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Characteristics of Fire Scenarios in Which Sublethal Effects of Smoke are Important

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Abstract. A number of simulations were performed using the CFAST zone fire model to predict 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 a review of 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. Real-scale HCl yield data were incorporated as available; the modeling indicated that the yield would need to be 5 to 10 times higher for incapacitation from HCl to precede incapacitation from narcotic gases, including CO CO_2, HCN and reduce O_2.

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.

Key words: compartment fires, fire, fire modeling, incapacitation, lethality, smoke, smoke toxicity

Both current prescriptive fire and building codes and the emerging performance-based fire and building codes operate on an implicit or explicit 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. In a companion paper, Hall [1] discusses the available fire statistics and defines the types of fires important for sublethal exposure. This paper, on the other hand, provides further guidance by evaluating a limited number of specific 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 for the susceptible population) 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 [2]. 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 [3]. 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:

Ultrafast	<75 s
Fast	75 s to 150 s
Medium	150 s to 400 s
Slow	>400 s

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 by Gann and Nevasier [4], 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 1.

Särdqvist [5] 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 [6] 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 [3] 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. [7] report on a series of tests to study the fire behavior of bed assemblies, including a mattress, foundation, and bedclothes. Table 1 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 [8, 9] 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

TABLE 1
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.

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 [10] reviewed a range of available test data comparing gas yields from small- and large-scale tests. Table 1 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 [11] and Morikawa et al. [12] 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 [13] 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 1. 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. [14] 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. [15] and Babrauskas et al. [16] 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 [17] 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 1 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 [18]. 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 [3] 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.

3. Computer Modeling Design

A number of simulations were performed using the CFAST (version 3.1) zone fire model [19]. 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. It is important to note that both the fire size (defined as a heat release rate) and the species generation rates (defined as species yields) are specified independently as inputs to the model. Thus, the impact of reduced ventilation on the resulting fire environment is not modeled directly by the model. This is a significant limitation of this (and all present) zone fire models.

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 fire statistics (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

TABLE 2
Conditions in Computer Simulations

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

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 2 summaries the simulations.

3.1. 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 3; the layout is shown in Figure 1.

3.2. 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 4 and the layout in Figure 2.

3.3. 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 5. The layout is also shown in Figure 3.

TABLE 3
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

TABLE 4
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

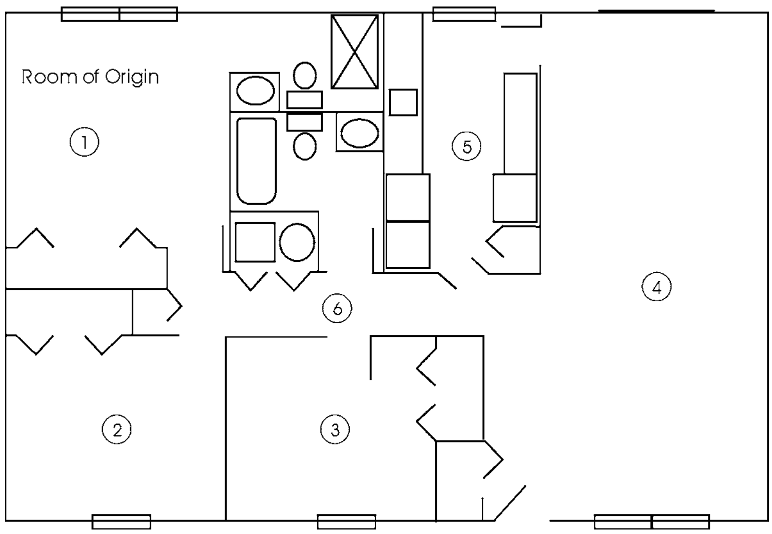

Figure 1. Schematic of the ranch house.

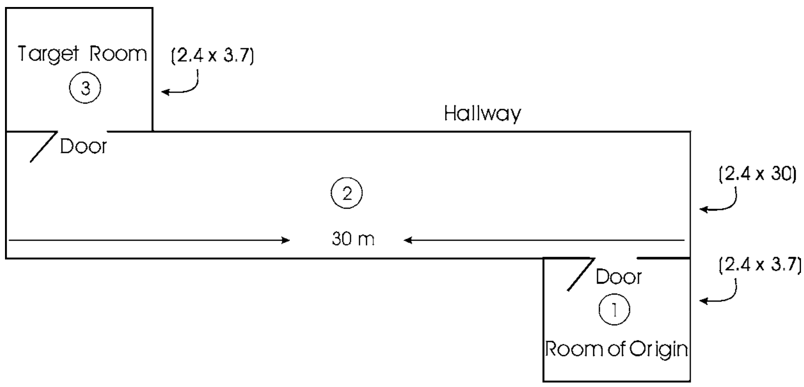

Figure 2. Schematic of the hotel.

3.4. *Design Fires*

Previous analysis had shown that fires that proceeded beyond flashover could and did produce lethal environments outside the room of fire origin [20]. These results suggest that sublethal exposures to smoke are also readily possible for post-flashover fires. This paper

TABLE 5
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

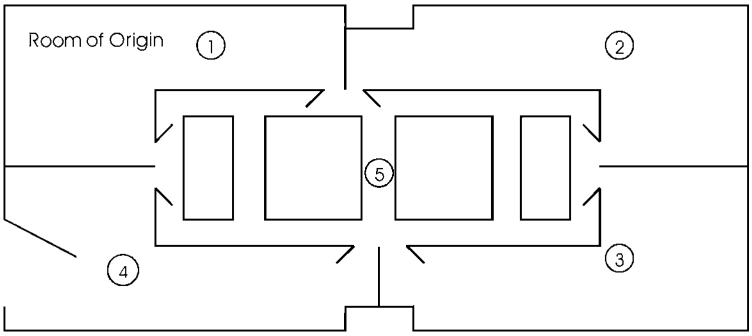

Figure 3. Schematic of the office.

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 [21] 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:

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

$\dot{Q}$ 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.

TABLE 6
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	1,490	$\sim t^2$
	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	5,974	Linear
	0.9 × Flashover	10,752	Linear

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 6 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.

3.5. *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 [22] 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:

$$\mathrm{FED_{HEAT}} = \sum_{t_1}^{t_2}\left(\frac{q^{1.33}}{1.33}\Delta t\right) + \sum_{t_1}^{t_2}\left(\frac{T^{3.4}}{5\times 10^7}\Delta t\right) \quad (2)$$

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:

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

The HCN term has been modified slightly from exp(HCN/43)/220 to eliminate an 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:

$$\begin{aligned}\mathrm{FEC} = {} & \frac{[\mathrm{HCl}]}{1000} + \frac{[\mathrm{HBr}]}{1000} + \frac{[\mathrm{HF}]}{500} + \frac{[\mathrm{SO_2}]}{150} + \frac{[\mathrm{NO_2}]}{250} + \frac{[\mathrm{acrolein}]}{30} \\ & + \frac{[\mathrm{formaldehyde}]}{250} + \sum \frac{[\mathrm{Irritant}]_i}{\mathrm{C}_i}\end{aligned} \tag{4}$$

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 too 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

4.1. 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

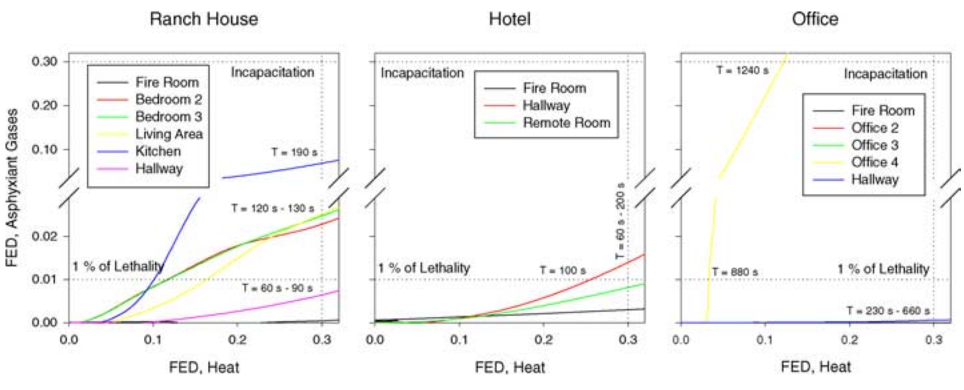

Figure 4. Comparison of thermal effects and narcotic gas effects for several different geometries.

at 1570 s. However, for this scenario the occupants are estimated to be evacuated from the fire floor within 370 s [23], well before incapacitation and even before the potential onset of sublethal effects in some areas. Causality for the differing scenario results is investigated below.

4.2. 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.

4.2.1. 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.

4.2.2. 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.

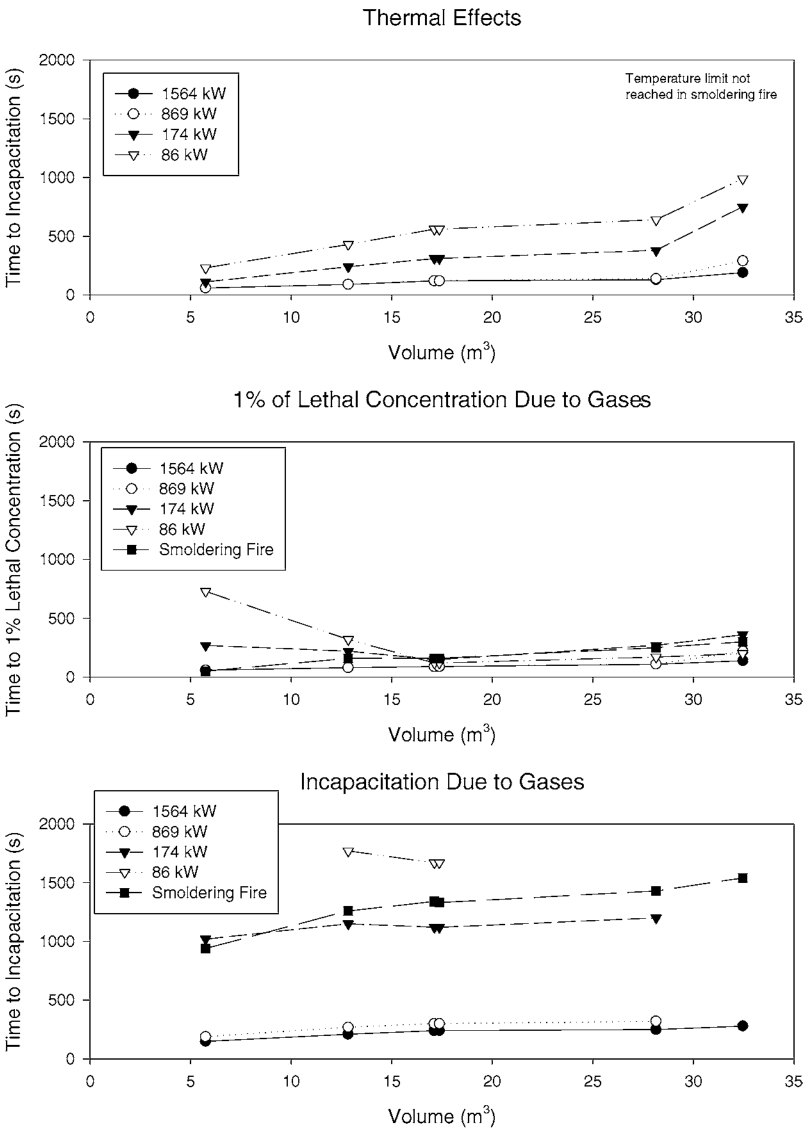

Figure 5. Effect of fire size on time to incapacitation due to thermal effects and narcotic gases for fires in a ranch house.

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.

4.2.3. "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.

4.3. 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. Again, it is worthy to note that the CFAST model includes only the effect of this oxygen limitation on the heat release rate of the fire. Species generation rates remain unchanged unless the model input is changed to account for such effects. Thus, the model results discussed here assume that species generation rates remain unchanged with decreased ventilation. Still, recent testing has shown little effect of severely reduced ventilation on species generation rates [24]. 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.

4.3.1. 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.

4.3.2. 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

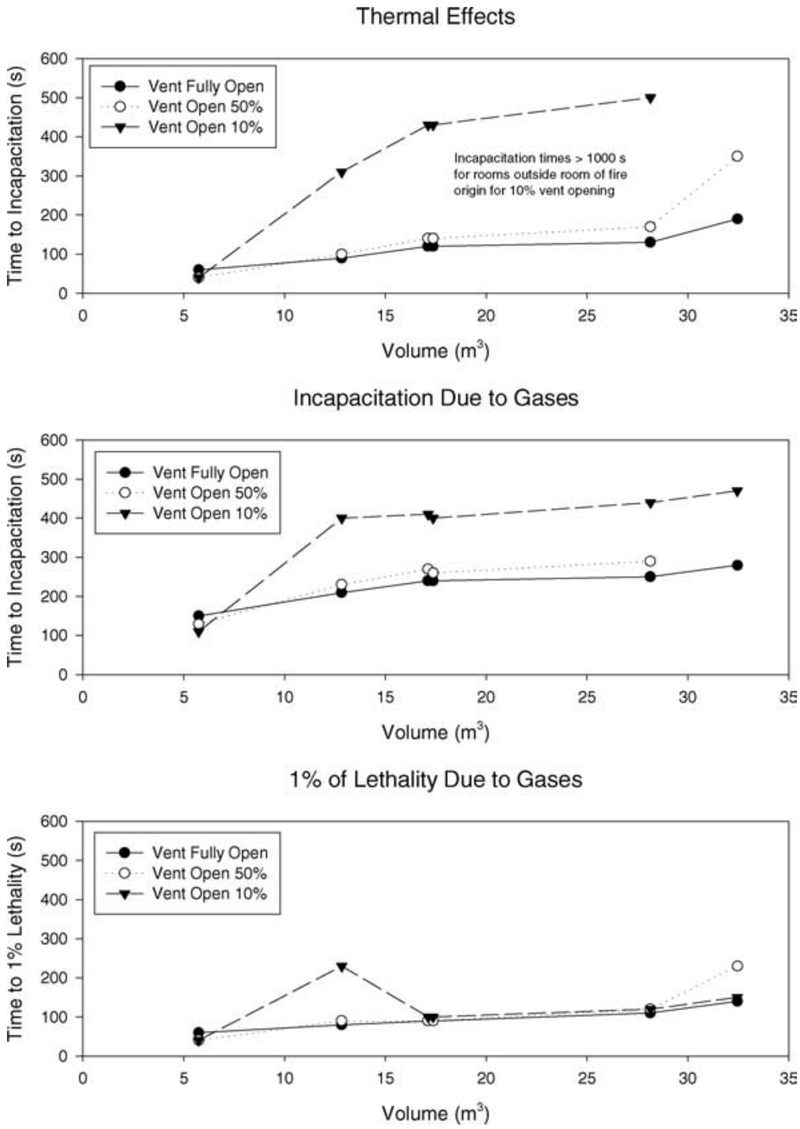

Figure 6. Effect of fire compartment vent opening on time to incapacitation due to thermal and narcotic gas effects for several rooms in a ranch house.

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.]

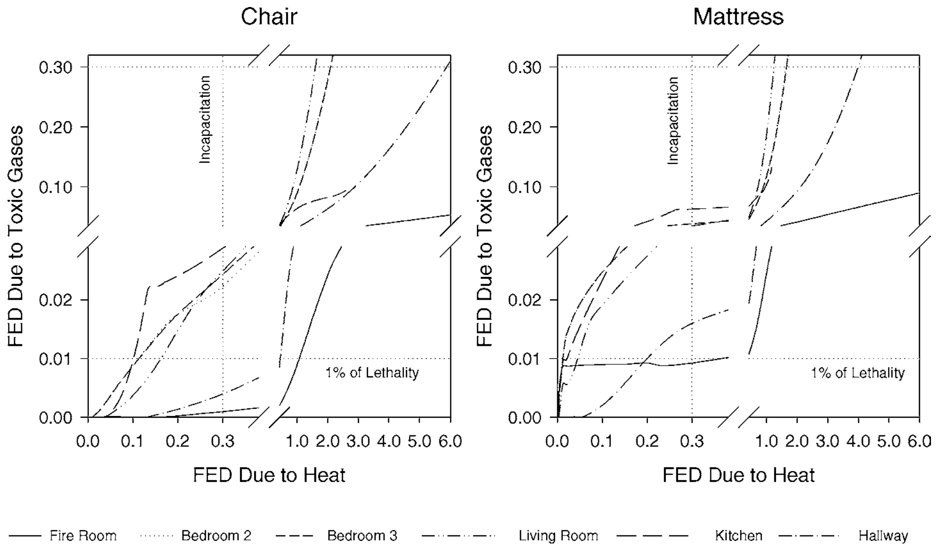

Figure 7. Comparison of incapacitation from thermal effects and narcotic gas effects for two single item fires in a ranch house.

4.3.3. "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. Available data for these two items includes both heat release rate and species yields as a function of time. 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. Several caveats on this observation are appropriate.

- The CFAST model includes only the effect of this oxygen limitation on the heat release rate of the fire. Species generation rates remain unchanged unless the model input is changed to account for such effects. Thus, the model results discussed here assume that species generation rates from the single-item fire tests are independent of available ventilation. Recent testing has shown little effect of severely reduced ventilation on species generation rates [24].
- The ranch house structure was a fairly small structure with a central hallway, minimizing the time necessary for the flow of hot gases throughout the structure. In the structure, incapacitation from narcotic gases becomes more important relative to thermal effects farther from the room of fire origin. For structures with longer gas flow times, this effect can be expected to become more pronounced and consistent with typical observations of the importance of toxic gas effects in spaces removed from the room of fire origin.

4.4. 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 [22]. 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

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 [20].

From the computer modeling, 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. 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.

Still, these projections, which would benefit from experimental confirmation, are consistent with analyses of U.S. fire incidence data [20]. 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.

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