ASET-RSET, Tenability, and Fatal Fire Investigations

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1.0 Introduction

The investigation of a fatal fire involves identifying the origin and cause of the fire and establishing why an occupant could have escaped but instead perished. This article addresses the physiological impact of fire on the occupants of a building with respect to their ability to respond and escape a fire, identifies guidelines used to establish threshold conditions of tenability during their development, and describes methodologies used to perform analyses to assess the available and required time (ASET-RSET) to safely exit a building before those thresholds are reached.

The response of an occupant to fire also has behavioral components that play an important role in the decision-making process of whether, when, and how to escape a fire before the point in time when it is impossible. Social and psychological factors relating to an individual's behavioral response to fire are beyond the scope of this article.

Hazardous conditions that affect persons during fires (Figure 1) are a deterioration of the occupied environment related to temperature, heat, smoke, O2, CO, and other by-products of combustion dependent on the nature of the fuels involved.

Figure 1 – Common Hazards of Fires include temperature, heat, smoke, and toxic gases.

The *cause of death* in many fires is frequently listed in the Medical Examiner's report as smoke inhalation accompanied by a significant elevation in postmortem carboxyhemoglobin (COHb) a stable complex of carbon monoxide (CO) that forms in red blood cells when carbon monoxide is inhaled during a fire. The report may also list the *manner of death* [1], defined as the underlying circumstances that placed in motion a physiological process culminating in the person's death, as natural, accident, homicide, or undetermined. It is common for *manner of death* findings to be described as *pending* while awaiting the findings of the fire investigator regarding whether the fire was accidental or intentional.

The fire investigator should understand that *cause of death findings* are the opinions of a trained physician regarding the *medical reason(s)* for a person's death. The findings may provide valuable insight into whether an individual was alive at the time of the fire or suffered from an impairment (e.g. age, intoxication, drugs, pre-existing handicaps) unrelated to the fire but, alone, are of limited value in explaining why an occupant did not survive the fire and instead perished. The answer to this and related questions requires a broader knowledge of the building, the fire, the location, movement, and actions of the occupant during the fire, the tenability conditions that existed throughout the fire's development, and the collective impact of those conditions on the occupant.

A fire becomes untenable when physical conditions in a room or building threaten the safety, health, or life of persons or impairs their ability to escape from a room, residence, or building. Incapacitation occurs when an occupant is no longer capable of self-preservation because of exposure to heat, smoke, or toxic gases in a fire. The threshold at which an environment becomes untenable varies with the individual, the building, and the fire. All are important considerations, both singularly and collectively, during the investigation of fatal fires.

Not all individuals exhibit the same sensitivity to fire effluents, and impairment factors inherent to an individual unrelated to the fire may also be present. Differences in age, mental capacity, physical handicaps, medication, and drug usage can all affect individual responses to fires. Threshold criteria for tenability developed through research [2] and relied on for building design and the development of codes can provide the fire investigator with guidelines to assess the reason(s) for why a fatality may have occurred in a particular fire. These guidelines represent the median of the distribution and physiological algorithms are based on experimental data for young, healthy humans and animals without impairments.

A fatal fire investigation should include an analysis of the tenability conditions that existed throughout the fire's development to identify and quantify the concentration of heat, smoke, and fire effluents (e.g. CO, CO2, HCN, and others) that an occupant was exposed to during the fire. Such analyses require tracing and documenting the occupant's location and movement from the time of the fire's ignition throughout its development and extinguishment. Premature removal of a victim for transportation and life-saving treatment after a fire is brought under control may complicate this analysis and the only information that the investigator may know is the final location of the victim's recovery.

Time, a key determinant of survival, is not a friend during a fire. " Forty years ago, victims had an average of 17 minutes to escape a burning home after the activation of a smoke alarm. Today, that time has dropped to 3 minutes or less due to evolutions in furnishings, homes incorporating more open layouts, and lightweight construction materials, allowing fires to spread much quicker. " [3]

The ability of an individual to escape a fire is measured by the time frame for which their environment remains survivable (Figure 2). If an occupant is delayed, trapped, or becomes incapacitated, conditions during a fire can deteriorate rapidly and reach lethal levels.

Figure 2 – Time is a key determinant of survival in a fire.

Of primary concern in the investigation of fatal fires is the point at which exposure to one or more variables (e.g. heat, visibility, toxic gases,) would cause injury or block the individual from successfully escaping the fire resulting in death. The order of development of these hazards and their magnitude is dependent on whether a fire begins as a smoldering or flaming fire. Surprisingly, the National Fire

Protection Associated (NFPA) does not currently compile statistical data on the fraction of structure fires starting in the smoldering mode.

Fires that begin in a smoldering state may reach hazardous thresholds of visibility and toxic gases before posing a thermal (i.e. heat) threat, particularly if the fire originates in a location remote from the occupant such as a different room or in another part of a building. Fires that either begin or transition quickly to flaming combustion, however, generally pose a thermal hazard before visibility or toxic gases become threatening if the occupant is close to the fire's origin.

2.0 Common Hazards of Fires

2.1 <u>Exposure to Heat</u>

Temperature and heat (i.e. radiant heat flux), primarily associated with flaming fires (Table 1), leads in different ways to incapacitation and eventual death.

Hyperthermia (i.e. heat stroke) involves prolonged exposure to heated environments at ambient temperatures too low to cause burns but that increase the body's core temperature above its normal temperature of 37 deg. C. (98.6 deg. F) During fires, however, unconsciousness may occur once a core temperature of 40 deg. C (104 deg. F) is reached. Irreversible damage may occur above 42.5 deg. C. (108 deg. F) and is fatal unless treated within minutes.

Burns are essentially the effects of heating the skin and are the same regardless of whether the heat is supplied by conduction from a hot body, convection from air contact, or the radiant transfer of heat from the fire. Pain from the application of heat to the skin occurs when the skin temperature at a depth of 0.1 mm reaches 44.8 deg. C. (112.4 deg. F).

Inhalation of hot gases and thermal damage to the respiratory tract and damage to the respiratory tract is dependent on the humidity of the inhaled hot gases. 60 deg. C (140 deg. F) is the highest temperature at which 100% water-vapor saturated air can be breathed.

Radiant heat flux is a major factor of survivability as it becomes the dominant mechanism of heat transfer during the latter part of a fire's development. The threshold limit commonly accepted for incapacitation related to radiant heat is 2.5 kW/m^2 which, in smaller compartments, may be reached when the hot layer temperature rises above 200 deg. C.

For comparison, 20 kW/m^2 is frequently cited as the floor level radiant heat flux at the beginning of flashover when upper gas layer gas temperatures reach 500-600 deg. C., the fire transitions from a fuel-controlled to a ventilation-controlled one, and occupants outside the room or compartment of origin are threatened.

Table 1: Tenability Thresholds for Heat Exposure

	Normal	Routine	Hazardous	Extreme	Critical
Maximum Time	Indefinite	25 minutes	10 minutes	1 minute	<1 minute
Minimum Air Temperature	20 deg. C	100 deg. C	120 deg. C	160 deg. C	>235 deg. C
Maximum Radiation	<1kW/m2	1kW/m2	3kW/m2	4-4.5 kW/m2	>10kW/m2

Table 1 – Threshold Limits for Temperature and Heat

2.2 Smoke (Obscuration/Visibility)

Smoke is the result of incomplete combustion and consists of airborne solid and liquid particulates, vapors, and gases that evolve whenever a fuel undergoes pyrolysis or combustion. Smoke is comprised of water vapor, CO, CO2, and toxic gases in aerosol form as well as soot large enough to produce visible particles. Soot can be inhaled in quantities sufficient to block airways physically and cause mechanical asphyxiation. Smoke may also contain toxic gases and obscure the vision of occupants.

A reduction in visibility alone is not a tenability endpoint, will not incapacitate individuals or cause death, or prevent an occupant from escaping or evacuating through the smoke. While not directly life-threatening, a reduction in visibility may, however, have both behavioral and physiological implications leading either to the decision of an occupant not to evacuate or delay or slow their evacuation thereby increasing exposure to both toxic gases and heat and preventing a timely escape before conditions become untenable [4]. Visibility limits are generally cited as 5 meters for small enclosures and 10 meters for large ones respectively [5].

2.3 Hypoxia

Oxygen is the primary oxidizing agent consumed in most fires and a reduced oxygen environment occurs as a natural consequence of combustion during enclosure fires. Consequently, insufficient oxygen affects not only the fire's growth but deprives occupants of needed life support. The minimum amount of free oxygen need to support combustion varies with the thermophysical properties of the fuel. In general, hydrocarbon gases and vapors cease burning at oxygen concentrations below 13 percent, whereas charring solid fuels may burn with oxygen concentrations as low as 7 percent [6].

The severity of oxygen deprivation and its physiological impact on an individual occupant depends on the concentration and duration of the exposure (Table 2). Low O2 (Hypoxia) is likely to be less hazardous than the thermal impact of the fire in situations where an occupant is in proximity to a developing fire, in contrast to smoldering fires and those with limited ventilation that consume oxygen. There is little effect of reduced environmental oxygen on an occupant down to 15 % oxygen in the air. However, as the oxygen concentration in inhaled air decreases from 15 % to 10 % a gradual increase in respiration occurs, followed by disorientation and loss of judgment. As the oxygen concentration in the ambient environment decreases below 10 %, critical hypoxia is reached resulting in probable death unless the oxygen supply is quickly restored.

Table 2: Tenability Thresholds for Oxygen				
Oxygen O2 (Hypoxia)	14-21% Little or no Effect	12-14% Slight increase in breathing and heart rate	10-12% Degradation of judgment and neuromuscular control	8-10 % Unconsciousness and death.

Table 2 – Threshold Limits for Oxygen

2.4 Exposure to Toxic Gases

Exposure to toxic gases (asphyxiants) is the primary cause of incapacitation (loss of consciousness) and death in building fires. Asphyxiant gases associated with fire also impair an individual's ability to self-evacuate by decreasing the amount of available oxygen, causing disorientation and possible loss of consciousness. Increases in breathing rate also occur both as a result of panic as well as inhalation of other fire gases.

2.4.1 CO (Carbon Monoxide)

Every person has a baseline amount of carboxyhemoglobin attributable to their environment. This is typically 1 - 3 % in non-smokers and 10 - 15 % in smokers. In residential or building fires, elevated levels of CO are always present at a greater concentration as a result of the combustion chemistry underlying most of the fuels comprising the elements of the building's construction and its contents.

Most fires do not produce lethal levels of CO until the fire becomes ventilation controlled and, as a result, victims of CO inhalation are frequently found outside the room of origin unless the fire resulted from a locally under-ventilated or smoldering ignition.

The concentration of CO in the blood during and after fires is not only a function of the inhaled CO concentration in the air but also the duration of exposure. At concentrations of 10-20 %, occupants will experience headaches and abnormal vision; 20-30 % headaches, nausea, and loss of fine motor skills; 20-40 % incapacitation; and 50% death.

CO is not a simple asphyxiant but a systemic one that alters and interferes with the body's uptake and absorption of oxygen at the cellular level, consequently lowering the amount of oxygen delivered to the tissues and organs of the body. Although CO is an inhalation toxin at the cellular level, it does not damage the lung tissue itself. If the victim, who is poisoned by CO, receives early medical treatment to remove the CO from the hemoglobin and replace it with O2, the probability of recovery without adverse effects is good.

NFPA 101 – Life Safety Code specifies a tenability limit as an integrated dose, of 30,000 PPM a minute or a steady concentration of 1,000 PPM over 30 minutes. The lowest concentration of a material in air that has been reported to have caused death in humans is termed Lethal Concentration Low (LCL0). The LCL0 for carbon monoxide, (inhalation) is listed at 0.5 % (5,000 PPM) for 5 minutes [7].

The body's update of CO ceases when breathing stops but because it has a long half-life in the tissues of a deceased individual, it is easy to identify in toxicology screening of fire victims. Depending on what is burning and how efficiently, however, other toxic products of combustion, including HCN, are also frequently present and may not be identified.

2.4.2 HCN (Hydrogen Cyanide)

HCN, another systemic asphyxiant present with CO during fires, is 35 times more toxic than CO and is produced when manmade plastic and other nitrogen-containing fuels are burned including polyacryo-nitriles, polyurethane foams, melamine, and nylon. Frequently these fuels are ubiquitously present as synthetic materials (e.g. insulation, carpets, clothing) in modern homes.

The pattern of incapacitation related to HCN is somewhat different than CO in that it is not held primarily in the blood but carried to the brain and its effects occur more rapidly. Unlike CO, HCN can enter the body by absorption, inhalation, or ingestion and targets the heart and brain. An exposure of 150 PPM to HCN for 5 minutes would lead to incapacitation and at 250 PPM, to death.

While the cause of death findings of smoke inhalation in a medical examiner's report generally includes an observation of elevated levels of carboxyhemoglobin, the presence or contribution of other fire-related toxic and asphyxiant gases, particularly HCN that may have contributed to the occupant's incapacitation and death, is seldom tested for in standard forensic toxicology screens.

Problematically, the measurement of HCN concentration in the blood or tissue of fire victims is more difficult than that of CO, and toxicology screening for its presence is neither standard, universally available, nor immediate. HCN also has a half-life of one hour in the blood compared with 6 hours for Carbon Monoxide. Coupled with these facts, though more deadly, the contribution of HCN, and other toxic gases, to an occupant's incapacitation and death is frequently overlooked and generally accepted to be understated.

2.4.3 CO2 (Carbon Dioxide)

Though less toxic than CO or HCN, Carbon Dioxide (CO_2) is produced in most building fires but at low concentrations and its effects are unlikely to occur before other effects. Inhalation of carbon dioxide, however, stimulates respiration and in turn promotes increased inhalation of both oxygen and other toxic gas. At 3 % (30,000 PPM) stimulation is approximately doubled and at 5% (50,000 PPM) respiratory rate is tripled. Above 7 % (70,000 ppm) unconsciousness results in a few minutes.

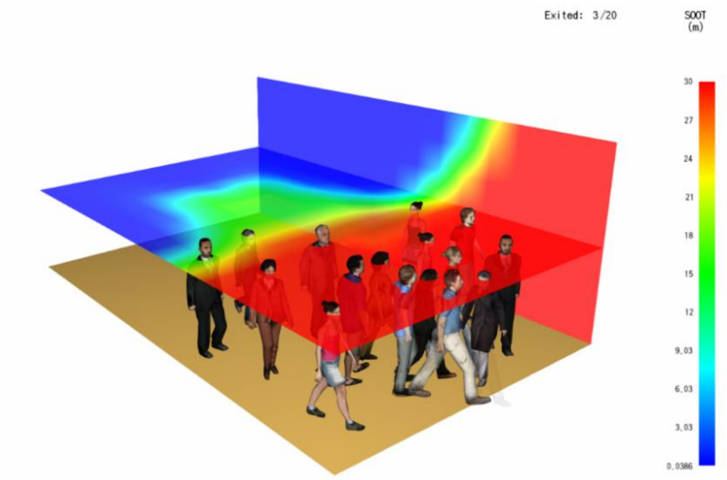
Table 3: Tenability Threshold Limits for exposures to Asphyxiant Fire Gases				
	5 Minute Exposure		30 Minute Exposure	
	Incapacitation	Death	Incapacitation	Death
Carbon Monoxide CO	6,000 ppm	12,000	1,400	2,500
Hydrogen Cyanide HCN	<80 ppm Hyperventilation	100-200 ppm Unconsciousness	>300 PPM Death	1,000 ppm Death
Carbon Dioxide CO2	70,000 ppm			

Table 3 – Threshold Limits for Asphyxiant Fire Gases (CO, HCN and)

2.4.4 FED (Fractional Equivalent Dosage)

Because occupants of a building are typically exposed to the combined effects of toxic gases, heat, and smoke during a building fire, their impact must also be considered collectively to account for their synergistic effects.

A more rigorous assessment of heat and toxic gas exposure may be carried out using the concept of a Fractional Effective Dose (FED). FED calculations involve the determination of an exposure dose at regular discrete time increments and summing the individual dosage for the total period of exposure. The model takes the concentration/time profiles of fire gases (CO, CO2, and HCN), smoke optical density, temperature, and radiant heat flux derived from other mathematical models or large-scale fire tests, and calculates the time to incapacitation based on the known toxic effects of these physical hazards, in man, primates, and rodents. [8]



The FED threshold is usually set between 0.3 and 1.0 because the average height or region from which products of a fire's combustion would be inhaled by a breathing person is frequently measured at any height between 1.5 and 2 meters above floor level (Figure 3). The doses are calculated as a fraction of incapacitation dosage and the maximum value of FED=1.0 represents the state of incapacitation.

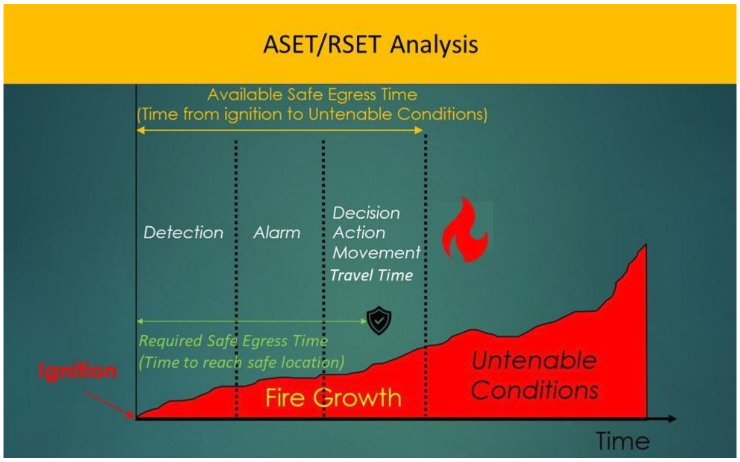
Figure 3 – FED Threshold at 1.5 meters above floor level.

Heat and toxic gas exposures are usually calculated separately and, using this method, the tenability criteria for heat and toxic gas exposures are usually set a FED=1.0 and FED =.3, respectively, and measured at heights of between 1.5 – 2.0 m in the fire environment.

3.0 Available Safe Egress Time (ASET) vs Required Safe Egress Time (RSET)

In assessing the impact of tenability conditions on a fire victim, the fire investigator must consider the mobility and movement of the victim before their incapacitation. A fire dynamics analysis should be performed to assess the predicted temperature and radiant output of the fire, the concentration of smoke and visibility, the percentage of available oxygen, and the concentration of combustion by-products throughout the fire's development as a function of time.

Using this data, the investigator can then identify the duration of time from ignition until tenability conditions are exceeded (*Available Safe Egress Time*) and the time required from the time of ignition to egress the building (*Required Safe Egress Time*). The latter must include the time from ignition to detection, the time needed for the occupant to decide, take action, and begin moving, and the travel time required to exit to a safe location). Tenability is a moving target continually changing with time throughout a fire's development and dependent on the location of the individual. ASET and RSET times may vary with each occupant depending on starting location, physical condition, and susceptibility to fire effluents.



With respect to survivability, the available safe egress time must be greater than the required safe egress time. (Figure 4) The magnitude of the difference between them is an indication of the margin of safety on which the life or death of the occupant hinges.

Figure 4 – Available Safe Egress Time vs Required Safe Egress Time

4.0 – Analyses and Methodology

While the outcome of a fire is generally known its initial conditions are not. Data is often unknown and incomplete. Information regarding the exact time and location of the fire's ignition may be unavailable. Frequently only a partial sequence of events is known and frequently witness accounts are often ambiguous or confusing. The randomized breaking of a window as a result of thermal exposure or opening of a door by an occupant during a fire may significantly alter the course of a fire's development, affect tenability conditions, change the fire's flow path, and impact the ability of an occupant to escape [9]. Uncertainty in the underlying data on which an analysis is based is inevitable and must be recognized and quantified to the extent possible.

Scientifically sound equations that permit reasonable quantitative approximations of the development of hazardous conditions (e.g. temperature, smoke, toxic products) from fire in a single room or several rooms can help assess the impact of these changing conditions. These equations and constants are based on empirically derived engineering relationships and are commonly based on curve fit experiments that were conducted to develop correlations under a limited set of conditions (e.g. time to flashover, heat release rates, fire growth rates. [10]

While useful in performing first-order approximations to calculate and frame a narrow aspect of fire development (e.g. time to ignition, time to flashover) at discrete time intervals, these equations lack the iterative capability of more advanced and robust CFD (Computational Fluid Dynamics) applications that provide more precise, and spatially and temporally resolved quantitative information and allow the investigator to explore and test possible outcomes of alternative scenarios or competing hypotheses in less time and with greater efficiency.

The same CFD-based analyses can be used to evaluate whether a properly designed, installed, inspected, maintained, and functioning fire protection component (e.g. smoke alarm, sprinkler) could have responded before threshold tenability conditions were reached and either mitigated the fire's development or provided sufficiently early warning for an occupant to have responded and escaped.

CFD analyses can be combined with evacuation models (e.g. Pathfinder) to calculate egress time as a function of occupant speed and distance. While typically used as part of performance-based design analyses to assess the level of life safety provided in buildings, coupling of tenability data and building geometry can be used to create simulations that visualize the outcome (i.e. success or failure) of movement of an occupant throughout a fire from their original location, through the building and throughout the fire's development, to egress or a safe egress location.

Tenability data extracted from a CFD analysis can be plotted or graphed as a timeline against important benchmark events gleaned from other sources (e.g. alarm system logs, fire incident reports, captured video of the fire) during the investigation of a fire. Of greatest interest are the time of the fire's ignition, when the fire was discovered, the time of sprinkler or smoke alarm activation, the time the fire department received the alarm, the time the fire department arrived, and the time the fire department began fire ground operations. A timeline comparison of these events to when threshold tenability conditions were exceeded is a powerful tool for visualizing and reinforcing whether an occupant who perished in a fire could have escaped within the available safe egress time predicted by the analysis.

For example, data extracted from an analysis using FDS and depicted on a timeline (Figure 5) reveals that threshold values for both temperature and heat flux are exceeded a full 2 minutes inside the master bedroom of a residence before the fire departments arrival and commencement of fire ground operations to extinguish the fire. The bodies of two occupants were recovered inside the bedroom after the fire's extinguishment.

Figure 5 – Tenability conditions plotted against benchmark events using data extracted from FDS (Fire Dynamics Simulator.)

5.0 Summary

The investigation of a fatal fire involves not only the determination of the origin and cause of the fire but establishing whether and how the fire prevented the escape of an occupant or contributed to and resulted in their death. Based on established guidelines of threshold criteria for tenability concerning fires, investigators must assess the mobility and movement of a fire victim before their incapacitation and the collective impact of changing tenability conditions throughout a fire to establish why an occupant could have escaped but instead perished.

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[1] A Guide for Manner of Death Classification – 1st ed., National Association of Medical Examiners -2002

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