups has been measured at about 50 % for n-hexane soot.[89] Smaller platelets are subject to oxidation before larger ones. While the maximum adsorptive capacity of a particle is largely determined by the specific surface area, the surface functionalities, which are specific to the type of fuel and combustion history, are important at lower adsorbate partial pressures.[90,93]

Pore structure. The adsorption properties of a soot particle are also affected by its porous structure. Pores are classified in three basic size ranges. Macropores, with pore width greater than 50 nm, provide access into the interior of the particle. Mesopores, with pore width in the range of 2 nm to 50 nm, are of the proper size for the formation of a meniscus of the liquefied adsorbate, and therefore provide sites where capillary condensation may take place. Micropore widths are under 2.0 nm, a size of the same order as that of molecules, and can represent a large fraction of the surface area available for adsorption. This category is further divided into supermicropores, from 0.7 nm to 2.0 nm, and ultramicropores, less than 0.7 nm in width.[92,94]

Information on the effects of the porous structure of real materials on adsorption can be obtained from the shape of the measured isotherm, which generally falls into one of five classes.[86] For a nonporous solid, gas adsorption follows a Type II isotherm, in which the quantity adsorbed increases with relative pressure to a point where it knees over into a smaller slope, then continues to rise with a slope that increases with relative pressure. The presence of micropores in the solid causes increased adsorption at low relative pressures due to the interactions of these sites, resulting in a Type I isotherm. The presence of mesospheres results in capillary condensation at higher relative pressures, increasing the adsorption over that of a nonporous surface and causing hysteresis in adsorption and desorption processes (Types IV and V). A small slope of adsorbed gas amount for low relative pressures (Types III and V) indicates that the adsorbent-adsorbate interaction is particularly weak.

Micropores less than about 2 nm were found by Jaroniec and Choma[95] to play an important role in the surface adsorption of benzene on activated carbon, a factor of 10 or more greater than that of water. It is of interest whether soots also display this enhanced adsorption and whether it also occurs for other organics such as acrolein. The authors also report a high degree of surface irregularity for the activated carbons with a fractal dimension of about 2.6. The increase over the non-fractal surface exponent of 2 is mainly attributed to the micropore structure.

Comparison of soot to carbon blacks and activated carbon. Considerable research has been done on the adsorption properties of carbon blacks and activated carbon. Care must be taken in projecting those results to adsorption on naturally-occurring smoke, however, since the engineering of these commercial products has modified their chemical and physical properties significantly. Both carbon blacks and activated carbon have considerably larger surface areas, due to the rapid cooling of soot to produce carbon blacks[90] and to the dehydration, carbonization, and activation processes that create the extensive network of pores in activated carbon gas.[96] In addition, mineral matter is incorporated into commercial activated carbons to improve reactivity, and surface properties such as polarity and pore size are designed to optimize adsorption of a specific adsorbate.

c. Adsorbate Gas Effects. The adsorption of a particular gas onto a soot particle also depends strongly on the properties of the gas molecules.

Polar molecules. For polar molecules (*e.g.*, H_2O, HF, HCl, HBr, CO, NH_3, NO, and HCHO), the combination of differences in atom electronegativity with molecular structure results in a dipole moment. These gas molecules are preferentially adsorbed over non-polar molecules by sites with unpaired electrons and by acidic oxide groups. In addition to the weaker van der Waals forces that control the physisorption of non-polar molecules, polar molecules are likely to be held by hydrogen bonding.[93] Molecules with high dipole moments are preferentially adsorbed over and may even displace those with smaller moments.[89,92] This factor is of particular importance in the presence of highly polar water molecules, which is discussed in more detail in the section on Soot Hydration below.

Paramagnetic molecules. For paramagnetic molecules, including O_2, NO_2, and NO, unpaired electrons with parallel spins inhabit a set of degenerate orbitals. Since many chemical functionalities on the soot particle surface also contain unpaired electrons, the attraction of this type of adsorbate molecule to these sites will be strong. The presence of paramagnetic molecules in the soot environment is expected to affect the adsorption properties of the soot toward other adsorbates, at least for those that may be adsorbed by these same sites. Study of the soot adsorption of these gases in combination with other diamagnetic or paramagnetic gases has provided insights into the coadsorption of more than one adsorbate.[97]

Aromatic molecules. Aromatic adsorbates, such as benzene and toluene, interact most strongly with carbonyl groups on the soot surface, with which they form an electron donor-acceptor complex.[92] This interaction is enhanced by substitutions in the carbon ring, such as NO_2 or aldehyde groups. The affinity of aromatic adsorbates is enhanced by an increase in the number of carbonyl groups, such as through soot aging, and decreased by acidic surface oxides.

Other organic compounds. Non-polar paraffinic compounds are hydrophobic in nature and adsorb preferentially on carbonaceous surfaces free from acidic surface oxides.[92] Such surfaces preferentially adsorb hydrocarbon vapors relative to water vapor.[89] Unsaturated organic compounds are preferred to saturated compounds on polar surfaces.[96]

d. Soot Hydration. Hydration of soot particles from adsorption of water molecules already present in the atmosphere, generated in the fire, or introduced during suppression is a cooperative process. The more H_2O molecules adsorbed, the stronger is the surface attraction toward additional H_2O molecules.[90] If water were adsorbed onto the surface of a soot particle in sufficient quantities to change the local surface appearance to that of a water droplet, its adsorption properties with respect to other gases would be quite different.

Chughtai *et al.*[90] used the following modified version of the DR isotherm to describe the mass of water adsorbed per gram of soot a as a function of humidity ρ/ρ_0 for a variety of soots and carbon blacks:

$$\log a = \log a_0 - D\,[\log(\rho_0/\rho)]^2 \qquad (9)$$

This equation applies for ρ/ρ_0 up to about 0.55 and allows determination of the chemisorption limit, soot surface coverage at that limit, and the onset of multilayer formation. For the soots tested, chemisorption takes place at low relative humidities up to about 0.25. The corresponding limiting surface coverages range from 6 % to 18 % for pine needle, n-hexane, coal, JP-8 (aviation fuel), and diesel fuel soots, reflecting the density of surface sites for irreversible adsorption of H_2O for each soot (oxygen-containing surface functionalities). For ρ/ρ_0 between 0.25 and 0.55, the dominant mechanism is quasi-reversible adsorption possibly facilitated by hydrogen bonding between surface sites, and for ρ/ρ_0 from about 0.55 to 0.83, multi-layer adsorption through the cooperative interaction between adsorbed and gas phase molecules, again through hydrogen bonding, dominates.

Even at the highest humidity measured, the mass of water adsorbed per gram of soot is only in the range of 0.02 g/g to 0.06 g/g for natural soots. For liquid water to play an important role in transporting HCl to the alveolar region of the lungs, the mass of water must be comparable to the mass of smoke rather than only a small fraction of it. Thus, soot may be considered the dominant means of transport unless the fire atmosphere is nearly saturated for H_2O. Actually, for a relatively high ambient humidity, approaching or even exceeding saturation is possible due to the conversion of most of the hydrogen in the fuel to water vapor. There is a need for data in the humidity range approaching saturation to assess whether there is a marked increase in the adsorbed water for these conditions.

e. Transport of Specific Toxic Gases. Table 46 contains a list of toxic gases that may be transported by smoke particles and some common materials that produce them during combustion. It also indicates the magnitudes of inhalation exposures that can cause sublethal effects ranging from significant sensory irritation to lung edema. Higher exposures can be fatal. Missing from Table 46 are the asphyxiants CO and CO_2. Although these are arguably the most important toxic gases in a fire, it is unlikely that these molecules will be transported by smoke particles because they lack the polarity, solubility, and other molecular features needed for adherence to the particles. All of the gases in the Table are irritants except HCN, which is an asphyxiant.

Table 46. Major Transportable Toxic Gases from Combustion

(Sublethal effects occurring: A, below 10^{-5} volume fraction (10 ppm by volume; B, 10^{-5} to 10^{-4} volume fraction (tens of ppm by volume); C, at 10^{-4} to 10^{-3} volume fraction (hundreds of ppm by volume); D, at 10^{-3} to 10^{-2} volume fraction (thousands of ppm by volume.[98])

Toxic Gas	Potential Sources	Sublethal Effects
Acrolein (CH_2=CHCHO)	Cellulosic materials, *e.g.*, wood, cotton, paper; polystyrenes, ABS	A
Toluene diisocyanate (TDI)	Flexible polyurethane foams	A
Formaldehyde (HCHO)	POM, polypropylenes	B
Hydrogen cyanide (HCN)	Nitrogen-containing materials, *e.g.*, wool, silk, PAN, ABS, acrylic fibers, nylons, urea/formaldehyde, melamine, polyurethanes, polyacrylamide	C
Nitrogen dioxide (NO_2)	Nitrogen-containing materials	B
Hydrogen chloride (HCl)	PVC and chlorinated additives	B, D
Hydrogen fluoride (HF)	PTFE, other fluorinated compounds and additives	B
Hydrogen bromide (HBr)	Brominated compounds and additives	B,D
Sulfur dioxide (SO_2)	Sulfur-containing materials, *e.g.*, wool, vulcanized rubbers, poly(phenylene sulfide)	B
Hydrogen sulfide (H_2S)	Sulfur-containing materials	C
Ammonia (NH_3)	Nitrogen-containing materials	C
Styrene (C_8H_8)	Polystyrenes, ABS	C
Toluene (C_7H_8)	Polystyrenes, PVC, polyurethane foams	D
Benzene (C_6H_6)	Polystyrenes, PVC, polyesters, nylons	C

Despite the awareness of the importance of aerosols in affecting smoke toxicity, there is relatively little quantitative information regarding the transport on particles of sufficient mass of noxious molecules to cause toxicological effects. The following summarizes the available information, the best of which is for HCl, with some on HCN and other toxicants

Hydrogen chloride. The transport of HCl has been studied largely because it is a major pyrolysis and combustion product of polyvinylchloride (PVC), a polymer in widespread use. Chlorine is also present in a number of flame retardant additives. Further, other halogens (bromine and fluorine) are present in a number of commercial products, whose combustion generates the analogous halogen acids, HBr and HF. Their transport should behave much like HCl. Thus HCl is a surrogate for any toxic combustion products with high polarity and high solubility in water.

Wall losses. Galloway and Hirschler[99] have developed a five parameter model to predict the adsorption of HCl vapor on a variety of surfaces. The model includes a bulk gas phase, a boundary layer with a mass transfer rate of the HCl across the boundary layer, equilibrium between the gas phase concentration and surface concentration, and first-order reaction with the surface. The values of the mass transfer coefficients for the ceiling and walls were obtained from Cooper's analysis of the convective heat transfer to ceilings above enclosure fires together with the Reynolds analogy between heat and mass transfer.[100] Once the parameters were determined empirically, the measured and predicted concentrations of HCl concentration for a wide range of surface-to-volume ratios and different kinds of flow agreed to within about 20 % in all cases reported, and often agreed within the measurement uncertainty. This model was incorporated within FAST to describe the surface adsorption of HCl for large-scale experiments.

- For one set of experiments involving a room and a corridor,[101] agreement between experiment and model prediction of the remaining gas-phase HCl concentration was typically within about 20 %. The amount of HCl deposited was about 25 % for the 50 kW fire and about 15 % for the 200 kW fire.

- A second set of experiments involved a room, a corridor, and a target room where the concentration was monitored in the second room.[102] The agreement between measurement and prediction was about 30 %. In this case, the deposition was much greater, ranging from 60 % to 85 %. This is due to the much smaller fire size (10 kW) together with the lower velocity for a "dead-end" flow into a second room compared to a flow through a corridor.

The full-scale tests demonstrate the sensitivity of the HCl loss to the details of the configuration and the fire size. It appears that the general approach used by Galloway and Hirschler could be applied for determining the parameters for other gases and then used to estimate the losses in full-scale tests. If such work were carried out now, one could incorporate the adsorption model into a field model for the smoke dynamics such as the Fire Dynamics Simulator developed by McGrattan and Forney.[103]

HCl adsorption on smoke particles. In order to transport a molecule of HCl deeply into the lungs and deposit it there, the molecule must be loosely bound to a smoke particle. To determine the partition of HCl gas molecules among those remaining in the gas phase, those bonded weakly to soot particles through physisorption, and those bonded tightly, or chemisorbed, Stone *et al.*[104] analyzed smoke products from combustion of cylinders of PVC film interleaved with sheets of polyethylene (PE). Nearly all chloride (98.4 %) was found in the gas phase, 0.7 % was easily desorbed from the soot during a 22 hour purge, and 0.9 % was tightly bound to the soot. This corresponds to about 20 mg of physisorbed HCl per gram of soot for a gas phase HCl volume fraction of 2.7×10^{-3} (2700 ppm by volume).

The quantity of physisorbed HCl provides another demonstration of the affinity of HCl gas for water. A comparison of the measured surface area of soot particles from this experiment with the 0.15 nm^2 covered by a single HCl molecule suggests that HCl coats each particle to a depth of 1.5 monolayers. This thick coating is best explained by mixed adsorption of water vapor and HCl together by the soot.

The authors also estimated the amount of HCl that may be deposited deep within the lungs. Assuming that the density of soot is equivalent to the aerosol in this experiment at 1.57 g/m^3, that 40 % of soot particles travel into the alveolar sacs, and that the breathing rate is 18 L/min over an exposure time of 1 h, the mass of HCl retained in the lower lungs would be 13 mg.[104] This soot density is very high, corresponding to a visibility of about 0.3 m for a light reflecting sign.[48] A more likely concentration for an escaping occupant would be 0.3 g/m^3, which would result in a considerably slower deposition of about 2 mg of HCl per hour. This is to be compared to about 1700 mg of HCl vapor deposited in the respiratory system assuming 50 % deposition of the inhaled HCl vapor.

Inhalation of smoke and gases from a fire containing halogenated materials is therefore expected to result in significant irritation to the upper respiratory tract from HCl gas with transport of a relatively small amount of HCl deeply into the lungs by small soot particles.

HCl solution in water droplets. Since HCl gas is highly water-soluble, it could attach to small water droplets in addition to soot for transport deeply into the lungs. To determine the fraction of HCl that could be transported by a water aerosol, Stone[105] set up a flow of HCl gas through a wetted wall tube of dimensions similar to those of the upper respiratory tract. The effect of a water aerosol stream on the transport of HCl through the tube was determined by comparing the amount of chloride deposited in the liquid film layer when the aerosol is present to that when it is not. A roughly even partition of HCl between gas phase and aerosol was found. Stone estimated that water droplets of 3 μm or less in diameter are nine times as effective as soot in transporting HCl into the lungs.

A reanalysis of Stone's data provides a much larger value for the effectiveness of water droplets relative to soot. The mass of physisorbed HCl on the soot obtained by Stone *et al.*[104] was 19 mg of HCl per g of smoke or 30 mg of HCl per m^3 of combustion gases. For soot particles with aerodynamic size in the range 0.5 μm to 2.5 μm, the alveolar deposition fraction is about 40 %.[104] Thus, the estimated amount of loosely bound HCl deposited in the lung from inhaling 1 m^3 of the smoke and combustion gases is 12 mg. The estimated mass concentration of HCl in the vapor state is 4300 mg/m^3 based on Stone's results that 0.7 % of the HCl was physisorbed. If this vapor were exposed to water droplets such as produced in Stone's droplet experiment, the fraction of HCl adsorbed on the droplets would be about 45 % of the total, which corresponds to 1900 mg/m^3. The estimated alveolar deposition for inhaled droplets in the size range between 1 μm and 5 μm is 40 %.[106] So in this case there would be about 800 mg of HCl deposited in the alveolar region for a subject inhaling 1 m^3 of these droplets. Comparing the droplet deposition (800 mg) with the soot deposition (12 mg), we see that the droplet mode of transport is about 65 times greater.

Either of these conclusions suggests that measurements are needed of the number and size distribution of water aerosols produced during fires. These are extremely difficult measurements to make, but would put the contribution of particle-borne acid gases in perspective.

HCN. Stone and Williams[107] also investigated the possibility that HCN could be transported into the lungs by a water aerosol using the same apparatus used to investigate HCl transport.[107] The difference in the amount of HCN measured in the gas phase with and without the aerosol stream was negligible, indicating that the amount of HCN carried on the water droplets was under 1 %. Water aerosol transport of HCN into the lungs is therefore not a strong concern.

Other toxic gases. The main focus of most studies of adsorption of gases onto soot particles is on the effects of atmospheric particulates on human health and the environment. Much research has been done on gases such as CO, CO_2, O_2, NH_3, NO_2, NO, and other NO_x, PAH, and SO_2, therefore, but the adsorption of other gases of particular concern in fires, such as acrolein and TDI, has not been studied. Chughtai *et al.*[97] have studied the adsorption and reaction of a variety of molecular species found in the atmosphere on the surface of soot. Their analysis methods include microgravimetry and electron paramagnetic resonance (EPR). Table 47 displays results for some gases of interest during combustion. The adsorption of SO_2 and NO_2 for gas concentrations on the order of 0.2 volume percent is on the order of 0.01 g of gas per g of soot and thus indicates that surface adsorption of such gases is not large enough to have a toxic effect on humans. The ability to distinguish different modes of surface adsorption for NO_2 compared to SO_2 from the EPR indicate that the SO_2 is primarily physisorbed while NO_2 is primarily chemisorbed.

Table 47. Gas Adsorbate Data[97]

Adsor-bate	Polar Molecule	Para- or Dia-magnetic	% Chem-isorbed	% Phys-isorbed	Temp	Comments
NO_2	Weak	P	90.3 %	9.7 %	22 °C	1010 ppm NO_2, 15 mg soot
NO	Weak	P	0 %	100 %		
NH_3	Moderate	D	100 %	0 %		17, 34, 57, 68 ppm NH_3 w/ 20 mg soot, 34 ppm NH_3 w/ 5, 10, 15, 20 mg soot, 0.21 mg NH_3/g soot, surface coverage 1.2 %
SO_2	Moderate	D	17.7 %	82.3 %	22 °C	1010 ppm SO_2, 15 mg soot, surface coverage 8.58, 6.84, 4.79, 2.25 %
			19.0 %	81.0 %	34 °C	
			22.8 %	77.2 %	46 °C	
			23.7 %	76.3 %	66 °C	

f. Toxicity of Ultrafine Particles. Particles in the ultrafine size range of 20 nm and smaller in diameter that are inherently nontoxic have been found to cause an inflammatory response in the respiratory system not seen with fine particles about 250 nm in diameter. For particles with intrinsic toxicity, the cell damage and release of inflammatory mediators is much greater for ultrafine than for larger particles. Epidemiological studies also indicate a link between the smallest particulate sizes and adverse effects on cardiopulmonary health.[108] Although the mechanisms of damage are not yet completely understood, recent research has provided some insights.

The lung damage mediated by ultrafine particles is hypothesized to result from the penetration of these particles into the interstitium deep within the lungs.[109] In this scenario, particles travel into the alveoli, where they overcome the capability of the macrophages to clear the lungs by engulfing foreign material and ingesting it or transporting it to the mucociliary escalator for removal. This may occur due to injury to the macrophage cells themselves, to particle numbers that overload the system,[109] or to contamination of the pulmonary surfactant.[110] Ultrafine particles that escape the macrophages are small enough to pass through the epithelium into the interstitium, where they can act as a chronic irritant to cells or be transported to the lymph nodes. This damage may occur even for particles that are chemically inert, as has been seen in experiments with ultrafine particles of TiO_2 and carbon black.[111]

There is one instance in which smoke toxicity due to ultrafine particles has been raised. Under certain specific laboratory conditions, the toxic vapors from combustion of pure perfluoropolymers (PFP), such as polytetrafluoroethylene (PTFE) and tetrafluoroethylene-hexafluoropropylene copolymer (FEP) were found to manifest toxic potency up to a thousand times that of the combustion gases from other materials or PTFE in other toxicity tests. Rats in a small-scale combustion toxicity test were found to die from 30 min exposure to as little as 0.04 mg of PTFE combustion products per liter,[112] as compared to a 30 min LC_{50} of 3.8 mg/l for CO gas and 20 mg/l to 50 mg/l for combustion products from woods and most plastics. Further testing established that the lethality of these fumes was significantly reduced or eliminated by aging, filtering, and co-combustion products with other materials, and that the high toxic potency could be restored during the aging process by reheating.[113,114,35] These results pointed to ultrafine monodisperse particulates as the active species. Measurements of highly toxic PFP aerosols showed that a significant number of particles are 20 nm in diameter or smaller, presumably formed by condensation of a dilute vapor of relatively low molecular weight (2 kD to 6 kD) fluoropolymer.[115] Recent experiments with rats show that PTFE fumes containing ultrafine particles cause severe inflammatory damage involving pulmonary macrophages and epithelial cells.[116] As the PFP aerosol cools and ages, however, 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 toxic potency is eliminated.

4. Summary

For the large fires of most consequence, there is little expected change in the nature of the smoke as one moves further from the fire room.

- Changes in respirability, resulting from changes in aerosol dimension, are expected to be modest. Most of the initial smoke aerosol is in the size range for effective transport to the lower portions of the respiratory tract.
- It is possible for toxicologically significant quantities of polar gases, such as halogen acids, to dissolve in water droplets.
- Surface adsorption of gases on the smoke aerosol surface is likely to be small compared to the amount of the gas needed for a toxic effect.
- Losses of gas phase toxicants from the breathable atmosphere should be relatively modest.
- The total smoke wall loss from fires in buildings is predicted to be a small fraction of the total smoke generated. Gasses are more likely than smoke aerosol to deposit on a surface because of their much larger diffusion coefficient.

Particles with a diameter of 2 nm to 30 nm may be much more toxic than particles with a larger diameter.

5. Future Work

There are three types of information that would influence exposures to airborne toxicants:

- Quantitative information on the losses of toxicants to walls for a range of realistic fires;
- Identification of whether nanometer smoke aerosol can be generated in realistic fire scenarios; and
- Determination of whether a cloud of water droplets forms during a fire and, if so, the conditions under which it may form and the size distribution of the droplets.

IV. CONCLUSION

In Phase I of the SEFS study, we have learned where and for what fire types sublethal effects of fire smoke are likely to result in harm to people. We have also learned that while sublethal effects from smoke exposures can play a substantive role in preventing safe escape, these effects lead to noticeable consequences in only a small fraction of the people exposed. Experimental information on the generation of irritant gases and aerosols in building-size fires will complete the picture.

We have compiled and analyzed all the data available from bench-scale toxicity devices. This produces a basis for estimating the lethal and incapacitating potential from smoke. There are no data on other sublethal effects from the smoke from burning materials. There are extensive laboratory-scale data on combustion gases that remain to be analyzed. There are few building-scale experiments to validate the bench-scale results, although the few that exist show some correlation.

Thus, the most important next step for the SEFS study is the establishment of an accurate reduced-scale measurement methodology for obtaining smoke (component) yield data for commercial products. An integral component of this is the generation of a reference data set of building-scale smoke and heat yield data.

Following that, we should examine the state of knowledge of any relationships between the physiological effects produced by smoke inhalation and the behavior people exhibit in a fire situation. There appears to be little established information, and the current analysis indicates that most smoke exposures are inconsequential. Nonetheless, escape modeling involves extensive assumptions in this area, and these need to be assessed.

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APPENDIX A: TOXICOLOGICAL DATA

TABLE A.1
LC_{50} AND IC_{50} VALUES FOR WELL-VENTILATED FLAMING COMBUSTION

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) g·m^{-3}	95 % Confidence Limits g·m^{-3}	30 min IC_{50} Value (with 14 day post-exposure observation) g·m^{-3}	95 % Confidence Limits g·m^{-3}
Acrylonitrile butadiene styrene					
Pellets	1	15.0	12.3, 18.3	10.6	7.4, 15.2
Pellets	1	15.6	13.2, 18.4	6.0	4.1, 8.9
Pellets	1	20.8	15.9, 27.2	17.0	15.0, 20.0
Pellets	1	19.3	16.7, 22.3		
Bismaleimide					
No details provided	2	14.9	12.8, 17.2	6.8	5.4, 8.3
Carpet foam (with nylon)	3	108.0	NA		
Carpet jute backing (with nylon)	3	57.0	NA		
Chlorofluoropolymers					
Ethylene-chlorotrifluoroethylene (39.4 % fluorine; 24.6 % chlorine)	4	15.1	NA		
Blown ethylene-chlorotrifluoroethylene (39.4 % fluorine; 24.6 % chlorine)	4	20.0	NA		
Epoxy					
No details provided	2	7.3	NA	6.2	5.2, 7.3
Fabric					
Vinyl	5	32.0	28.0, 37.0		
Fluoropolymers (data set A)					
Ethylene-tetrafluoroethylene (59.4 % fluorine)	4	30.2	22.8, 40.0		
Polyvinylidene fluoride (59.4 % fluorine)	4	27.3	17.9, 41.7		
Tedlar – thin opaque	2	40.0	NA	21.0	14.2, 27.8
Fluorenone-polyester - thin clear film	2	13.2	11.8, 14.6	10.7	9.9, 11.5
Fluoropolymers (data set B)					
Fluorinated ethylene/fluorinated propylene – 76 % fluorine	4	0.075	0.03, 0.27		

TABLE A.1
LC_{50} AND IC_{50} VALUES FOR WELL-VENTILATED FLAMING COMBUSTION

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) g·m^{-3}	95 % Confidence Limits g·m^{-3}	30 min IC_{50} Value (with 14 day post-exposure observation) g·m^{-3}	95 % Confidence Limits g·m^{-3}
Polytetrafluoroethylene- Teflon	6	0.045	0.04, 0.05		
Polytetrafluoroethylene- Teflon	7	0.017	NA		
Polytetrafluoroethylene -powder	1	0.164	0.07, 0.37	0.8	0.06, 1.51
Polytetrafluoroethylene -powder	1	0.400	0.02, 6.81		
Polytetrafluoroethylene -powder	1	0.045	0.04, 0.05	0.25	NA
Modacrylic					
Knit fabric	1	7.1	6.4, 7.9		
Knit fabric	1	4.7	3.2, 6.9	2.8	2.0, 3.0
Knit fabric	1	4.4	3.9, 5.0	3.1	2.2, 4.3
Phenolic resin					
Rigid foam	8	8.4	7.3, 9.5	2.0	NA
Polyacrylonitrile					
No details provided	7	38.7	36.2, 42.4		
No details provided	7	41.8	NA		
Polyester					
NFR Fiberfill	9	30.8	28.2, 33.6		
NFR polyester upholstery fabric	10	37.5	35.3, 39.8		
NFR polyester upholstery fabric with NFR FPU	10	39.0	36.0, 42.2		
NFR laminated circuit boards; polyester resin with $CaCO_3$ filler	11	53.0	NA		
Polyester fabric/PU foam composite	10	42.0	NA		
Polyethylene					
NFR semi-flexible foam	12	35.0	34.0, 41.0		
FR semi-flexible plastic foam	12	31.3	29.3, 33.3		
Wire	1	46.0	NA		
Polyphenylene oxide					
NFR business machine housing	11	31.5	NA		
Polyphenylsulfone					
Pellets	1	25.3	22.0, 29.2	15.0	NA
Pellets	1	36.0	24.9, 39.6	21.8	12.9, 36.7
Pellets	1	11.7	9.1, 15.0	10.0	NA
Pellets	1	19.8	14.8, 26.5		
Polystyrene					
NFR rigid foam; GM-51	1	53.5	NA	30.0	NA

TABLE A.1
LC_{50} AND IC_{50} VALUES FOR WELL-VENTILATED FLAMING COMBUSTION

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$	30 min IC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
FR foam; GM-49;expanded	13	35.8	23.6, 48.0	17.9	NA
NFR rigid foam; GM-51	1	32.6	30.5, 34.8		
NFR rigid foam; GM-51	1	38.9	37.9, 39.9	28.7	27.5, 30.4
NFR rigid foam; GM-51; extruded	13	33.8	30.7, 36.9	12.7	NA
NFR foam; GM-47; expanded	13	27.8	NA	15.4	12.0, 18.8
NFR TV cabinet housing; high impact polystyrene base formulation	11	40.0	NA		
Polyurethane, Flexible					
NFR FPU #12	9	40.0	NA		
FR FPU #11	9	40.0	NA		
No details provided	5	52.0	46.0, 59.0		
Melamime type foam	5	12.5	9.7 - 16.1		
Melamime type foam with vinyl fabric	5	26.0	24.0 - 28.0		
FR FPU #14	9	27.8	23.3, 33.1		
FR foam; 22.3 kg/m^3	14	26.0	NA		
FR GM-23	13	34.5	31.2, 37.8	15.1	NA
FR GM-27	13	33.1	26.5, 39.7	9.6	6.0, 13.2
NFR FPU #13	10	40.0	NA		
NFR foam; 22.3 kg/m^3	14	40.0	NA		
NFR GM-21	1	38.0	NA	9.6	4.1, 22.1
NFR GM-21	1	49.5	NA	49.5	NA
NFR GM-21	1	40.0	NA	37.5	35.8, 39.3
NFR GM-21	13	43.2	39.8, 46.6	8.3	NA
NFR GM-25	13	37.5	NA	14.5	11.3, 17.7
NFR foam	8	43.2	39.8, 46.6	8.1	6.7, 9.5

TABLE A.1
LC_{50} AND IC_{50} VALUES FOR WELL-VENTILATED FLAMING COMBUSTION

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$	30 min IC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
NFR upholstered chairs with flexible polyurethane padding foam, a cover fabric, and steel frame; density of foam is 25 kg/m^3	11	35.0	NA		
Polyurethane, Rigid					
NFR foam, 25 mm thick, 96 kg/m^3	15	11.0	10.0 - 13.0		
FR GM-31	13	14.2	NA	6.7	5.5, 7.9
No details provided	5	22.0	21.6, 22.2		
NFR GM-30	1	38.4	NA		
NFR GM-30	1	13.3	12.2, 14.5		
NFR GM-30	1	11.3	7.6, 16.8	8.9	5.1, 15.6
NFR isocyanurate; GM-41	13	11.4	9.3, 13.5	4.1	3.3, 4.9
NFR isocyanurate; GM-43	13	5.8	5.0, 6.6	2.8	2.3, 3.3
NFR GM-29	13	11.2	9.3, 13.1	5.2	3.4, 7.0
NFR GM-35	13	12.1	8.0, 16.2	5.8	4.5, 7.1
NFR GM-37	13	10.9	9.4, 12.4	3.9	2.9, 4.9
NFR GM-39; sprayed	13	16.6	NA	4.8	2.7, 6.9
Polyvinyl chloride, Plasticized					
Plasticized PVC	16	26.0	NA	7.1	4.9, 9.3
CPVC water pipe	3	16.0	NA		
Commercial rigid 1/2" PVC conduit	3	29.5	NA		
Polyvinyl chloride, Resin					
Sheets, 12.7 mm thick, 1,490 kg/m^3 density	15	20.0	NA		
No details provided	5	26.0	21.0, 31.0		
Sheets	15	25.0	NA		
Pellets	1	15.0	10.0, 19.0	6.0	4.0, 8.9
Pellets	1	17.3	14.8, 20.2	18.5	17.5, 19.8
Pellets (w/ zinc ferrocyanide)	1	9.4	7.2 ,12.3	11.8	10.1, 15.1
Pellets (w/ zinc ferrocyanide)	1	14.3	12.5, 16.3	13.2	11.3, 15.4
Pellets (w/ zinc ferrocyanide)	1	15.0	15.0, 15.5		
Tempered Hardwood					

TABLE A.1
LC_{50} AND IC_{50} VALUES FOR WELL-VENTILATED FLAMING COMBUSTION

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$	30 min IC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
No details provided	17	58.1	40.8 - 67		
Urea formaldehyde					
Foam	8	11.2	10.4, 12.0	7.4	6.5, 8.3
Wires and Cable Products					
Commercial PTFE coaxial wire (product)	3	9.6	NA		
Commercial THHN wire with nylon-PVC jacket (product)	3	55.0	NA		
NFR wire insulation made of cross-linked EVA copolymer (product)	11	51.0	NA		
Wood					
Douglas fir	15	150	NA		
Douglas fir	1	35.8	28.6, 44.9	20.0	16.4, 24.3
Douglas fir	1	45.3	39.0, 52.7	18.4	14.0, 24.1
Douglas fir	1	24.0	19.0, 29.0	14.5	10.0, 19.1
Douglas fir	1	29.6	22.7, 38.6		
Douglas fir	1	38.4	35.2, 41.9	14.0	10.5, 18.6
Douglas fir	1	41.0	33.0, 50.9	21.8	15.5, 30.7
Douglas fir	1	39.8	38.2, 41.4	23.5	23.0, 24.0
Douglas fir	1	29.8	23.9, 37.1	20.9	NA
Douglas fir	18	106.5	NA		
Douglas fir	18	69.4	NA		
Douglas fir	13			13.3	10.1, 16.5
Red oak	1	45.0	39.9, 50.8	40.6	NA
Red oak	1	56.8	51.6, 62.5	34.8	31.1, 39.0
Red oak	1	60.0	56.6, 63.6		

NA: Values not available in literature.

TABLE A.2
LC_{50} VALUES FOR VENTILATION-LIMITED FLAMING COMBUSTION

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
Fabric, vinyl	5	19.0	17.7, 20.9
Polyester, Resin	11	40.5	NA
Polyphenylene oxide	11	24.0	NA
Polyvinyl chloride, Plasticized	5	16.0	13.7, 17.5
Polyurethane, Flexible			
No details provided	5	18.0	16.9, 18.4
FR upholstered chairs with flexible polyurethane padding foam, a cover fabric, and steel frame	11	23.0	NA
Melamime type foam	5	8.0	7.2, 10.4
Melamime type foam with vinyl fabric	5	15.0	14.7, 16.2
Polyurethane, Rigid			
No details provided	5	14.0	14.3, 14.5
Wires and Cable Products			
FR wire insulation made of cross-linked EVA copolymer (product)	15	25.0	NA

NA: Values not available in literature

TABLE A.3

LC_{50} AND IC_{50} VALUES FOR OXIDATIVE PYROLYSIS

Material	**Reference**	**30 min LC_{50} Value (with 14 day post-exposure observation)** $g \cdot m^{-3}$	**95 % Confidence Limits** $g \cdot m^{-3}$	**30 min IC_{50} Value (with 14 day post-exposure observation)** $g \cdot m^{-3}$	**95 % Confidence Limits** $g \cdot m^{-3}$
Acrylonitrile butadiene styrene					
Pellets	1	19.3	13.9, 26.9	21.0	15.1, 25.2
Pellets	1	38.4	NA	5.8	2.8, 8.4
Pellets	1	33.3	23.1, 47.9	23.0	18.5, 27.5
Pellets	1	30.9	21.2, 45.0		
Bismaleimide					
No details provided	2	41.9	38.8, 45.1	20.1	16.3, 24.0
Carpet foam (with nylon)	3	68.0	NA		
Carpet jute backing (with nylon)	3	90.0	NA		
Chlorofluoropolymers					
Ethylene-chlorotrifluoroethylene (39.4 % fluorine; 24.6 % chlorine)	4	20.1	18.4, 22.0		
Blown ethylene-chlorotrifluoroethylene (39.4 % fluorine; 24.6 % chlorine)	4	28.9	20.3, 41.1		
Epoxy					
No details provided	2	11.0	8.9, 13.1	4.1	3.3, 5.0
Fluoropolymers (data set A)					
Ethylene-tetrafluoroethylene - 59.4 % fluorine	4	3.3	NA		
Polyvinylidene fluoride - 59.4 % fluorine	4	24.3	19.1, 31.2		
Tedlar – thin opaque	2	34.0	NA	18.8	12.0, 25.6
Fluorenone-polyester - thin clear film	2	17.2	NA	10.9	NA
Fluoropolymers (data set B)					
Fluorinated ethylene/fluorinated propylene – 76 % fluorine	4	0.05	NA		
Polytetrafluoroethylene - powder	6	0.045	0.02, 0.12		

TABLE A.3
LC_{50} AND IC_{50} VALUES FOR OXIDATIVE PYROLYSIS

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$	30 min IC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
Polytetrafluoroethylene – powder	1	0.125	0.08, 0.19	0.68	0.31, 1.49
Polytetrafluoroethylene - powder	1	0.235	0.05, 1.20		
Modacrylic					
Knit fabric	1	5.2	4.9, 5.5	2.7	2.1, 3.4
Knit fabric	1	7.8	6.3, 9.7		
Knit fabric	1	7.0	5.0, 9.7	3.0	2.0, 4.0
Knit fabric	1	5.3	4.0, 7.1	3.2	2.8, 3.7
Phenolic resin					
Rigid foam;GM-57	8	5.9	4.8, 7.0	1.5	NA
Polyester					
Fabric	10	5.0	NA		
NFR polyester upholstery fabric	10	39.0	38.4, 39.5		
NFR polyester upholstery fabric with NFR FPU	10	47.5	43.0, 52.5		
Polyester fabric/PU foam composite	10	30.0	NA		
Polyethylene					
NFR semi-flexible polyethylene foam	12	5.3	4.4, 6.6		
FR semi-flexible plastic polyethylene foam	12	6.1	5.3, 6.9		
Polyphenylsulfone					
Pellets	1	18.7	15.2, 23.0	8.8	6.8, 11.2
Pellets	1	32.2	27.7, 37.5	19.0	10.2, 35.3
Pellets	1	10.7	8.4, 13.6	7.0	NA
Pellets	1	9.5	9.1, 10.1		
Polystyrene					
NFR rigid foam; GM-51	1	50.0	NA	50.0	NA
FR foam; GM-49;expanded	13	40.0	NA	30.9	26.2, 35.6
NFR rigid foam; GM-51	1	46.2	NA		
NFR rigid foam; GM-51	1	40.0	NA	40.0	NA
NFR rigid foam; GM-51; extruded	13	40.0	NA	40.0	NA
NFR foam; GM-47; expanded	13	40.0	NA	27.2	23.0, 31.4
Polyurethane, Flexible					

TABLE A.3

LC_{50} AND IC_{50} VALUES FOR OXIDATIVE PYROLYSIS

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$	30 min IC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
NFR FPU #12	9	37.8	36.6, 39.0		
NFR FPU #13	10	37.0	29.8, 46.0		
NFR foam; 22.3 kg/m^3	14	33.0	NA		
NFR GM-21	1	27.8	16.9, 45.8	7.0	3.6, 13.6
NFR GM-21	1	40.0	31.2, 51.3	20.2	8.6, 47.3
NFR GM-21	1	26.6	15.3, 46.2	53.0	
FR FPU #11	9	17.2	13.2, 22.4		
FR FPU #14	9	40.0	NA		
FR foam; 22.3 kg/m^3	14	23.0	NA		
FR GM-23	13	12.6	10.5, 14.7	7.3	5.5, 9.1
FR GM-27	13	30.5	23.1, 37.9	25.2	4.7, 45.7
NFR GM-21	13	13.4	NA	3.2	1.6, 4.8
NFR GM-25	13	36.9	30.9, 42.9	15.1	12.4, 17.8
NFR foam	8	14.3	11.9, 16.7	4.2	3.3, 5.1
NFR GM-21; 2 PCF	3	34.7	NA		
Polyurethane, Rigid					
NFR GM-30	1	34.0	NA		
NFR GM-30	1	39.6	NA		
NFR GM-30	1	35.1	NA	29.3	NA
FR GM-31	13	40.0	NA	9.0	6.8, 11.2
NFR isocyanurate; GM-41	13	8.0	7.1, 8.9	3.0	2.7, 3.3
NFR isocyanurate; GM-43	13	5.0	4.6, 5.4	3.4	2.8, 4.0
NFR GM-29	13	40.0	NA	8.9	5.1, 12.7
NFR GM-35	13	36.7	NA	10.8	NA
NFR GM-37	13	36.7	NA	6.8	3.4, 10.2
NFR GM-39; sprayed	13	10.9	9.3, 12.5	4.0	2.4, 5.6
Polyvinyl chloride, Plasticized					
CPVC water pipe	3	9.1	NA		
Plasticized PVC	16	21.0	18.8, 23.2	3.4	2.8, 4.0
Commercial rigid 1/2" PVC conduit	3	37.0	NA		
Polyvinyl chloride, Resin					

TABLE A.3
LC_{50} AND IC_{50} VALUES FOR OXIDATIVE PYROLYSIS

Material	Reference	30 min LC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$	30 min IC_{50} Value (with 14 day post-exposure observation) $g \cdot m^{-3}$	95 % Confidence Limits $g \cdot m^{-3}$
Pellets	1	16.0	14.0, 19.0	9.4	NA
Pellets	1	20.0	14.7, 27.2	30.0	NA
Pellets (w/ zinc ferrocyanide)	1	7.6	5.5, 10.5	5.4	5.1, 10.1
Pellets (w/ zinc ferrocyanide)	1	13.3	11.5, 15.4	11.7	10.3, 13.2
Pellets (w/ zinc ferrocyanide)	1	11.3	8.5, 14.9		
Strandboard					
Oriented Strandboard	18	47.0	37.7, 57.3		
Tempered Hardwood					
No details provided	17	86.5	79.4, 93		
Urea formaldehyde					
Foam	8	1.2	1.1,1.3	0.7	0.6, 0.8
Wires and Cable Products					
Commercial PTFE coaxial wire (product)	3	12.5	NA		
Commercial THHN wire with nylon-PVC jacket (product)	3	100.0	NA		
Wood					
Douglas fir	1	16.7	14.5, 19.3	15.0	12.3, 18.2
Douglas fir	1	27.6	22.9, 33.3	10.1	7.2, 14.2
Douglas fir	1	26.8	21.3, 33.7	5.6	3.1, 9.9
Douglas fir	1	24.0	19.9, 29.0	22.0	13.2, 36.7
Douglas fir	1	25.9	20.0, 33.5	10.1	7.2, 14.2
Douglas fir	1	20.4	16.4, 25.3	18.3	14.5, 23.0
Douglas fir	1	22.8	20.2, 25.8	13.5	12.0, 14.2
Douglas fir	1	18.5	17.3, 19.8	14.7	13.3, 16.2
Douglas fir	18	100.8	NA		
Douglas fir	18	64.6	60.6, 77.1		
Douglas fir	13	14.6	8.1, 21.1	4.8	3.8, 5.8
Red oak	1	25.0	18.7, 35.5	25.0	NA
Red oak	1	30.3	26.0, 35.4	23.0	NA
Red oak	1	35.0	24.5, 50.1	24.1	NA

NA: Values not available in literature.

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