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Dedicated to Dr. John L. Bryan, for his inspiration, leadership, and support.

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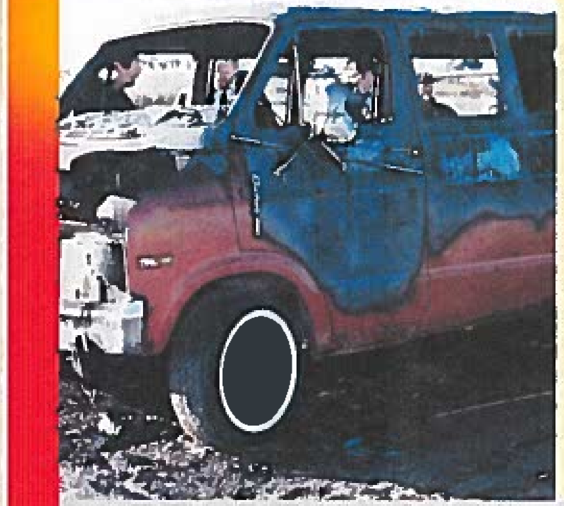
CHAPTER 7

Fire Deaths and Injuries



> “There’s a scarlet thread of murder running through the colorless skein of life, and our duty is to unravel it, and isolate it, and expose every inch of it.”
>
> —Sir Arthur Conan Doyle
> *A Study in Scarlet*

KEY TERMS

- **anoxia,** *p. 320*
- **cause of death,** *p. 329*
- **fractional effective concentration (FEC),** *p. 313*
- **Haber’s rule,** *p. 314*
- **hypoxia,** *p. 320*
- **tenability,** *p. 310*

OBJECTIVES

After reading this chapter, the student should be able to:

- Recognize problems and pitfalls of death or injury scenes.
- Interpret the various contributions to human injuries and deaths at fire scenes.
- Compare case histories and their outcomes.
- Evaluate scenes and the cooperation of investigators.

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In every country, particularly in highly industrialized ones, fire kills a significant number of people. In the United States, it is one of the five leading causes of accidental death. Fire investigators should evaluate the common problems and pitfalls when conducting forensic reconstructions, particularly when death occurs. The purpose of this chapter is to review these human tenability factors, present some analytical approaches, and provide illustrative case histories.

The involvement of the fire investigator or forensic specialist in fatal fires can come in any form, from any sector, and challenge his or her talents and knowledge to come to just and accurate conclusions. These cases require the highest degree of cooperation among the investigators, all of whom have contributions to make toward a successful investigation. When deaths occur in a fire, the event becomes the focus of the press and the public, as well as police, fire, insurance, and forensic professionals. When problems occur, they can have far-reaching consequences.

Problems and Pitfalls

There are several problem areas that can complicate investigations of fires involving fatalities and compromise the accuracy and reliability of the conclusions reached.

- ***Linkage between the fire and death investigations:*** Prejudging the fire and its attendant death as an accident and automatically treating the scene investigation accordingly is a major problem. Fires can be intentional, natural, or accidental in their cause, and deaths can be accidental, homicidal, suicidal, or natural. The linkage between the two events can be direct, indirect, or simple coincidence. The responsibility of the fire investigation team in these cases is to establish the cause of the fire and assist the medical examiner in the death investigation and to determine the connection (if any) between the two.
- ***Time interval to death:*** Sudden violent deaths are assumed to be due to an instantaneous exposure to insult followed by immediate collapse and death of a victim (e.g., a shot is fired, and the victim collapses to die shortly afterward). Many forensic investigations are considered (and successfully concluded) in this light. Fires, however, occur over a period of time, creating dangerous environments that vary greatly with time and can kill by a variety of mechanisms. A person may be killed nearly instantaneously by exposure to a flash fire or only after hours of exposure to toxic gases. Investigators must have an appreciation for the nature of fire, its lethal products, and variables that must be considered and not treat the event as a single exposure to a single set of conditions at a precise moment in time that results in instant collapse.
- ***Heat intensity and duration:*** There is little accurate information available to detectives, pathologists, and medical examiners about the temperatures and intensities of heat exposure that occur in a fire as it develops. Misunderstandings and misapprehensions can lead investigators seriously astray in their interpretations when they try to assess injuries or postmortem damage resulting from fires.
- ***Fire-related human behavior:*** In most violent deaths, the victim responds to what is often referred to as a “fight or flight” response to a threat, then suffers an injury, collapses, and dies. In fires, the potential responses of victims often include going to investigate; simply observing; failing to notice or appreciate the danger; failing to respond owing to infirmity or incapacitation from drugs or alcohol; returning to the fire or delaying escape to rescue pets, family, or personal or valuable property; as well as fighting or attempting to fight the fire. This variability of responses can vastly complicate the process of solving critical problems of why the victim failed to escape the fire (and perhaps why other people escaped).

- *Time interval between fire and death:* Fires can kill in seconds, or death can occur minutes, hours, days, or even months after the victim is removed from the scene. The longer the time interval between the fire and the death, the harder it is to keep track of the actual cause (the fire) and the result (the death). Evidence is lost when a living victim is removed from a scene and dies later, away from the scene; it may be too late to recover or document that evidence. Fatalities that occur after a victim is hospitalized are inevitably omitted from the NFIRS statistics and may also be omitted from the national vital statistics.
- *Conflicts among investigating agencies:* Conflicts can arise regarding the perceived or mandated responsibilities of police, fire, medicolegal, and forensic personnel who are often involved in fire scene deaths.
- *Postmortem effects:* After death, severe postmortem fire effects on the body can vastly complicate the investigation by obliterating evidence. The body can bear fire patterns of heat effects and smoke deposits that can be masked by exposure to fire after death. The body can be incinerated by exposure to flames, so that evidence of prefire wounds or even clinical evidence such as blood samples is destroyed. Structural collapse and effects of firefighting hose streams and overhaul can cause additional damage to the scene and to the body.
- *Premature removal of the body:* A major problem is the premature removal of a deceased victim from the fire scene. The compulsion to rescue and remove every fire victim is a very strong one, particularly among dedicated firefighters. However, once the fire is under control and unable to inflict further damage to the body of a confirmed deceased, there is nothing to be gained and much to be lost in the way of burn pattern analysis, recovery of body fragments (especially dental evidence), projectiles, clothing and associated artifacts (e.g., keys, flashlight, dog leash), and even trace evidence, by the undocumented and hurried removal of the remains.

Tenability: What Kills People in Fires?

Structural fires can achieve their deadly result in a number of ways—heat, smoke, flames, soot, and others—but fire conditions change continually as a fire grows and evolves, and the conditions of victim exposure can vary from conditions involving little or no threat or injury to almost instant lethality. Lethal agents of fires can and usually do act in combination and include heat, smoke, and inhalation of smoke or toxic gases, hypoxia, flames, and blunt trauma. These lethal agents of fires are discussed in further detail later in this chapter.

The ability of humans to escape a fire, **tenability**, is measured by the time frame during which their environment remains survivable. Fires can produce incapacitating effects on humans when they are exposed to heat and smoke. These physiological effects are generally categorized into the following areas (Purser 2008):

tenability ▪ An assessment of the potential for harm that may be imposed from a fire based on (1) an analysis of the source, heat release rates, and rates of production of the combustion products; (2) when occupants might become exposed to these harmful conditions; and (3) the effects on the occupants to this exposure.

- *Toxic gases and irritants:* Toxic gas inhalation can cause mental confusion, respiratory tract injuries, loss of consciousness, asphyxiation, and skin reactions depending on the chemical compositions in the toxic gases.
- *Heat transfer:* Excessive heat irritates exposed skin and the respiratory tract, causing severe pain as well as varying degrees of burn injuries, hyperthermia, or heat stroke.
- *Visibility:* Optical opacity of the smoke and irritants from a fire produces impaired vision as the distribution of thick smoke descends toward the floor through rooms, stairwells, and hallways.

Fire investigators should also consider the synergistic effects of two or more of these factors when conducting a forensic analysis. Of primary concern is assessing the point at which exposure to one or more of the preceding variables would cause injury or block the individual from successfully escaping the fire, resulting in death. The psychological behavior of people in fires when exposed and reacting to these variables affects their decisions and the time required to travel via safe escape routes.

Critical limits to human tenability include a limit of visibility to 5 m (16.4 ft), an accumulated exposure rate of carbon monoxide of 30,000 parts per million minute (ppm-min), and a critical temperature of approximately 120°C (240°F). The synergistic effects of two or more of these critical factors may override an individual's limits (Jensen 1998).

The major goal of the investigator when conducting a *tenability analysis* is to determine how an individual attempting to escape a burning structure becomes impaired and how the fire changes his or her environment and perceptions. These tenability analysis techniques are grounded in both experimental and forensic data, giving the investigator a balanced and practical approach.

The physiological and toxicological effects of heat transfer and toxic smoke on animals and humans are based on scientifically valid experiments. For example, studies correlating carbon monoxide exposure to carboxyhemoglobin levels in the bloodstream used individual subjects ranging from laboratory rats to volunteer medical students (Nelson 1998). Some of these data were extrapolated to model the results at higher levels of exposure to carbon monoxide. These models must take into account variations in age, health, and stature of the individual, because an individual's height affects exposure when he or she is standing upright in the stratified upper smoke layer, where nearly all the toxic gases normally reside. See Figure 7-1 for a graphic illustration of the exposure of humans walking upright through smoke layers (Bukowski 1995b).

Forensic evaluations of incapacitation of a fire victim also come from forensic data derived from actual case histories and investigations. The major studies of the behavior of people in fires come from subject interviews of people surviving large fires and explosions (Bryan and Icove 1977).

Toxic Gases

The previous section on tenability discussed visibility and irritant effects on humans as they try to navigate and survive fires. *Toxic gases* contained within smoke can also have a narcotic effect that asphyxiates victims. The dominant narcotic gases in smoke that affect the nervous and cardiovascular systems are carbon monoxide (CO) and hydrogen cyanide (HCN). Carbon dioxide and reduced oxygen levels (hypoxia) that are not toxic individually may have severe synergistic effects on tenability.

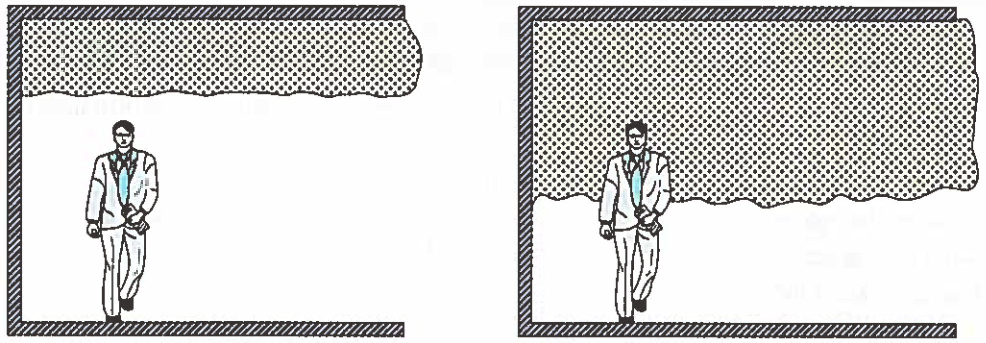

FIGURE 7-1 Illustration of human tenability in varying smoke layer levels. *R. W. Bukowski, "Predicting the Fire Performance of Buildings: Establishing Appropriate Calculation Methods of Regulatory Applications," National Institute of Standards and Technology, Gaithersburg, MD, 1995.*

Increased exposure to toxic gases may cause confusion, loss of consciousness, and eventually asphyxial death. The prediction of asphyxiation resulting in incapacitation and death in fires can be modeled (Purser 2008). Toxic products of combustion can include a wide variety of chemicals depending on what is burning and how efficiently it is burning (temperature, mixing, and oxygen concentration are all important variables in determining what chemical species are created).

Toxic gases can generally be classified into three basic categories:

- *Nonirritant gases:* (sometimes referred to as "narcotic gases"): CO, HCN, H_2S (hydrogen sulfide), and phosgene (CCl_2O).
- *Acidic irritants:* HCl (hydrogen chloride)—produced during the combustion of polyvinyl chloride (PVC) plastics; sulfur oxides (SO_x), which form H_2SO_3 (sulfurous acid) and H_2SO_4 (sulfuric acid)—produced by oxidation of sulfur-containing fuels; and nitrogen oxides (NO_x), which form HNO_2 (nitrous acid) and HNO_3 (nitric acid)—from nitrogen-containing fuels.
- *Organic irritants:* Formaldehyde (CH_2O) and acrolein (2-propenal, C_3H_4O) are produced by the combustion of cellulosic fuels. Isocyanates are produced by the combustion of polyurethanes.

Acidic irritant gases dissolve in the water of the mucous membranes and generate the corrosive acids listed. These acids disrupt the epithelial cell membranes and cause the cells to lyse, releasing fluids and producing edema, as evidenced by extreme watering of the eyes, coughing, and inability to breathe. Sulfur dioxide combines with water to form sulfurous acid, a strong irritant. These reactions can all result in incapacitation, preventing escape from lethal gases such as hydrogen cyanide and carbon monoxide. Exposure to hydrogen chloride (HCl) starting at concentrations of 50 ppm usually causes respiratory or visual impairment sufficient to affect walking movement. Total cessation of movement occurs at a concentration of hydrogen chloride gas approaching 300 ppm. The effects of concentrations of HCl above the 1000 ppm level are most likely severe enough to prevent escape (Purser 2001).

Table 7-1 shows the effects of various fire gases on both the escape and the incapacitation of humans. Most fires present occupants with a complex mixture of toxic and irritant gases and vapors combined with high carbon dioxide and *hypoxic* (low-oxygen) conditions. The fire investigator must assess what fuels were burning, under what conditions (smoldering, open flame, underventilated), and where the occupants would have been exposed to the toxic gases and vapors when assessing the tenability of the fire exposure.

TABLE 7-1 Irritant Concentrations of Fire Gases Predicted to Cause 50 Percent Impaired Escape or Incapacitation in the Human Population

COMMON FIRE GASES	IMPAIRED ESCAPE (ppm)	INCAPACITATION (ppm)
Hydrogen chloride (HCl)	200	900
Hydrogen bromine (HBr)	200	900
Hydrogen fluoride (HF)	200	900
Sulfur dioxide (SO_2)	24	120
Nitrogen dioxide (NO_2)	70	350
Formaldehyde (CH_2O)	6	30
Acrolein (C_3H_4O)	4	20

Source: Derived from Purser 2001.

HCl is a major combustion/decomposition product of vinyl plastics, in both the flaming and the smoldering modes. Hydrogen bromide (HBr) or hydrogen fluoride (HF) is produced when some synthetic rubbers are burned. Acrolein is created when wood or cardboard or cellulosic materials are burned.

The term **fractional effective concentration (FEC)** was developed to assess the impact of toxic smoke and by-products of combustion on a subject (Purser 2001). The use of the concept of FECs by fire investigators will give them a greater appreciation and understanding of what tools in combustion toxicology are available to calculate the impact of lethal toxic products as hazardous to humans (Purser 2008).

fractional effective concentration ■ A measurement that assesses the impact of toxic smoke and by-products of combustion on a subject. The FEC depends on the concentration of particular toxins within the fire gases, and the duration of exposure.

The FEC is expressed in general terms as

$$\text{FEC} = \frac{\text{dose received at time } t(C_t)}{\text{effective } C_t \text{ dose to cause incapacitation or death}}. \tag{7.1}$$

The FEC, in special situations, is also referred to as the *fractional incapacitation dose* (FID) or the *fractional lethal dose* (FLD).

CARBON MONOXIDE

Carbon monoxide (CO) is produced in fires by the incomplete combustion of any carbon-containing fuel; however, it is not produced at the same rate in all fires. In free-burning (well-ventilated) fires, the CO concentration can be as little as 0.02 percent (200 ppm) of the total gaseous products of the fire. The CO concentrations in smoldering, postflashover, or underventilated fires range from 1 to 10 percent in the smoke stream.

CO must be inhaled into a living human to be transferred to the bloodstream. Thus, there is no measurable diffusion from an external atmosphere rich in CO into the blood or tissues of a dead body, owing to the lack of respiration. Similarly, CO content is stable in the blood of a dead body and is not lost until postmortem decomposition.

When inhaled and absorbed into the bloodstream, CO combines with the hemoglobin molecules and forms the complex carboxyhemoglobin (COHb) in the red blood cells. The binding affinity of CO for the heme portion of the hemoglobin is 200–300 times stronger than that of O_2. CO also binds with the heme group in myoglobin, which is the "red" in red muscle tissue. The affinity of CO for myoglobin is about 60 times that of O_2. Myoglobin stores and transports O_2 in muscle tissue, particularly in cardiac muscle. Under hypoxic conditions, CO can shift from the blood into the muscle and has a higher affinity for cardiac muscle than for striated muscle (Myers, Linberg, and Cowley 1979). This may explain why low concentrations of COHb are sometimes found in the blood of deceased victims with heart conditions.

Carbon monoxide also affects Cya_3 oxidase, an enzyme that catalyzes production of ATP in the cell (Feld 2002). The stability of the COHb complex reduces the O_2-carrying capacity of the blood. Without O_2 and water, ATP cannot be produced in the mitochondria of the cell, and the cell dies (Feld 2002). CO also impairs cellular tissue respiration by combining with cytochromes b and aa3 (Purser 2010, 129).

Goldbaum, Orellano, and Dergal (1976) reported that experimentally reducing the hematocrit (the blood-carrying capacity) of dogs by as much as 75 percent did not result in death. Even replacing blood with blood containing 60 percent COHb by transfusion or infusion of CO through the peritoneal cavity did not result in death. Only when these experimental animals inhaled the CO, did deaths occur. This suggests that respiration of CO and its interference with metabolism plays a critical role in causing death (Goldbaum, Orellano, and Dergal 1976).

The mere presence of CO in the blood is not a sign of breathing fire gases. The normal human body has COHb saturations of 0.5–1 percent as a result of degradation of heme in the blood. Higher concentrations (up to 3 percent) may be found in nonfire victims with anemia or other blood disorders (Penney 2000, 2008, 2010). Smokers can have levels of 4–10 percent, since tobacco smoke contains a high concentration of

CO. People in confined spaces with emergency generators, pumps, fuel-burning heaters, and compressors can have elevated—sometimes dangerous—blood COHb concentrations.

When a victim is removed from a CO-rich environment to fresh air, the CO is gradually eliminated from the blood. The higher the partial pressure of O_2 (such as administered by medical personnel), the faster CO is eliminated. In fresh air the initial concentration of COHb will be reduced by 50 percent in 250–320 minutes (approx. 4–5 hr). In 100 percent O_2 via mask, a 50 percent reduction can be achieved in 65–85 minutes (approx. 1 to 1.5 hr). In O_2 at hyperbaric pressures (3–4 atm), there is a 50 percent reduction of COHb in 20 minutes (Penney 2000, 2008, 2010). Treatment for high concentrations of CO or nitrogen gases in the blood may include time in a hyperbaric chamber to reduce the effects of CO or nitrogen gas poisoning.

The time at which a blood sample is drawn from a fire victim must be noted, as well as the nature of any medical treatment (such as the antemortem administration of O_2). The COHb saturation of blood in a dead body is very stable, even after decomposition has begun. CO poisoning kills many fire victims before they are ever exposed to fire. Because CO gas is colorless and odorless; it may go undetected by the victim. It can kill victims even some distance away from a fire when they are not exposed to any heat or flames, but it is not the only factor in many fire deaths.

Carbon dioxide is a product of nearly all fires. Levels of 4–5 percent CO_2 in air causes the adult respiratory rate to double (Purser 2010, 127). Levels of 10 percent cause it to quadruple and probably cause unconsciousness (Purser 2010). This increase in respiration increases the rate at which CO and other toxic gases are inhaled. High concentrations of CO_2 may also dilute the concentration of breathable oxygen to the point of inducing hypoxic collapse. Carbon dioxide concentration in the blood can be measured in living subjects, but blood chemistry begins to change after death. As a result, accurate CO_2 (and O_2) saturation measurements are difficult to obtain postmortem, since postmortem decomposition can also contribute to the CO_2 measured.

PREDICTING THE TIME TO INCAPACITATION BY CARBON MONOXIDE

Haber's rule ■ The dosage of toxic gases assimilated by an individual is assumed to be equivalent to the concentration times the duration of exposure.

The estimation of dosage levels for predicting times to incapacitation is an important concept. Under **Haber's rule** the dosage of toxic gases assimilated by an individual is assumed to be equivalent to the concentration times the duration of exposure. For example, a 1-hour exposure to a toxic gas at one concentration would be equivalent to a 2-hour exposure to half that concentration.

The Coburn-Forster-Kane (CFK) Equation In certain cases, Haber's rule does not hold exactly true for exposure to CO. The relationship between concentration and uptake is linear only for high CO concentrations and is not valid at extremely high concentrations. For lower concentrations, the time to incapacitation is an exponential relationship and is described by the CFK equation. The CFK equation (7.2) also predicts that the half-time elimination of CO is a hyperbolic function of the ventilation rate (Peterson and Stewart 1975).

$$\frac{A[\mathrm{COHb}]_t - BV_{\mathrm{CO}} - PI_{\mathrm{CO}}}{A[\mathrm{COHb}]_0 - BV_{\mathrm{CO}} - PI_{\mathrm{CO}}} = e^{-tAV_bB}, \qquad (7.2)$$

where

$[\mathrm{COHB}]_t$ = concentration of CO in blood at time t (mL/mL),
$[\mathrm{COHb}]_0$ = concentration of CO in blood at beginning of exposure (mL/mL),
PI_{CO} = partial pressure of CO in inhaled air (mm Hg),
V_{CO} = rate of CO production (mL/min),
A = derived constant,
B = derived constant, and
V_b = derived constant.

TABLE 7-2 Standard Inhalation Values (RMV; L/min)

ACTIVITY	MAN	WOMAN	CHILD	INFANT	NEWBORN
Resting	7.5	6.0	4.8	1.5	0.5
Light activity	20.0	19.0	13.0	4.2	1.5

Sources: Derived from Health Canada 1995; SFPE 2008, 2-102; Bide, Armour, and Yee 1997.

An obvious disadvantage of using the CFK equation is the number of variables needed. The CFK equation is appropriately used for exposure to CO concentrations of less than 2000 ppm (0.2 percent), exposure durations greater than 1 hour, or estimation of time to death where COHb is 50 percent (Purser in SFPE 2008, 2-117). The CFK equation is of limited value in reconstructing most fire death cases where the CO concentration is greater than 0.2 percent and the COHb saturations are often much greater than 50 percent.

The Stewart Equation When predictions of time to incapacitation deal with atmospheric CO concentrations higher than 2000 ppm (0.2 percent), and COHb in the blood is determined to be less than 50 percent saturation, a simpler equation known as the *Stewart equation* (7.3) applies:

$$\%\mathrm{COHb} = \left(3.317\times10^{-5}\right)(\mathrm{ppm\ CO})^{1.036}(\mathrm{RMV})(t), \qquad (7.3)$$

where

CO = CO concentration (ppm),
RMV = respirations per minute of volume of air breathed (L/min), and
t = exposure time (min).

Solving the Stewart equation for exposure time gives

$$t = \frac{\left(3.015\times10^{4}\right)(\%\mathrm{COHb})}{(\mathrm{ppm\,CO})^{1.036}(\mathrm{RMV})}. \qquad (7.4)$$

The standard inhalation values (RMV) are listed in Table 7-2, providing typical data for a man, woman, child, infant, and newborn. For additional information on RMVs, see Health Canada 1995; SFPE 2008, 2-102; and Bide, Armour, and Yee 1997.

According to Stewart, a few breaths of CO in concentrations of 1 to 10 percent (10,000 to 100,000 ppm) rapidly elevate the COHb saturation in the blood. For example, a 120-second exposure at 1 percent (10,000 ppm) CO results in a 30 percent COHb saturation, and a 30-second exposure at 10 percent (100,000 ppm) CO results in a 75 percent COHb saturation (Spitz and Spitz 2006).

The standard approach for evaluating incapacitation from CO is to calculate the fraction of the CO inhaled per minute in 1 hour. During moderate activity, human RMV value is approximately 25 L/min, and loss of consciousness occurs at 30 percent COHb in the blood (Purser in SFPE 2008, 2-117). The formula for the fractional incapacitating dose (FID) valid for up to 1 hour is

$$F_{I\mathrm{CO}} = \frac{3.317\times10^{-5}[\mathrm{CO}]1.036(V)(t)}{D}, \qquad (7.5)$$

where

$$F_{I\mathrm{CO}} = \text{fractional incapacitating dose (FID)} = \frac{\text{concentration of irritant to which subject is exposed at time } t}{\text{concentration of irritant required to cause impairment of escape efficiency}}, \qquad (7.6)$$

[CO] = carbon monoxide concentration (ppm v/v 20°C)
t = exposure time (min), and
D = exposure dose (percent COHb) for incapacitation.

Resting or sleeping	$V = 8.3$ L/min	and	$D = 40\%$ COHb
Light work: walking to escape	$V = 25$ L/min	and	$D = 30\%$ COHb
Heavy work: slow running, walking up stairs	$V = 50$ L/min	and	$D = 20\%$ COHb

EXAMPLE 7-1 ■ CO Incapacitation

Problem. Rescuers found an adult female unconscious in her bed at the scene of a house fire. Assume that rough estimates suggest that she was exposed to a CO concentration of approximately 5000 ppm. Calculate the time to incapacitation and fractional incapacitating dose, assuming that the victim was at rest.

Suggested Solution. Use Table 7-3 for RMV data.

Volume of air breathed — RMV = 6.0 L/min (resting)
Loss of consciousness — COHb = 40% (resting)
CO concentration — CO = 5000 ppm

Time to incapacitation (eq. 7.4)
$$t = \frac{(3.015\times10^{4})(40)}{(5000)^{1.036}(6.0)} = 30\,\text{min}$$

Fractional incapacitating dose (eq. 7.6)
$$F_{I_{CO}} = \frac{(8.2925\times10^{-4})(5000^{1.036})}{30} = 0.188$$

EXAMPLE 7-2 ■ CO Incapacitation and Death of Firefighters

Problem. Computer fire modeling was used to reevaluate a U.S. Fire Administration investigation (Routley 1995) into a reported Pittsburgh fire that killed three firefighters (Christensen and Icove 2004). NIST's Fire Dynamics Simulator (FDS) was employed to model the fire and estimate the concentration of carbon monoxide present in the dwelling, which was the immediate cause of death of two of the firefighters, who were unable to escape the interior of a burning dwelling.

The fire occurred in a four-story townhouse when an arson fire was ignited using gasoline in a room on the ground floor. Firefighters entered on the street level and were attempting to locate the seat of the smoky fire. Details of the minutes prior to the deaths of the firefighters were unclear, but it appeared that at some point they realized they were running short of air in their self-contained breathing apparatus (SCBA), needed to leave, were unable to find an exit, and exhausted their air supplies. Two of the firefighters were believed to have removed or loosened their face pieces and made attempts to share the air that was available by "buddy breathing," involving the alternating the use of a single breathing apparatus. It was concluded that both had been rendered unconscious owing to toxic gas inhalation. They were found to have COHb saturations of 44 percent and 49 percent, respectively, at autopsy. A third firefighter was found with his face piece in place, and his COHb was 10 percent, indicating death from oxygen deficiency.

Solution. This estimate, along with an assumed respiration volume and known blood COHb levels, was used with the Stewart equation to estimate the time of exposure. The FDS model, as shown in Figure 7-2, indicated that 27 minutes into the fire, the CO concentration in the atmosphere at the location where the firefighters were found had already reached approximately 3600 ppm. At this concentration and a respiration rate of 70 L/min, an estimated 3 to 8 minutes of exposure would have been required to accumulate the average 47 percent COHb measured in two of the firefighters' blood at autopsy.

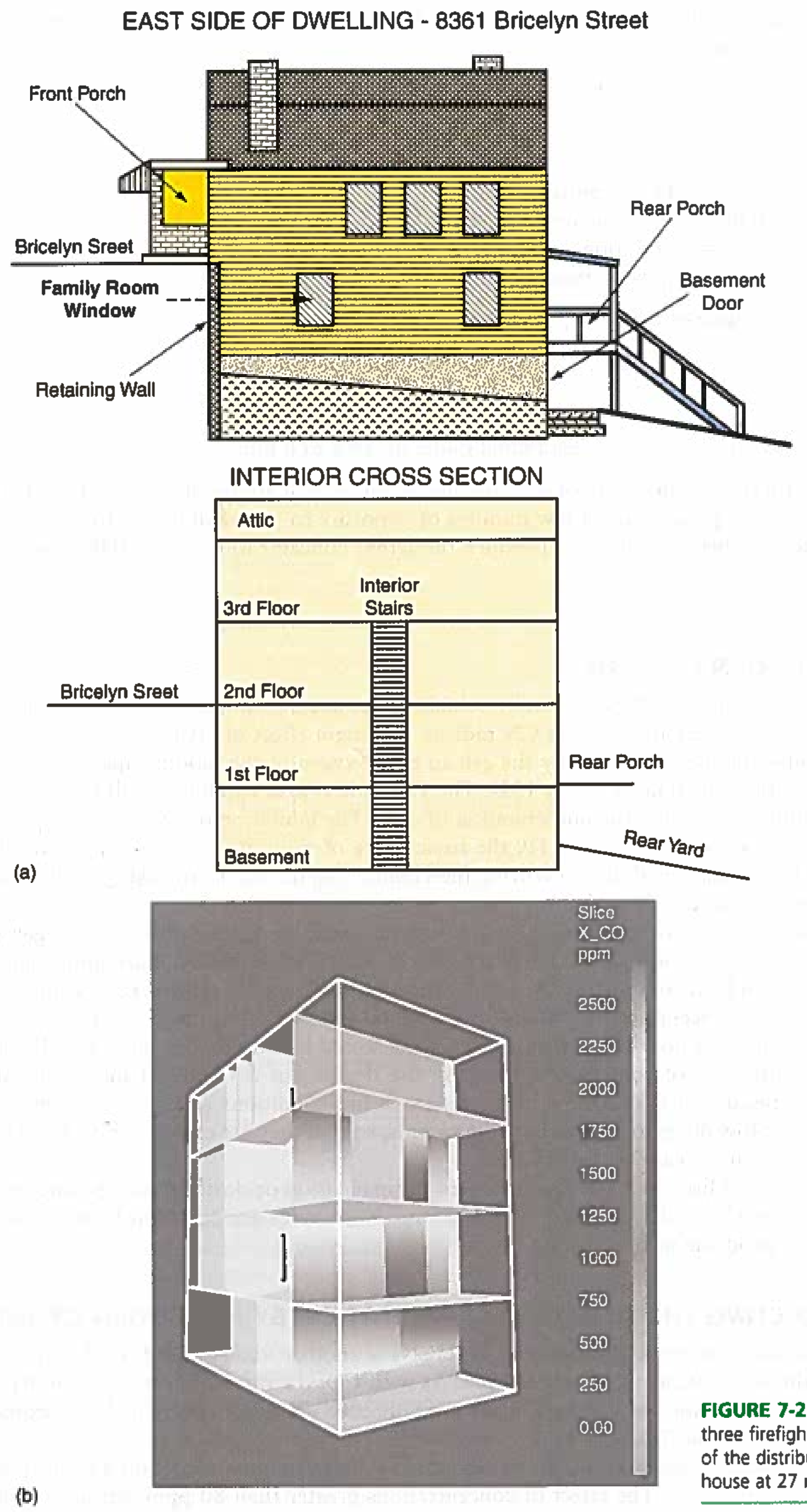

FIGURE 7-2 (a) Plan of town house where three firefighters were trapped. (b) FDS model of the distribution of carbon monoxide in town house at 27 minutes. *Courtesy of D. J. Icove.*

Solution of this problem with the Stewart equation using the CO value from the FDS model calculation gives

$$\%\mathrm{COHb} = \left(3.317\times10^{-5}\right)(\mathrm{ppm\,CO})^{1.036}\,(\mathrm{RMV})(t),$$

where

CO = CO concentration = 3600 ppm
%COHb = carboxyhemoglobin saturation = 47%
RMV = respirations per minute of volume of air breathed = 70 L/min
t = exposure time (min).

Solving for time of exposure, we obtain

$$47\% = \left(3.317\times10^{-5}\right)(3600)^{1.036}\,(70)(t)$$

$$t = 4.2\,\mathrm{min}$$

Estimated range for t=3 to 8 min

A total exposure time of 4.2 minutes suggests that following removal of the firefighters' face pieces, only a few minutes of exposure to CO with no air from the SCBA would have been required to produce the lethal concentrations of COHb observed at autopsy.

HYDROGEN CYANIDE

Hydrogen cyanide (HCN) is readily soluble in the aqueous phase of blood plasma, cells, and organs, where it forms the CN radical. The main effect of HCN or CN in the cell is to inhibit the use of oxygen by the cell so that oxygen in the blood cannot be properly used by the cells (Purser 2010, 132). The CN radical also combines with Cya$_3$ oxidase, inhibiting its action in the mitochondria of cells. The inhibition of Cya$_3$ oxidase prevents the formation of water and ATP, the basic route of respiration in the cell (Feld 2002). HCN is produced in all fires involving fuels containing nitrogen, especially acrylic rubber, ABS plastics, and polyurethane.

As with CO, the production of HCN varies with the temperature and oxygen supply in the combustion zone. Unlike the effects of CO, those of HCN are immediate but complex and are often dependent on concentration and inhalation rate. Unlike with COHb, the concentration of HCN in the blood is unstable in the body, decreasing by 50 percent in 24 hours after death and also in stored blood samples (Purser 2010, 160). CN is suspected of contributing to many fire deaths but is often not measured immediately. Because it is produced under the same fire conditions as CO, it is likely to act quickly at low doses to incapacitate the victims, so that they are exposed to CO and other fire gases longer, causing their deaths.

Table 7-3 lists the tenability limits for incapacitation or death from exposure to CO, HCN, low O_2, and CO_2. The periods 5 and 30 minutes are common benchmarks for narcotic products of combustion.

PREDICTING THE TIME TO INCAPACITATION BY HYDROGEN CYANIDE

As discussed earlier, hydrogen cyanide (HCN) is another toxic gas in fires that incapacitates through biochemical asphyxiation. As with CO, the time to incapacitation depends on the uptake rate and dosage (Purser in SFPE 2008). Typical effects of HCN exposure are listed in Table 7-4.

Exposure to less than 80 ppm is expected to have minimal effect on a healthy adult (Purser 2010, 165). The effect of concentrations greater than 80 ppm can be calculated

TABLE 7-3 Tenability Limits for Incapacitation or Death from Exposures to Common Toxic Products of Combustion

	5 MIN		30 MIN	
	INCAPACITATION	DEATH	INCAPACITATION	DEATH
CO (ppm)	6000–8000	12,000–16,000	1400–1700	2500–4000
HCN (ppm)	150–200	250–400	90–120	170–230
Low O_2 (%)	10–13	<5	<12	6–7
CO_2 (%)	7–8	>10	6–7	>9

Source: SFPE 2008, Table 2.6.B1, 2-185, Courtesy of the Society of Fire Protection Engineers, © 2008, reprinted with permission.

TABLE 7-4 Typical Effects of HCN Exposure

REPORTED EFFECTS ON HEALTHY ADULTS
Extremely toxic 170—230 ppm = death in 30 minutes 250—400 ppm = death in 5 minutes (SFPE)
Produced by any fuel that contains nitrogen (hair, wool, fur, leather, polyurethane, nylon)
Absorbed through inhalation and ingestion

Source: Lecture by J. D. DeHaan. "What Kills People in Fires?"

(Purser in SFPE 2008, 2-119). The formula for time to incapacitation for inhalation of 80–180 ppm HCN concentrations is

$$t_{ICN}\,(\mathrm{min}) = \frac{185-\mathrm{ppm\,HCN}}{4.4}; \qquad (7.7)$$

the formula for time to incapacitation for HCN exposure concentrations above 180 ppm is

$$t_{ICN}\,(\mathrm{min}) = \exp\left[5.396-(0.023)(\mathrm{ppm\,HCN})\right]; \qquad (7.8)$$

and the fractional incapacitating dose per minute (FID/min) is

$$F_{ICN} = \frac{1}{\exp\left[5.396-(0.023)(\mathrm{ppm\,HCN})\right]}. \qquad (7.9)$$

Note that "exp" in equations (7.8) and (7.9) denotes the exponential form. As shown in Table 7-3, the HCN dosages required for incapacitation are much lower than the CO dosages. The lowest blood concentration associated with adult death by acute cyanide poisoning is 1–2 mg/ml. More typical levels are 2.4–2.5 at death (Purser 2010, 183). A case study using these equations is illustrated in Example 7-4.

EXAMPLE 7-3 ▪ HCN Incapacitation

Problem. An adult male was found unconscious in the waiting room after being exposed to toxic by-products from the fire in Example 7-1. Fire modeling estimated that a burning polyurethane plastic mattress cushion had produced an HCN concentration of approximately 200 ppm in the air being breathed.

Solution. Calculate the time to incapacitation and the fractional incapacitating dose per minute (FID/min).

HCN concentration HCN = 200 ppm

Time to incapacitation $t = \exp[5.396-(0.023)(200)] = 2.2\,\text{min}$

Fractional incapacitating dose per minute $F_{I\text{CN}} = \left(\dfrac{1}{\exp[5.396-(0.023)(200)]}\right) = 0.45\,\text{FID/min}$

INCAPACITATION BY LOW OXYGEN LEVELS

anoxia ■ Condition relating to an absence of oxygen.

hypoxia ■ Condition relating to low concentrations of oxygen.

Anoxia (absence of oxygen) or **hypoxia** (low concentration of oxygen) is the condition of inadequate oxygen to support life. This situation can occur when oxygen is displaced by another inert gas, such as nitrogen or carbon dioxide, by a fuel gas such as methane, or even by benign products of combustion such as CO_2 and water vapor. Normal air contains 20.9 percent O_2. At concentrations down to 15 percent O_2, there are no readily observable effects in humans owing to decreased oxygen concentrations. At concentrations between 10 and 15 percent, disorientation (similar to intoxication) occurs and judgment is affected. At levels below 10 percent, unconsciousness and death may occur. Hypoxia is aggravated by high levels of CO_2, which accelerate breathing rates. The effects of hypoxia include cerebral depression, causing lethargy, problems with memory and mental concentration, loss of consciousness, and death (Purser 2010, 184) (see Table 7-5).

The time to loss of consciousness for an adult exposed to a hypoxia equivalent is

$$(t_{lo}) = \exp[8.13-0.54(20.9-\%O_2)], \tag{7.10}$$

where

t_{lo} = exposure time in minutes

$\%O_2$ = concentration at 20°C in the air being inhaled

PREDICTING THE TIME TO INCAPACITATION BY CARBON DIOXIDE

Exposure to carbon dioxide can produce a wide range of effects, ranging from respiratory distress to loss of consciousness (SFPE 2008, 2-119) (see Table 7-5).

Along with being an asphyxiant capable of displacing oxygen, carbon dioxide also increases the RMV, which in turn causes the individual to increase the uptake of the other toxic gases (Purser in SFPE 2008). This formula for the multiplication factor VCO_2 is

$$VCO_2 = \exp\left(\frac{CO_2}{5}\right), \tag{7.11}$$

TABLE 7-5 The Effects of Exposure to Low Oxygen Levels

PERCENT OXYGEN	REPORTED EFFECTS ON HEALTHY ADULTS
14.14–20.9	No significant effects, slight loss of exercise tolerance
11.18–14.14	Slight effects on memory and mental task performance, reduced exercise tolerance
9.6–11.8	Severe incapacitation, lethargy, euphoria, loss of consciousness
7.8–9.6	Loss of consciousness, death

Source: Derived from SFPE 2008.

TABLE 7-6 The Effects of Exposure to Carbon Dioxide

PERCENT CARBON DIOXIDE	REPORTED EFFECT(S)
7–10	Loss of consciousness
6–7	Severe respiratory distress, dizziness, possible loss of consciousness
3–6	Respiratory distress increasing with concentration

Source: Derived from SFPE 2008.

$$VCO_2 = \left(\frac{\exp[(1.903)(\%CO_2)+2.0004]}{7.1}\right). \tag{7.12}$$

The formula for the time to unconsciousness (incapacitation) from carbon dioxide is

$$t_{I\text{CO}_2} = \exp[6.1623-(0.5189)(\%CO_2)], \tag{7.13}$$

and the fractional incapacitating dose per minute (FID/min) is

$$F_{I\text{CO}_2} = \left(\frac{1}{\exp[6.1623-(0.5189)(\%CO_2)]}\right). \tag{7.14}$$

Heat

The human body is capable of surviving exposure to external heat as long as it can moderate its core temperature by radiant cooling of the blood through the skin and, more importantly, by evaporative cooling. This process occurs internally via evaporation of water from the mucosal linings of the mouth, nose, throat, and lungs and externally via evaporation of sweat from the skin. If the core body temperature exceeds 43°C (109°F), death is likely to occur.

Prolonged exposure to high external temperatures, 80–120°C (175–250°F), with low humidity can trigger fatal hyperthermia. Exposure to elevated temperatures accompanied by high humidity (which reduces the cooling evaporation rate of the water from the skin or mucosa) can also be lethal. Fire victims can die of exposure to heat alone even if they are protected from CO, smoke, and flames. These victims may have minimal postmortem changes, although skin blistering and sloughing can occur after death owing to heat denaturation of collagen and other proteins in the connective tissue and skin.

PREDICTING THE TIME TO INCAPACITATION BY HEAT

For exposure to convected heat in a fire environment, the fractional incapacitating dose per minute (FID/min) is calculated as follows:

$$F_{Ih} = \left(\frac{1}{\exp[5.1849-(0.0273)(T[°C])]}\right). \tag{7.15}$$

Assimilation of various data formed the basis for the *Toxic and Physical Hazard Assessment Model* (Purser in SFPE 2008, 2-179). Data such as toxic chemical and physical species concentration levels generated by fire models can serve as input to this hazard assessment model. According to this model, the normally accepted threshold for tolerance of radiant heat is 2.5 kW/m^2 for only a few minutes. Besides the burns to the skin (from both radiant and convected heat), thermal damage to the upper respiratory tract can also occur when dry gases at temperatures over 120°C (250°F) are inhaled.

Information needed to evaluate this hazard model is derived from two sets of information: concentration and time profiles of major toxic products, including time, concentration, and toxicity relationships. The estimated toxic products within the victim's breathing zone include concentrations of gases such as carbon monoxide, hydrogen cyanide, carbon dioxide, and factors such as radiant heat flux, and air temperature. Some of these values can be calculated by sophisticated computer models discussed previously.

INHALATION OF HOT GASES

Inhalation of very hot gases causes edema (swelling and inflammation) of mucosal tissues. This edema can be severe enough to cause blockage of the trachea and physical asphyxia. Inhalation of hot gases may also trigger *laryngospasm,* in which the larynx involuntarily closes up to prevent entry of foreign material, and *vagal inhibition,* in which the breathing stops and the heart rate drops.

Rapid cooling of the inhaled hot gases occurs on inhalation as the water evaporates from mucosal tissues, so thermal damage usually does not extend below the larynx if the inhaled gases are dry. If the hot gases include steam or are otherwise water saturated, evaporative cooling is minimized, and burns/edema can extend to the major bronchi and alveoli, which are tiny air sacs in the lungs. If inhaled gases are hot enough to damage the trachea and internal lung infrastructures, they will usually be hot enough to burn the facial skin and mouth as well as singe the facial or nasal hair.

EFFECTS OF HEAT AND FLAME

The human body is a complex target when being affected by heat from a fire. Skin consists of two basic layers. A thin upper outer layer of *epidermis* (dead, keratinized skin cells) overlies a thicker inner dermal layer of actively growing cells in which are embedded the nerve endings, hair follicles, and blood capillaries that supply nutrients to the growing skin. Beneath the dermal layer is a layer of tough elastic connective tissue, subcutaneous fat, and, finally, muscle and bone.

Each of these components is affected differently by heat and flames. Application of heat can cause the epidermis to separate from the underlying *dermis* and form blisters in much the way paint or wallpaper blisters away from the wood or plaster beneath when heated. Blistering of skin occurs when the tissue reaches temperatures in excess of 54°C (130°F). The raised epidermal layer is very thin and is more easily affected by continuing heat, which can cause the epidermal layer to char and turn black if the temperature is high enough. The epidermis can also separate in larger areas and form generalized skin slippage. Exposure of the denuded dermal layer to heat can cause extreme pain when its temperature exceeds 43°C–44°C (110°F–112°F) (Purser in SFPE 2008, 2-179).

More prolonged exposure can destroy the proteins of the dermal layer and cause further desiccation and discoloration. Higher heat fluxes can cause higher temperatures that cook and even char the tissues. As the skin desiccates, it shrinks, eliminating wrinkles and changing facial contours (making visual identifications of victims very risky). If the skin continues to shrink, it can split open, leaving jagged, irregular, torn surfaces (as opposed to the sharply defined surfaces of knife cuts), as shown in Figure 7-3 (Smith and Pope 2003). Heat-split skin often exhibits subcutaneous bridging of underlying tissue, whereas cut skin does not.

FIGURE 7-3 Effects of heat and flame shrink skin, eliminating wrinkles and changing facial contours. If the skin continues to shrink, it can split, leaving jagged, irregular torn surfaces, as opposed to the sharply defined surfaces of knife cuts. This photo illustrates postfire recognition of knife cuts to the chest versus splitting of the skin on the arm. *Courtesy of Dr. Elayne J. Pope.*

If a victim survives for some time, shrinkage can constrict blood vessels, so incisions (called *escharotomies*) are made through the damaged dermal layer to relieve the pressure and maintain circulation. If a fire victim survived for some time after the fire and underwent medical interventions such as an escharotomy or skin graft harvesting, the investigator must recognize the effects of these and distinguish them from fire effects.

FIGURE 7-4 Shrinkage of muscle and tendons can cause the joints to flex, causing what is called *pugilistic posturing*. *Courtesy of Dr. Elayne J. Pope.*

Owing to its small individual dimensions and low thermal mass, hair is affected very quickly by heat. Colors will change (typically changing to darker or redder colors or completely to a gray, ashen color). The hair shaft will bubble, shrink, and fracture as it singes from heat. This shrinkage causes the curling of hair shafts seen as singeing. The microscopic appearance of singed hair shafts is very distinctive (as compared with cut or broken hair shafts). If the hair is burned in large masses, it can form a black puffy entangled mass.

If the body continues to be exposed to heat, the shrinkage can affect muscles. When the skin and muscles of the neck shrink, they can force the tongue out of the mouth. Shrinkage of muscle and tendons can cause the joints to flex, causing what is called *pugilistic posturing,* as shown in Figure 7-4. This flexing and posturing can cause bodies to move during fire exposure. If the body is on an irregular or unstable surface, this movement can cause the body to fall from a bed or chair and, possibly, change the direction of heat application, eliminating or obscuring previously protected areas. Pugilistic posturing has been observed during legal cremations after 10 minutes of exposure to flames at temperatures of 670°C–810°C (1240°F–1490°F) (Bohnert, Rost, and Pollak 1998; Pope 2007).

Direct flame impingement, with its high-temperature gases of 500°C–900°C (930°F–1650°F) and high heat fluxes (55 kW/m^2), produces responses from the human body very quickly. Blisters will form in about 5 seconds, with charring following seconds later. Skin can be charred completely away in 5–10 minutes of direct flame contact, especially where stretched over the bone (joints, nose, forehead, skull) (Pope and Smith 2003, 2004; Pope 2007). Very short but intense (flash) fire exposure can cause blistering of the epidermal layer without the sensation of pain (because the pain sensors are in the dermal layer beneath), and the heat takes longer to penetrate deeply.

Even in the absence of fire, prolonged exposure of the body to high temperatures (over 50°C; 122°F) causes desiccation and shrinkage of muscle tissue, which causes pugilistic posturing. Exposure to flames can cause muscles to combust and major limb bones to fracture as they degrade where the bone is exposed to flames. Extreme heat causes bones to twist and fracture, and continued flame exposure (30 minutes or longer in observed cremations) causes calcination (in which the charred organic matter is burned away). As the bones become calcined, they become very fragile and may disintegrate of their own accord. The lower-density major bones from elderly victims of osteoporosis have been seen to disintegrate under fire exposure more quickly and completely than bones with normal densities (Christensen 2002). Tests have revealed that fire exposure can cause fluid that cushions the brain as well as the brain cell fluids to leak through fissures in the exposed skull but not cause the skull to explode. Internal organs that are exposed to the fire desiccate and char, thus requiring at least 30–40 minutes of cremation to burn away (Bohnert, Rost, and Pollak 1998). The adult torso will require longer exposure to a normal structure fire before the organs are affected. Bones exposed to fire can also shrink in length, thus giving rise to potential errors in the estimation of antemortem height.

The thin bones of the skull may delaminate, with the inner and outer layers failing separately. This delamination has given rise to thermally caused holes in the skull that have beveled edges similar to those produced by gunshots (Pope and Smith 2003). Recent experiments have demonstrated that failure of the skull can occur from fire damage whether or not there was preexisting mechanical or blunt force trauma. Some thermally induced failures can mimic bullet wounds, requiring extreme care in casework investigative interpretations (Pope and Smith 2004).

Heat exposure to the head can cause blood and fluids to accumulate and form a hematoma in the *extradural* or *epidural* space between the skull and the tough bag of tissue (the *dura mater*) that surrounds the brain. With further heating, these fluids boil, desiccate, and then char, producing a rigid, foamy, blackened mass. Physical trauma to the brain as a result of the impact from falling structures overhead also can cause *subdural* hematomas. However, fractures at the base of the skull have not been observed to be produced by fire exposure (Bohnert, Rost, and Pollak 1998; Pope 2007). Fire exposure chars and seals exposed tissues, so as a rule, bodies exposed to an enveloping fire do not bleed. When the body is moved, however, the fragile layer of char covering the tissues can be broken, allowing body fluids to seep out. Thus great care must be taken when moving a charred body with exposed charred tissues, and its condition prior to being moved must be carefully documented.

Within certain considerations, the amount of fire damage on a body can be related to the duration of exposure if the intensity of the fire can be estimated from the fuel, ventilation, and distribution factors described elsewhere in this text. Factors such as combustion rates, thermal inertia, and relative combustibility of body components have been explored in recent studies (DeHaan, Campbell, and Nurbakhsh 1999). Some aspects of postmortem fire damage to the human body are discussed later in this chapter.

FLAMES (INCINERATION)

When heat is applied to a surface, the rate at which it penetrates that surface is determined by the thermal inertia of the material (the numerical product of thermal capacity, density, and thermal conductivity). The thermal inertia of skin is not much different from that of a block of wood or polyethylene plastic (see Table 2-4). The pain sensors for human skin are in the dermis, about 2 mm (0.1 in.) below the surface. If heat is applied very briefly, there may not be any sensation of discomfort or pain. The longer the heat is applied, the deeper it will penetrate into the skin. The higher the intensity of the heat applied, the faster it will penetrate into the skin. Pain is triggered when skin cells reach a temperature of about 48°C (120°F), and cells are damaged if their temperature exceeds 54°C (130°F) (Stoll and Greene 1959).

Exposing skin to 2–4 kW/m^2 radiant heat for 30 seconds causes pain but no permanent cellular damage. Higher heat fluxes trigger damage such as blisters and skin slippage. Exposing skin to 4–6 kW/m^2 radiant heat for 8 seconds produces blisters (second-degree burns). Exposing skin to 10 kW/m^2 radiant heat for 5 seconds causes deeper, partial-thickness injuries. Exposing skin to 50–60 kW/m^2 radiant heat for 5 seconds produces third-degree burns with destruction of the dermis (Stoll and Greene 1959).

BURNS

Burns may appear in the absence of fire or flames as a result of prolonged exposure of the body or body parts to heat that raises their overall temperature above 54°C (130°F) and causes desiccation, sloughing, and blistering. These effects can also be caused by exposure of the body to caustic chemicals. It is often very difficult, if not impossible, to distinguish between these types of burns suffered near the time of death (*perimortem*) and those inflicted after death (postmortem). Fluid-filled blisters can result from fire exposure both antemortem and postmortem as well as from postmortem decomposition.

Most, but not all, medical personnel agree that *first-degree burns* involve only reddening of the skin. *Second-degree burns*, sometimes referred to as *partial-thickness burns*, involve damage to the epidermis with blistering and sloughing. Because the germinative layer of the dermis remains, the entire surface of such burns will usually heal, most often without grafts. *Third-degree burns* are called *full-thickness burns* because the dermis is damaged, and the wound heals from the edges only and requires grafting. *Fourth-degree burns*, sometimes also referred to as full-thickness burns, can include those in which the skin is destroyed, exposing muscle and the bones beneath the muscles.

When gasoline or a similar volatile liquid fuel with low viscosity and low surface tension is poured on bare skin, some is absorbed into the epidermis, but the bulk of the fuel runs off, leaving a very thin film of liquid, particularly on vertical surfaces. This thin film burns off very quickly (less than 10 seconds). The skin beneath may be spared completely or reddened (first-degree burns), except where folds of the skin or clothing retain enough fuel to sustain longer burning, producing severe blistering, and even charring of the epidermis in extreme cases. Deep penetrating burns exposing the subcutaneous fat or muscle below require flame exposures of several minutes, much longer than the typical thin-film gasoline fire. On horizontal skin surfaces, a deeper pool may be retained long enough to produce a halo or ring of blisters (second-degree burns) around the circumference of the pool (DeHaan and Icove 2012).

BLUNT FORCE TRAUMA

Blunt force trauma can also cause or contribute to the death of fire victims. Structural collapse or explosions can cause solid materials to strike victims. Falls or impacts with stationary surfaces (furniture or door frames) during escape attempts can induce blunt trauma that only a careful medical examination can distinguish from an assault. Wound patterns, bloodstains, or even trace evidence can be used to interpret blunt trauma injuries and establish whether they resulted from assault or from some fire-related event. The fire investigator should consider consulting with the pathologist and the criminalist to help evaluate blunt trauma injuries and possibly link them to features at the fire scene.

Visibility

The optical opacity of dense smoke and its irritants impairs the vision and respiration of normal-sighted people who may find their ability to travel impaired by the smoke. This optically dense smoke affects

- Exit choice and escape decisions,
- Speed of movement, and
- Wayfinding ability.

During structure fires, the occupants often depend on their ability to seek out exit signs, doors, and windows (Jin 1976, Jin and Yamada1985). *Visibility* of an object depends on several factors such as the smoke's ability to scatter or absorb the ambient light, the wavelength of the light, whether the item viewed (e.g., an exit sign) is light emitting or light reflecting, and the individual's visual acuity (Mulholland in SFPE 2008, 2–297).

An insight into the underlying principles on the first use of red exit signs can be found in historical studies by the U.S. Naval Medical Research Laboratory, Bureau of Medicine and Surgery. The studies examined the detectability of colored field targets at sea. Colors that were distinguishable at the greatest distances were the red fluorescents (yellow-red and orange-red) (USN 1955). Later research by the U.S. Air Force (Miller and Tredici 1992) on night vision expanded these findings when it was determined that the sensitivity of the eye changes from the red end of the visible spectrum toward the blue end when shifting the *photopic* vision (high illumination levels) to *scotopic* vision (reduced illumination levels, typically at night).

Note that the naval study on the ability of the eye to perceive the color red at greater distances gives credence to the logic of using the color red for fire exit signs, whether they be passive fluorescent or illuminated. OSHA regulations state that exit signs, when required, shall be lettered in legible red letters, not less than 6 inches high, on a white field [*OSHA 29 CFR 126-200(d)*].

OPTICAL DENSITY

Visibility can be estimated in terms of the *optical density* per meter. The calculation involves a collateral term known as the extinction coefficient, K, which is the product of an *extinction coefficient* per unit mass, K_m, and the mass concentration of the smoke aerosol, m:

$$K = K_m m; \qquad (7.16)$$

$$D = \frac{K}{2.3}, \qquad (7.17)$$

where

K = extinction coefficient (m^{-1})
K_m = specific extinction coefficient (m^2/g),
m = mass concentration of smoke (g/m^3), and
D = optical density per meter (m^{-1})

The values for K_m are typically 7.6 m^2/g for smoke produced during flaming combustion of wood or plastics, and 4.4 m^2/g for smoke produced during pyrolysis (SFPE 2008).

In terms of the extinction coefficient K, one problem at a fire is determining the visibility, S, of light-emitting and light-reflecting exit signs to occupants. The value S is a measure of how well an individual can see through the smoke. Light-emitting signs are two to four times more visible than light-reflecting signs (Mulholland in SFPE 2008, 2-297), as the values for KS reveal in equations (7.18) and (7.19),

$$KS = 8 \text{ for light-emitting signs,} \qquad (7.18)$$

$$KS = 3 \text{ for light-reflecting signs,} \qquad (7.19)$$

where

K = extinction coefficient (m^{-1}) and
S = visibility (m).

Methods for estimating visibility based on the mass optical density are considered realistic. In studies, the optical density at which people turned back from a smoke-filled area was a visibility distance of 3 m (9.84 ft) (Bryan 1983). The study also showed a tendency for women to be more likely to turn back than men. Other factors include the ability of the persons to see exit signs directing them to safe egress from the building. Height of exit signs as well as the height of the viewer may be critical to visibility.

Estimates of visibility are based on mass optical densities, D_m, derived from test data (Babrauskas 1981). Typical values of mass optical density produced by mattresses in flaming combustion are listed in Table 7-7.

The following equation is used to estimate the density, D, of the visible smoke:

$$D = \frac{D_m \Delta M}{V_C}, \qquad (7.20)$$

TABLE 7-7 Mass Optical Density (D_m) for Flaming Mattresses

TYPE OF MATERIAL	MASS OPTICAL DENSITY (m^2/g)
Polyurethane	0.22
Cotton	0.12
Latex	0.44
Neoprene	0.20

Source: Derived from Babrauskas 1981.

where

D = optical density per meter (m^{-1}),
D_m = mass optical density (m^2/g),
ΔM = total mass loss of sample (g), and
V_c = total volume of compartment or chamber (m^3).

EXAMPLE 7-4 ▪ Visibility

Problem. A small, 300-g (0.66-lb), polyurethane mattress cushion on a waiting-room bench is set afire by a juvenile arsonist and is undergoing flaming combustion. The bench is located in a 6-m-square (20-ft-square) waiting room with a ceiling height of 2.5 m (8.2 ft). Determine the closest visibility of both light-emitting and light-reflecting signs leading to the exit door.

Solution. Assume that the smoke filling the waiting room is uniformly mixed.

Total mass loss of mattress	ΔM = 300 g
Mass optical density	D_m = (from Table 7-6) = 0.22 m^2/g
Volume of compartment	V_c = (6 m)(6 m)(2.5 m)=90.0 m^3
Optical density	$D = (0.22^2/g)(300\ g)/(90.0\ m^3) = 0.733\ m^{-1}$
Extinction coefficient	$K = 2.3D = (2.3)(0.733m^{-1}) = 1.687m^{-1}$
Visibility (light emitting)	$S = 8/K = (8)/(1.687m^{-1}) = 4.74\ m$
Visibility (light reflecting)	$S = 3/K = (3)/(1.687m^{-1}) = 1.77\ m$

The calculations indicate that a light-emitting sign can be seen in this fire at a distance of up to 4.74 m (15.5 ft), compared with 1.7 m (5.58 ft) for an unlit sign. In real rooms the buoyancy of the hot smoke layer makes it harder to see signs in the upper half of the room than this example indicates. Exit signs are being placed at knee level or lower today to make them more visible longer.

FRACTIONAL EQUIVALENT CONCENTRATIONS OF SMOKE

The following formulas relate to enclosed spaces. As the value of FEC_{smoke} approaches 1, the level of visual obscuration increases, and the chance of escape decreases significantly.

$$FEC_{smoke} = \frac{D}{0.2} \text{ for small enclosures;} \qquad (7.21)$$

$$FEC_{smoke} = \frac{D}{0.1} \text{ for large enclosures,} \qquad (7.22)$$

where

D = optical density per meter of the smoke being encountered.

WALKING SPEED

As previously summarized, the optical density of the smoke affects a person's decision to choose the closest exit and ability to make proper escape decisions, as well as wayfinding ability and speed of movement. Normal adult walking speed is about 2 m/s in clear areas and with normal visibility. During smoky conditions furniture and other occupants impeding the escape can reduce this rate. The fire investigator should take this factor into consideration when assessing witness statements as to egress times from structures during fires.

Experiments with human subjects navigating through nonirritant smoke–filled corridors indicated that speed of movement decreases with increased smoke density (Jin 1976; Jin and Yamada1985).

Based on Jin's (1976) research, equation (7.23) provides an expression of this relationship:

$$\mathrm{FWS} = (-1.738)(D) + 1.236 \text{ for the range } 0.13\,\mathrm{m}^{-1} \le D \le 0.30\,\mathrm{m}^{-1}, \qquad (7.23)$$

where

FWS = fractional walking speed (m/s), and
D = optical density per meter (m^{-1}).

For this equation, the smoke optical density ranges between 0.13/m (below normal walking speed) and 0.56/m (above walking speed of 0.3 m/s in darkness). The limits on the equation do not allow for delays such as erratic walking and sensory irritation. Jin used wood smoke in his experiments.

WAYFINDING

Jin's expression does not correlate midcourse corrections in wayfinding, reduced visibility, and irritability of the smoke. Studies have shown that the average density in smoke at which persons turn back is a visibility distance of 3 m (9.84 ft) ($D = 0.33\ \mathrm{m}^{-1}$ and $K = 0.76$). Poor visibility and irritation of the eyes are the leading factors in reduced wayfinding, followed by irritation of the respiratory system (Jensen 1998).

SMOKE

Smoke contains water vapor, CO, CO_2, inorganic ash, toxic gases, and chemicals in aerosol form as well as soot. Soot is agglomerations of carbon from incomplete combustion large enough to produce visible particles. These particles may be very hot and are not cooled readily as they are inhaled, so they may induce edema and burns where they lodge in the mucosal tissue of the respiratory system. Soot particles are active adsorbents, so they may carry toxic chemicals and permit their ingestion or inhalation (with direct absorption by the mucosal tissues). Soot can be inhaled in quantities sufficient to physically block airways and cause mechanical asphyxiation. Soot, water vapor, ash, and aerosols in smoke can also obscure the vision of victims and prevent their escape.

Time Intervals

INTERVAL BETWEEN FIRE AND DEATH

One of the problems outlined earlier is the time interval between exposure to a fire and its fatal aftermath. Death can occur nearly instantaneously or within minutes or hours later. Under these conditions it is not difficult to connect the death to its actual cause. When a person dies weeks or even months after a fire, the cause can still be the fire, but the linkage can be obscured by extensive medical interventions.

There is a range of effects that can determine the time interval between the fire and death. Death can occur within seconds to minutes from *hyperthermia,* exposure to very hot gases or steam, or from anoxia, the lack of oxygen. With *instantaneous death,* vagal inhibition or laryngospasm occurs on inhalation of flames and hot gases, causing cessation of breathing followed very quickly by death. Explosion trauma and incineration from exposure to a fully developed fire (often resulting in structural collapses) results in nearly instantaneous death.

Inhalation of toxic gases such as hydrogen cyanide, carbon monoxide, or other pyrolysis products; blockage of airways by soot, exposure to flames; physical trauma (with loss of blood); internal injuries; and brain injuries can cause death within minutes.

Death can occur within hours from carbon monoxide exposure, edema from inhalation of hot gases, burns, and brain or other internal injuries. Dehydration and shock from burns cause death days after the fire. Even weeks or months after the fire, deaths can occur owing to infections or organ failure triggered by fire injuries.

Cause of death is defined as the injury or disease that triggers the sequence of events leading to death. In a fire, the cause of death may include inhalation of hot gases, CO, or other toxic gases, heat, burns, anoxia, asphyxia, structural collapse, or blunt trauma. The *mechanism of death* is the biological or biochemical derangement incompatible with life. Mechanisms of death can be respiratory failure, exsanguination, infection, organ failure, and cardiac arrest. The *manner of death* is a medicolegal assessment and classification of the circumstances in which the cause of death was brought about. In the United States, these classifications are most often *homicide, suicide, accident, natural,* or *undetermined.*

cause of death ■ The injury or disease that triggers the sequence of events leading to death. In a fire, the cause of death *may* include inhalation of hot gases, carbon monoxide, or other toxic gases; heat; burns; anoxia; asphyxia; structural collapse; or blunt force trauma.

The longer the interval between the cause (the fire) and the onset of the mechanism of death (organ failure, septicemia, etc.), the more likely it is that the connection will be lost. This is especially true when victims are moved from trauma care hospitals to long-term care facilities, sometimes in other geographic areas. The investigator must be diligent to ensure that the cause of death is not listed on the final death certificate as some generic mechanism term such as respiratory failure, cardiac arrest, or septicemia.

SCENE INVESTIGATION

The reconstruction of the activities of a fire victim may depend on finding and documenting bloodstains (from impact with a wall or door jamb) or handprints on a wall, mechanical (blunt trauma) injuries, or artifacts found with the body. The nature of dress (street clothes, robe, nightgown) or objects (dog leash, jewelry, flashlight, fire extinguisher, house keys, phone, keepsakes, etc.) can provide clues as to what the person was doing prior to collapse.

The position of the victim (face up or face down) is not usually significant, as people known to have died during a fire have been found in all positions. Owing to pugilistic posturing, the attitude of the body bears little reliable relation to antemortem actions. As mentioned earlier, pugilistic posturing occurs as a physical reaction of the body to the heat and can occur whether the person was dead before the fire or died during the fire. It can cause bodies to shift position, sometimes to the point where they roll off unstable surfaces like chairs or mattresses. Young children may hide under beds or in closets, but finding them in other locations is not proof that they did not have the time or physical capacity to seek safety.

POSTMORTEM DESTRUCTION

A body exposed to fire can support combustion, the rate and thoroughness of which depend on the nature and condition of exposure of the body to the flames. The skin, fat, muscles, and connective tissues will shrink as they dehydrate and char. If exposed to enough flame, they will burn and yield some heat of combustion. The relatively waterlogged tissues of the internal organs must be dried by heat exposure before they can combust, and that dehydration step increases their fire resistance and delays their consumption.

Bones have moisture and a high fat content, especially in the marrow, so they will shrink, crack, and split and contribute fuel to an external fire. The subcutaneous fat of the human body provides the best fuel, having an effective heat of combustion on the order of 32–36 kJ/g (DeHaan, Campbell, and Nurbakhsh 1999). Like candle wax, however, it will not self-ignite or smolder and will not normally support flaming combustion unless the rendered fat is absorbed into a suitable wick. The material for the wick can be charred clothing, bedding, carpet, upholstery, or wood in the vicinity (as long as it forms a porous, rigid mass). The size of the fire that can be supported by such a process is controlled by the size (surface area) of the wick. Depending on the position of the body and its available wick area, fires supported by the combustion of a body will be of the order of 20–120 kW, similar to a small wastebasket fire. Such a fire will affect only items close to it, and fire damage will often be very confined.

Flame temperatures produced by combustion of body fat range from 800°C to 900°C (1475°F–1650°F), and if flames impinge on the body surface, they can aid the destruction of the body. The process, if unaided by an external fire, is quite slow, with a fuel consumption rate on the order of 3.6–10.8 kg/hr (7–25 lb/hr). It is possible, given a long enough time (5–10 hr), that a great deal of the body can be reduced to bone fragments (DeHaan 2001; DeHaan, Campbell, and Nurbakhsh 1999; DeHaan and Pope 2007).

If a body is exposed to a fully developed room or vehicle fire, however, the rate of destruction is much closer to that observed in a commercial crematorium. In those cases, flames of 700°C–900°C (1300°F–1650°F) and a heat intensity of 100 kW/m^2 envelop the body and can reduce it to ash and fragments of the larger bones in 1.5–3 hours (Bohnert, Rost, and Pollak 1998; DeHaan and Fisher 2003; DeHaan 2012).

Summary of Postmortem Tests Desirable in Fire Death Cases

The complexity of many fire death cases may necessitate finding the answers to questions that were not apparent earlier. Having comprehensive forensic samples and data is the best route to a successful and accurate investigation. Although not all the following forensic tests and data may be needed in all fire death cases, once the body is released for burial or cremation, it will be too late for forensic examination (DeHaan and Icove 2012, chap. 15).

- ***Blood*** (taken from a major blood vessel or chamber of the heart, not from the body cavity): tested for COHb saturation, HCN, drugs (therapeutic and abuse), alcohol, and volatile hydrocarbons.
- ***Tissue (brain, kidney, liver, lung):*** Tested for drugs, poisons, volatile hydrocarbons, combustion by-products, CO (as a backup for insufficient blood).
- ***Tissue (skin near burns):*** Tested for vital chemical or cellular response to burns.
- ***Stomach contents:*** Tested for establishment of activities before death and possible time of death.
- ***Eye fluid:*** An uncontaminated source of drugs and metabolites.
- ***Airways:*** Full longitudinal transection of airways from mouth to lungs to examine and document the extent and distribution of edema, scorching/dehydration, and soot.
- ***Internal body temperature:*** Should be measured at the scene. It may be elevated owing to fire exposure, postmortem decomposition, or antemortem hyperthermia, but unexpectedly *low* body temperatures after a recent fire should indicate that the victim was dead well before the fire.
- ***X-rays:*** Full-body (including associated debris in body bag) and details of teeth and any unusual features discovered (fractures, implants).
- ***Clothing:*** All clothing remnants and associated artifacts removed and preserved.
- ***Photographs:*** General (overall), with close-ups of any burns or wounds, in color, with scale.
- ***Postmortem Multidetector Computed Tomography (MDCT):*** Experimentally has been found to be a valuable tool, should this resource be available (see Levy and Harcke 2011).
- ***Postmortem weight:*** Postmortem weight of the body with organs determined, *not* including the fire debris or body bag.

It is very useful for the fire investigator to be present when the postmortem examination and autopsy are conducted, not only to ensure that all appropriate observations are made but also to be on hand to answer any questions that arise during the examination. Few pathologists have extensive knowledge of fire chemistry or fire dynamics, or can interpret the effects of fire on the body, so the investigator is in a good position to advise the pathologist as to the fire conditions in the vicinity of the body.

CASE EXAMPLE 1

Death Followed by Fire—Cause and Duration

At about 9 a.m., Mr. John Doe (obviously not his real name) discovered the severely burned bodies of his sister-in-law and his 3-year-old nephew in the dining room of their home. He had been called minutes earlier by his brother, Mr. Jim Doe, a salesman, who reported that he had left home that morning and had not been able to reach his wife (who was 8 months pregnant) by telephone. Concerned, he called his brother and asked that he stop by and check on her.

On arrival, John Doe found the house full of smoke but only small flames showing in the vicinity of the bodies that were sprawled amid an area of burned carpet in the dining room. He reportedly batted out the small flames with a hand towel and then withdrew to call emergency 9-1-1. The local fire department arrived by 9:10 a.m. and, forewarned of the conditions within, limited its response to one firefighter with a pressurized water tank who entered the building, sprayed a very small amount of water on or near the body to extinguish the small flames still present, and then withdrew along the same path. Except for opening windows to vent the accumulated smoke, that was the extent of fire suppression.

Jim Doe returned to the house while the investigation was beginning and claimed that he had left the house at about 6:00 a.m. and had found everything to be in order. He had stopped to put gasoline in his car and then at a restaurant while making his sales calls for the morning, establishing his presence elsewhere after 6:00 a.m.

The fire damage was limited to an oval area of carpet about 2 m^2 (21.5 ft^2) in size, centered on the two bodies. The mother was sprawled roughly facedown, and the child was spread-eagled on his back alongside her, as shown in Figure 7-5. There were areas of scorching on the walls and baseboards of the dining room near

FIGURE 7-5 The fire damage was limited to an oval area of carpet about 2 m^2 (22 ft^2) in size, centered on the two bodies. The mother was sprawled roughly facedown, and the child was spread-eagled on his back alongside her. *Courtesy of Cosumnes Fire Department.*

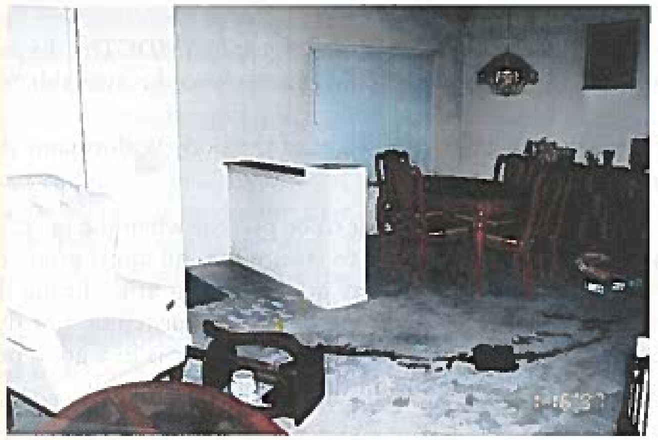

FIGURE 7-6 Fire investigators quickly determined through laboratory analysis that automotive gasoline had been poured on the carpet around the bodies and in nearby areas of the living room, kitchen, and hallway. *Courtesy of Cosumnes Fire Department.*

the entry to the kitchen and two areas of damage to the vinyl floor of the kitchen immediately adjacent to the mother's lower right leg. There were areas of scorching on her legs adjacent to these floor patterns. The fire investigators quickly determined through laboratory analysis that automotive gasoline had been poured on the carpet around the bodies and in nearby areas of the living room dining room, kitchen, and hallway (Figure 7-6).

Both victims had zero COHb levels, and no soot was detected in the airways. Both bodies bore signs of physical (blunt force) trauma, and the child's cause of death was ascribed to severe multiple head wounds. Bloodstain patterns indicated that the child had been beaten or kicked in the vicinity of where the bodies were found, but fire damage to the mother's face, neck, and upper torso precluded the establishment of an exact cause of death (Moran 2001).

The major fire-related issues pertained to the duration of the fire: What had fueled the fire? How long would a body burn in such circumstances? What is the mass loss rate for a body when it represents the main fuel package for a fire (as opposed to being involved in a massive enveloping fire fueled by furnishings and other external fuel load)? A test protocol was designed to collect data by which some hypotheses could be tested.

Carpet and pad from the scene were recovered in large quantities to serve as comparison samples and test targets for fire testing. The carpet was 95 percent polypropylene and 5 percent nylon face yarns bonded to a polypropylene mesh backing. The pad underneath was low-density polyurethane foam. Testing revealed that this carpet/pad combination could be ignited to support a self-sustaining combustion by the ignition of a small quantity of gasoline. The burning carpet was observed in tests to produce small flames, 5–8 cm (2–3 in.) high that advanced to consume approximately 0.5 m^2 of carpet per hour. Based on the limited amount of carpet burned very deeply (i.e., in direct contact with the gasoline pool fire), it was estimated that less than 2 L of gasoline had been used. Such a quantity would be expected to produce a fire of approximately 500 kW if ignited on carpet, with a duration of 2 to 3 minutes. Testing confirmed these estimates.

As can be seen in the floor plan in Figure 7-7, the living room, dining room, kitchen, and family room formed one large room, with a high vaulted ceiling extending throughout those areas, and a partial-height wall separated the living/dining portion from the family room/kitchen. The vaulted ceiling over the location of the bodies was an estimated 3.6 m (12 ft) from the floor and bore no heat damage. A flame plume from a 500 kW fire approximately 1 m (3.3 ft) in diameter would be (per Heskestad) about 1.8 m (6 ft) high and would not be expected to produce any ceiling damage.

The wall nearest the main plume would have been the south dining room wall and would have been more than a meter away. All walls were painted gypsum wallboard, and none bore any heat damage. There was no heat damage to any of the wood furniture in the dining room. There was a narrow, arc-shaped burn mark on the carpet identified as a gasoline trail between the entry door and the bodies, but there was no damage to any furnishings except to the carpet.

Several areas of the carpet bore scorched and melted areas whose appearance could be reproduced by the burning of a splattering of small droplets of gasoline on the surface of such synthetic carpet pile. Smoke had penetrated throughout the house, and soot had lightly coated all horizontal surfaces and condensed out on vertical surfaces (showing the outlines of wall studs, ceiling joists, and other concealed structural elements).

Blood spatters on surfaces and coatings of soot on floors showed that objects such as vases, boxes, and cutlery that were strewn about to simulate a burglary had been placed in those positions after the blood was splattered but before the fire. The areas of scorching and sooting on the vinyl flooring of the kitchen were

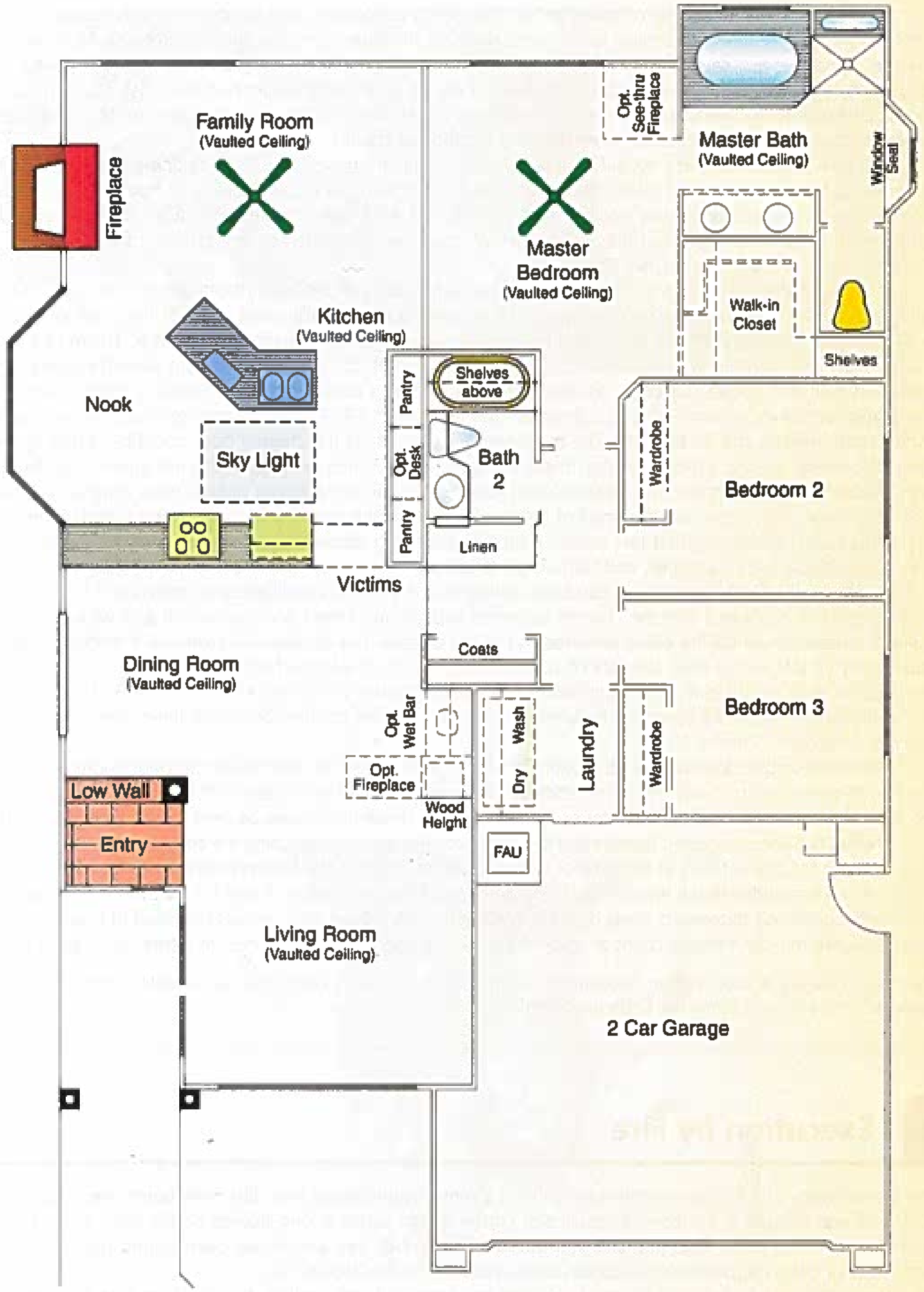

FIGURE 7-7 Floor plan showing the living room, dining room, kitchen, and family room, which formed one large area with a high vaulted ceiling. *Courtesy of Bruce Moran, Sacramento County District Attorney's Laboratory of Forensic Services, Sacramento, CA.*

identified as being produced by gasoline or a similar ignitable liquid of relatively low boiling point by comparison with tests of such fluids on similar floor coverings. The most significant fire damage was to the bodies of the two victims. No clothing could be identified on the child's body, and the remains of a knit top and panties on Mrs. Doe would not have constituted a significant fuel load.

A reasonably small quantity of gasoline had apparently been used, and so attention was focused on the combustion of the bodies as a major factor in establishing the time frame for the fire. Because Mrs. Doe had been receiving prenatal care, there was good documentation of her antemortem body weight. Compared with the postmortem weight, it was estimated that some 12 kg (25 lb) of body weight had been lost. No such data of comparable quality were available for the child victim, so it was decided that the mass lost from Mrs. Doe's body would be the most reliable measure of establishing duration of the fire.

Testing was conducted at the California Bureau of Home Furnishings (BHF) room calorimeter to establish the heat release rates and mass loss rates of body fat. Pork fat was selected for its similarity to human subcutaneous fat and availability. Tests of various small (1- to 2-kg, 2.2- to 4.4-lb) quantities of pork fat (with skin) wrapped in cotton cloth established that small fires, 20 to 70 kW, could be maintained by combustion of the rendered fat (DeHaan, Campbell, and Nurbakhsh 1999).

The size of the fire was controlled largely by the surface area of the wick (the charred cloth), and the duration of the fire was controlled by the supply of fuel. Mass loss rates appeared to be of the order of 1–2 g/s (3.6–7.2 kg/hr). Testing was also conducted in the cone calorimeter at BHF using a 10 cm × 10 cm (3.9 in. × 3.9 in.) tray, with paraffin wax as a control. It was found that at 35–50 kW/m^2 incident radiant heating, pork fat would melt and smoke but could not be ignited to support a continuous flame unless a cotton cloth wick was placed across its surface (DeHaan, Campbell, and Nurbakhsh 1999). The radiant heat would then char the cotton cloth, melting the fat beneath. The melted fat wicking up via the charred cloth could be readily ignited. Cone calorimeter testing established that the effective heat of combustion for both pork and human fat was approximately 34 kJ/g and that their rates of heat release (per unit surface area of fuel) were roughly the same, 200–250 kW/m^2. The observed properties of melting behavior and ignitability for human and pork fat were also indistinguishable, confirming that test results using pork fat or pig carcasses would yield results applicable to human cadavers (DeHaan, Campbell, and Nurbakhsh 1999).

A final series of tests in which pig carcasses clothed in knit garments and ignited by means of a 1-L (0.22-gal) pour of gasoline confirmed that the charred garments and charred carpet and pad served as a wick and would support combustion of the fat being rendered out of the carcass. This combustion produced a smoky fire of approximately 50 kW, with a mass loss rate of approximately 1.5 g/s (5.4 kg/hr) for times exceeding 1 hour. Further, the gasoline pour would burn off in approximately 3 minutes while producing a fire of 250–400 kW. This brief fire would initiate fire in the surrounding carpet that would continue to burn for various times, consuming carpet at a rate of about 0.5 m^2/hr.

Of interest in this case was the observation that the gasoline-fed fire was not of sufficient duration to cause the skin to shrink and split and allow the rendered fat to escape to support external flames. Only after the clothing and carpet had burned for 10 minutes or longer could the rendering process be seen to be supporting the fire.

The fire behavior supported by tests and data were considered when reaching the conclusion that the fire had been burning for 2 to 4 hours at the time of its extinguishment. Since the fire was still burning at approximately 9 a.m., it was concluded that it was ignited using gasoline sometime between 5 and 7 a.m. This time frame, combined with conflicting statements made by the suspect, led to his prosecution. He was convicted of three counts of second-degree murder and one count of arson. He is serving consecutive sentences for a total of 60 years to life.

This case is courtesy of Bruce Moran, Sacramento County District Attorney's Laboratory, Sacramento, California, and Jeff Campbell, Sacramento County Fire Department (retired).

CASE EXAMPLE 2 Execution by Fire

The burned body of a young woman was found in a remote agricultural area. She bore burns over most of her body and was dressed in the burned remains of cotton denim pants, a long-sleeved cotton shirt, and a bra, all identified by brand name tags that survived the fire (Figure 7-8). Her ankles had been bound together with a heavy leather belt wrapped over her cotton socks, prior to the fire (Figure 7-9).

The victim was found lying on her back with her arms and legs partially flexed. There was a burned pile of clothing some 2.6 m (8 ft 8 in.) away from her head (probably in a cloth duffel bag). The clothing and other contents indicated that this bag belonged to the victim.

There were a number of small areas of scorching or charring visible on the dry soil nearby, isolated from both the clothing and the body. Although these could have been the result of isolated burning splashes of flammable liquid, they were more consistent in appearance with having been the result of contact between the burning clothing and the soil.

Examination of the scene revealed that there was a faint pattern of wrinkled fabric (as from garments like shirt and pants) impressed into the dry sandy soil between the body and the pile/bag of clothing. There was an additional pattern of wrinkled fabric in the soil to the right of the body adjacent to the torso and upper right leg.

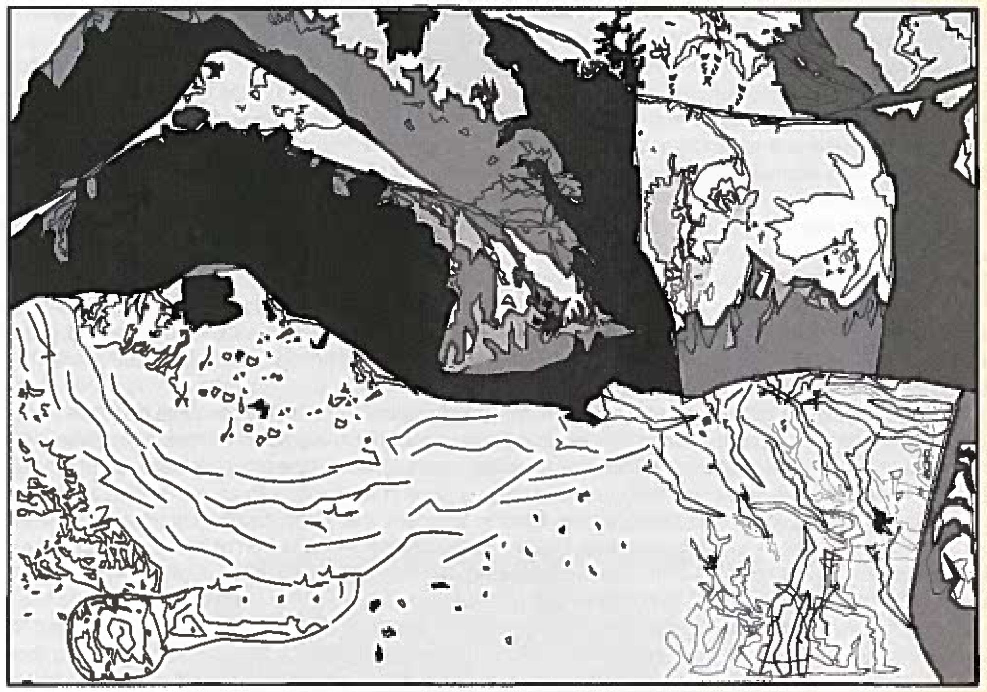

FIGURE 7-8 Victim of murder by burning as found at scene. Repeated scuff marks with limited scorching in soil adjacent to torso and limbs show movement during the fire. Impressions of creased fabric of shirt on soil next to torso were produced as victim rolled on ground. Charred residue of denim jeans remain on left leg and waist. Charred cloth fragments away from body also show movement after and while burning. Shoe print in lower left corner is partially overlain by "leg" fabric impression, showing sequence.

FIGURE 7-9 Scuff marks in soil near toes and feet show repeated movement. Flexion of toes is due to heat shrinkage of tendons. Feet of victim bear only first- and second-degree burns from burning of cotton socks. Sock material trapped beneath leather belt around ankles burned longer (supported by gasoline wicking out) and induced charring of skin beneath.

The soil at the fire scene revealed additional information. There were deep scuff marks in the soil, of the type made by bare or stocking feet, under and beside the toes of the victim. Scorched areas of soil to the right side of the body were displaced and disturbed by patterns of movement of the soil, probably by movement of the right arm and right leg of the victim. There were a number of shoe prints and tire prints in the vicinity of the body, some of which overlaid the scuff marks, but in most cases the scuff marks obscured the shoe impressions, confirming sequencing and timing of movements.

Laboratory tests revealed the presence of gasoline in the clothing of the victim, in the burned clothing pile, and in the soil sampled in several areas. There was no gasoline container found in the vicinity. No estimate could be made of the quantity of gasoline that had been used. No other fuels were present except for the clothing.

There was extensive scorching and blistering of the skin across nearly all exposed areas of the victim's body. The back was more burned than the front of the torso, and most of the clothing was burned away, particularly on the back and sides. There were signs of vital reaction to many burned areas of skin. The burns were only partial thickness (second degree) over nearly all the body, with the only exception being deep charring of the ankles and lower legs immediately adjacent to the cotton socks held in place by the leather belt. Nearly all the scalp hair was burned away, reduced to black masses. Charred remains of cloth were clutched in the fingers of the right hand.

Postmortem examination revealed internal heat/flame damage to the mucosa of the throat and larynx as a result of inhalation of extremely hot gases. Toxicological analysis reported a COHb level of approximately 14 percent. The fire issues here were whether gasoline had been poured and ignited on the victim while she was conscious and what the result of such an event would be.

Re-creations in the laboratory using a dressmaker's mannequin approximately the same height as the victim demonstrated that two full revolutions of a body that size as it rolled on the ground resulted in the same displacement as seen at the scene between the body and the clothing pile. Owing to the taper of the body from the shoulders to the feet, the path taken by a body rolling in this manner is in the form of an arc rather than a straight line.

A gasoline fire is known to produce heat transfer sufficient that direct flame contact induces blistering (partial-thickness burns) in about 5 seconds at 50 kW/m^2. Based on the distribution of burn damage to the body and the clothing, it was concluded that the fire damage could not have been the result of gasoline having been poured over an inert, unconscious body. The absence of protected areas and the extensive damage to the back and buttocks could have resulted only from the victim's consciously moving. The charred cloth clutched in the hand away from other fire damage indicated a conscious attempt to grasp the burning clothing during the fire.

Although flexion of the major joints as a result of fire exposure can result in some movement of an unconscious or even a deceased body, the pattern of cloth/fabric impressions in the soil was the result of a rolling movement of the body. The scuff marks in the soil to the right side of the body were most likely the result of movement of the right arm and right leg of the victim while she was lying on her right side. The body apparently fell or rolled onto its back, where it assumed its final resting position. Movement of the feet and toes would have produced the deep scuffs found there. Fire damage to the clothing and the isolated scorch marks on the soil were also consistent with conscious movement of the body.

The duration of a gasoline-fueled fire would be of the order of 2 minutes or less (assuming that less than a gallon was used). The duration would be shorter if the gasoline was spread on bare skin or thin cotton fabric. Such a short-duration fire would produce the limited-depth burns found here, with the only exception being the gasoline-soaked cotton socks, which acted as a wick to sustain flames long enough to induce deep burns to the adjacent tissue. The presence of shoe prints overlying some of the scuff marks in the soil was an indication that the victim was set afire in the vicinity of the clothing bag and that her assailants were present during (at least) the initial stages of the fire as she rolled on the ground in an attempt to extinguish the flames. It was concluded that she was conscious for many seconds during this fire.

The three people who carried out this execution were acquaintances of the victim who decided that it would be interesting to dispose of her in this manner and transported her in a truck while they purchased the can and the gasoline. All three pled guilty to murder charges.

CASE EXAMPLE 3 Fatal Van Fire

At about 5:30 on a cold November morning a farmer heard shouts of alarm coming from across the river. He looked out to see a camping-style van fully engulfed in flames. He phoned the fire department, but owing to the remote location of the site, it was 15 minutes or more before fire crews arrived and another 10 minutes before the fire was extinguished.

Inside the van were the remains of an adult female victim who had reportedly been asleep in the back of the van with her boyfriend at the time the fire was discovered. The boyfriend, after awakening and reportedly discovering the smoke and limited flames within the van, had allegedly tried to rouse the victim, who was non-responsive, and then escaped the van by butting his head against a rear window. He attempted to rescue his friend from outside but discovered that all but one of the doors to the van were locked, and he could not reach her through the one unlocked door because a blanket hung between the cargo compartment and the driver's compartment. He claimed that they had been camping on the river just for a day. Both were recreational drug users, and he had a record for breaking-and-entering and minor drug charges.

Investigators called to the scene discovered that all the windows to the "Sportsman-style" van had been broken but could not tell if any had been broken by mechanical force. The side and rear windows were tempered glass, which shatters into similar small pieces whether broken by thermal shock or mechanical impact, but all appeared to have been soot covered. The van had been gutted, with most damage to the cargo and driver's compartments (Figure 7-10). There were signs that the fire had penetrated into the engine from inside the van. The sheet metal of the roof had been badly distorted by the fire. There were no signs that the vehicle had been in operation at the time of the fire. The vehicle's fuel tank was still half full, and the fuel system was normal.

Fire damage outside the vehicle was limited to the grass immediately around and under it; there were no indications of an external grass fire growing to involve the vehicle. The van was heavily loaded with bags and boxes of clothing, food, camping supplies, tools, and blankets. There were a propane camping lantern and camp stove with two 1-lb propane bottles, but they were not in use. All exposed fuels in the van were fire damaged.

A friend who had visited the man and woman the night before the fire said that they were eating snacks (with no cooking) and were using small votive candles for light. Luckily the fire chief in this jurisdiction always kept a point-and-shoot camera in his vehicle and was able to get several photos of the still-smoldering interior of the vehicle before the contents were removed to permit overhaul. The upholstery of the seats and dash and paneling of the cargo compartment were completely consumed (Figure 7-11). The fire damage clearly demonstrated that

FIGURE 7-10 Exterior damage to the gutted van, showing most damage to the cargo and driver's compartments. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

FIGURE 7-11 Interior of the vehicle immediately after extinguishment and before overhaul. The victim is sitting facing the camera, with her back resting against the back of the passenger seat. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

FIGURE 7-12 Fire victim as found in the vehicle. Note the extensive destruction by flames, with exposed ribs, spinal column, and internal organs. The skull has calcination and fracture damage resulting from prolonged fire exposure. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

the fire within this compartment had gone to flashover, with ventilation supplied by the windows (closed at the start of the fire but failing as the fire grew).

The decedent was found in a partial sitting position on the right side of the cargo compartment (Figure 7-12) facing the rear of the van. The body had suffered massive fire damage; nearly the entire right half of the body had burned away (exposing the spinal column), with major bones reduced to fragments. The victim had a 41 percent COHb level, with no alcohol and very low levels of amphetamine metabolites. She was young (23 years old), healthy, and physically unimpaired. Extensive fire exposure had destroyed the soft tissues of the head and neck and had caused the exposed skull to calcine and fracture into a number of pieces. There were no underlying hemorrhages indicating antemortem trauma. The fire had compromised the lungs and airways such that the presence of combustion products could not be determined.

The COHb level left no doubt that the victim had been alive and breathing for some time during the fire and had died as a result of exposure to smoke and flames. The extensive damage to the body was ascribed by the pathologist to incineration by a flammable liquid fire, despite later laboratory findings that revealed no petroleum distillates in the small segment of carpet recovered from beneath her.

No flammable liquid residues were detected on the exterior of the van or beneath it. The extensive damage to the van, the absence of accidental ignition sources, and the nonoperational status of the van led investigators to conclude that the fire had been deliberately ignited with a flammable liquid on or around the decedent, which prevented her escape. The boyfriend was charged with murder.

The surviving victim (boyfriend) was found outside the van dressed in T-shirt and undershorts (he was the person shouting for help whom the farmer heard). He had a coating of soot on his face, arms, and hands but no burns. His facial hair (including mustache) was unburned, but hair at the top of his head was singed. He had fresh abrasions on his knuckles, one on the top of his head, and scratches and abrasions on his lower legs. Tiny fragments of glass were found in his scalp hair. His blood was not sampled immediately but was taken later and was found to bear low CO concentrations, low levels of amphetamine metabolites, and no alcohol. He claimed that he and the decedent had gone to sleep side by side wrapped in blankets on the floor of the cargo compartment and awakened to discover the fire. He denied any conflict with the decedent.

A review of the evidence (by one of the authors) at the request of the local district attorney's investigator resulted in the conclusion that the physical, medical, pathological, and toxicological evidence was more consistent with an accidental fire occurring as described by the accused than with a murder with flammable liquid. A fire-related human behavior analysis revealed that if the survivor had been sleeping on his back in a smoke-filled van, his face and arms would be expected to be coated with soot but not exposed to the hot gas layer until he sat up and attempted escape. At that time, his scalp hair would be exposed to the highest temperatures. Beating at the window glass or fumbling in the dark for the door locks could have produced the abrasions on his right hand. Butting his head against the rear window until it broke could have produced the abrasion on the top of his head and the glass fragments in his hair. Sliding out the high rear window would be expected to induce cuts and scratches to the lower legs.

The 41 percent COHb level in the decedent is similar to the levels encountered in victims of accidental house fires. In the opposing hypothesis, throwing gasoline on someone in sufficient quantities to prevent his/her escape would be likely to leave unburned residues after the fire in protected areas under the body and would also be likely to produce a flash fire of sufficient size to induce singed facial hair on someone close by (i.e., the thrower). The ignition of a quantity of gasoline vapor in the vicinity of a victim's face can induce rapid cessation of breathing so that CO levels in the blood would be very low. The first few seconds of a gasoline vapor/air fire are also very low in CO, so the gases that are inhaled are unlikely to produce an elevated COHb level. Such a scenario would not produce the glass fragments, singed scalp hair, or leg injuries. A gasoline-fueled fire would also be unlikely to induce such extreme damage to the decedent's body unless it involved massive quantities of fuel.

The fire issues involved were the following.

- What were the contributions of the fuel load in the van?
- Did the size of the van (compartment) and the breakage of windows play a role?
- Could a fire in a closed van produce a fire that would be escapable and produce the physical and clinical evidence seen on the survivor?
- Could such a fire progress to flashover?
- If the fire did progress to flashover, could postflashover fire produce the damage to the body and to the van without the presence of any ignitable liquids?

A long-wheelbase Sportsman van similar to the one in the incident was obtained by the district attorney's office. Based on calculations of the window area and height, it was determined that when all the windows failed, enough air would be admitted to the van to support a fire of 3.2 MW. The internal volume of the van was calculated to be 9.8 m^3, so there was considerably more air inside even a closed van than there would be in the average passenger vehicle.

The van obtained (Figure 7-13) had nearly the same arrangement of windows but had one solid side panel instead of a large window, so a vent panel was cut through the metal and left attached by a hinge so it could be opened during the fire test to simulate failure of the window by thermal shock. The interior finish was duplicated, with paneling, carpeting, and seats similar to the original.

Wooden tool boxes and a wool blanket curtain were fitted to simulate the original, and some 120 kg (265 lb) of clothing, blankets, plastic crates, cardboard, and miscellaneous combustibles was added, estimated to be about half the added fuel mass in the original van, as shown in Figure 7-14.

Temperatures were monitored via three thermocouples mounted on a tree in the center of the van near the position of the decedent and one thermocouple near the rear door where the survivor allegedly made his escape. Ignition was produced with an open flame in ordinary combustibles and the van was then closed up. A misplaced votive candle was probably the ignition source for the actual fire. Given the nature of the fire and the fuels available, it was very unlikely to have been a smoldering source.

In the test, within 3 minutes heavy smoke had formed throughout the van, and temperatures in the smoke layer ranged from 80°C to 100°C (176°F to 212°F), as shown in Figure 7-15. Soot was observed condensing on all windows. The rear window was broken from outside by mechanical impact at 3 minutes 45 seconds. Gas layer temperatures exceeded 600°C (1112°F) by 7 minutes, and flashover occurred as windows began to fail from thermal shock. The side vent was opened as all the windows failed between 6 and 8 minutes into the fire, and by 8 minutes, temperatures in the hot gas layer exceeded 1000°C (1832°F). Temperatures of over 600°C (1112°F) were maintained for over 12 minutes as the fire consumed the fuel load and went into decay. Total burn time

FIGURE 7-13 The test van obtained had nearly the same arrangement of windows but had one solid side panel instead of a large window, so a vent panel was cut through the metal and left attached by a hinge so it could be opened during the fire test to simulate failure of the window by thermal shock. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

FIGURE 7-14 Wooden toolboxes and a wool blanket curtain were fitted to simulate the original, and some 120 kg of clothing, blankets, plastic crates, cardboard, and miscellaneous combustibles was added, estimated to be about half of the added fuel mass in the original van. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

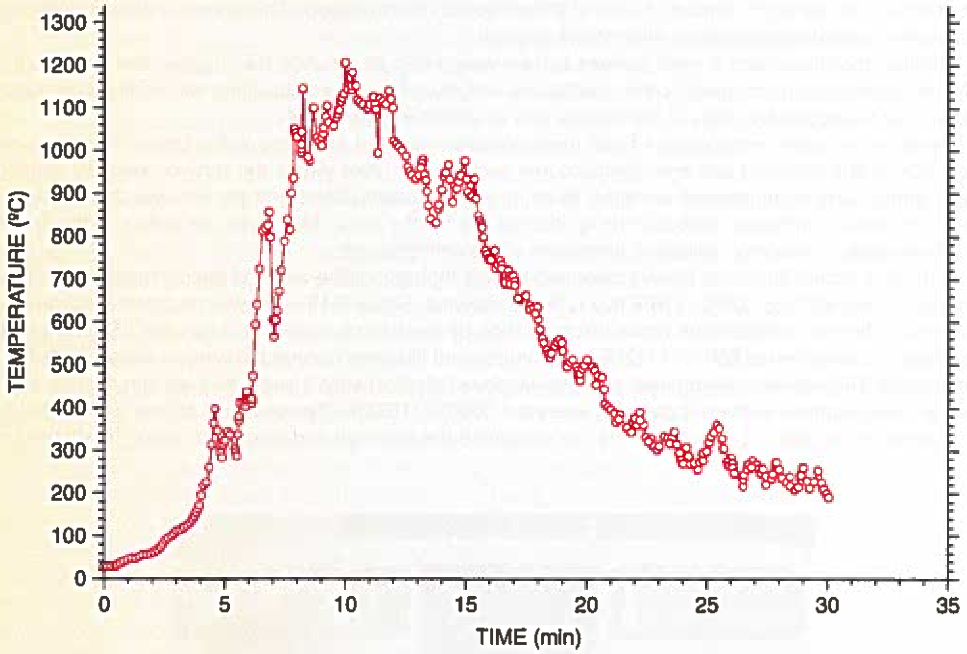

FIGURE 7-15 Test results for fire in a test vehicle documenting the interior temperature versus time at a thermocouple located near the victim's location. *Courtesy of Fred Fisher, Fisher Research & Development, Inc., Vacaville, CA.*

was 30 minutes. Damage to the exterior and interior of the van duplicated that of the original fire scene van, as shown in Figures 7-16 and 7-17.

Temperatures and heat fluxes in excess of those found in commercial crematoria were measured in the center of the van. The victim's body would have been exposed to these intense fire exposures from her right side, near the center of the compartment, where the postflashover burning would have been most intense. The fuel load available in this test limited the duration of the fire, but not its intensity. The intensity was determined by the surface area of fuel involved in the postflashover burning and the ventilation available to support the combustion.

FIGURE 7-16 Thermal damage to exterior of test van. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

FIGURE 7-17 Thermal damage to interior of test van. *Courtesy of Solano County Sheriff's Dept., Fairfield, CA.*

Although no heat release data were captured during this test, the test team, with their extensive forensic fire experience, estimated that the heat release rate was in excess of 3 MW during the peak of the fire (at 10 to 12 min). Because the ventilation inside the test van was the same as in the van involved in the fatality, the size and intensity of the fires would have been equivalent. With the more substantial fuel load in the scene van, it was potentially capable of supporting a full postflashover fire for much longer than the test van could.

Witness observation by the farmer confirmed that the van was fully engulfed when he first saw it and it burned that way until extinguished some 25–30 minutes later. Based on the results of this test, the district attorney agreed that an accidental fire could not be ruled out and was, in fact, more consistent with the physical evidence. All charges against the male suspect were dropped.

The test data in this case are courtesy of Fred Fisher, P.E., of Vacaville, California. The authors thank Professor R. Brady Williamson of the University of California, Berkeley; Dr. Charles Fleischman of the University of Canterbury, Christchurch, New Zealand; and members of the Solano County Fire Investigation Team for their contributions and for making this test possible.

CASE EXAMPLE 4 Murder by Fire, or Accident?

At approximately 4 p.m. on a weekday, fire and ambulance services were alerted to attend to a female who had been burned and to a fire in a kitchen inside a suburban apartment block. On arrival, ambulance and fire personnel found a deceased adult female, with obvious burn injuries, at the street frontage gate. A male indicating he was the partner of the deceased provided the location of the suspected fire in an apartment kitchen. Firefighters located and inspected the apartment, only to find that a small fire had occurred in the kitchen, causing slight fire damage. They extinguished the fire and requested that an investigator attend owing to the fatality.

The initial theory (hypothesis) provided by firefighters at the scene was that the male was working on a model car engine, the fuel being used had ignited, and the female was involved by the ensuing fire. Another theory (hypothesis), developed by police at the scene, was that the male and female had been quarrelling, and fuel had accidentally been spilled on the kitchen floor. Subsequently, an accidental ignition had occurred that involved the clothing of the female. She ran out of the apartment and downstairs into the yard, where she was found on fire. She was found approximately 50 m away, at the front gate, where she succumbed to her injuries from the fire, and where she was found by attending emergency services.

The body of the deceased was inspected in situ, and it was noted that she was wearing a cotton-type material tracksuit, with long legs and long sleeves; underwear; and what appeared to be nylon-type socks on her feet. The victim's clothing was severely fire damaged, principally from the hips/thighs up and involved the upper body and head (Figure 7-18). The victim's upper body was severely burned, and her head and chin area had suffered extreme burn injuries. Her hands and forearms had suffered severe burn injuries as well. The lower legs of the pants, however, were intact and not consumed by the fire (Figure 7-19).

Burned remnants of clothing and skin, from the body, were found in a trail from the front gate along a path leading to the front door and up the internal stairs to the second level. Several pieces of burned skin adhered to the wall along the stairs outside the fire-affected apartment.

Inside the apartment, investigators found that a small fire had damaged sections of the kitchen. There were some small scorch marks on the tiled floor and some slight scorch marks on the bottom of the timber cupboards, but more important, several areas of the top surface of the cupboards had been fire damaged (Figure 7-20). A paper towel roll had a V-shaped pattern from the benchtop upward on its front surface; a microwave oven had a V-shaped pattern of scorching on its front window surface; and one of the plastic feet on a kitchen appliance, located on the benchtop, was slightly melted. An odor of methylated spirits (denatured alcohol) was evident within the kitchen and was emitted from beneath the microwave oven (Figure 7-21). A partially melted plastic container was located on the floor adjacent to the bottom of the kitchen cupboards (approximately 4-L capacity, or approximately 1 gal).

A one-fifth scale model car engine was located within an adjoining room, and details were recorded of the model and serial numbers. Subsequent research through a model car supplier revealed that this engine was fueled by methylated spirits (denatured alcohol) and not petrol (gasoline), as suggested by the male occupant as the fuel for the fire.

FIGURE 7-18 Upper body of fire victim, found outside residence. Note fire damage to clothing, upper body, and face. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-19 Legs of fire victim. Note pants legs are intact. Nylon socks are melted. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-20 The kitchen where the incident occurred. Note small fire damage at center bottom of cupboards and on paper towel roll at countertop near microwave. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

After inspection of the injuries suffered by the deceased and of the fire damage within the kitchen, the police and investigators held a discussion. The notion (hypothesis) that the deceased had been accidentally caught in a fire, which had been ignited by spilled fuel on the kitchen floor, was considered. The reasoning used to test this theory was that the deceased was still wearing nylon socks and that the lower section of her cotton clothing was intact and not fire damaged. In fact, if the fire had actually been on the floor of the kitchen—based on normal fire behavior—the socks and lower body clothing would have been the first to ignite. The fire theory advanced was that the deceased had had fuel splashed/poured/thrown over the upper half of her body and ignited, causing the injuries and damage found. Subsequent scientific testing showed that the clothing and areas of the kitchen were indeed contaminated with methylated spirits.

Police interviewed the suspect male who subsequently provided information that he had quarreled with his female partner. The suspect had been in possession of a 4-L plastic container of methylated spirits (approximately half full) and had been so enraged that he had thrown some of the liquid onto her, had thrown the container onto the floor, and had kicked it around in his rage. He had then held a disposable lighter up and away from her and lit it in an effort to scare her. The liquid on the floor had accidentally ignited, and her clothing had caught on fire, so she had run down the stairs and out of the apartment. He had followed, smothered the fire on her clothing with a bed sheet, and carried her to the front gate.

A further search of the apartment revealed some of the male's clothing, burned and wet on the bathroom floor. This clothing evidence, along with burns that the suspect had suffered showed his clothing had caught fire as well during the incident and that he had gone to the shower and extinguished himself prior to following the female downstairs. The police subsequently charged the male suspect with murder.

FIGURE 7-21 Fire damage on kitchen countertop at scene of fire. Note V pattern on paper towel roll and burn mark on microwave front window. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-22 Testing of theory with clothing and flammable liquid in a fatal fire death case. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

In an effort to test the investigator's theory, the clothing that had been worn by the deceased was scientifically analyzed, and similar sets of clothing were purchased. Two store mannequins were also obtained, and a test was conducted to fire test the clothing. The Fire Service Training College Fire Training Tower was used, and all tests were videotaped and photographed, to be used as evidence (Figure 7-22). The mannequins were clothed in the identical clothing, and two tests were conducted using methylated spirits, one with liquid poured only on the floor around the base of the mannequin and another with liquid poured over the upper body of the mannequin and onto the floor.

The liquid was ignited in both cases and the resulting fire recorded. Even though the concrete room was bare of furnishings, fittings, and cupboards it was considered a basic test to determine whether the resulting fire would produce injuries similar to those of the deceased. In both cases with the liquid on the floor, the lower-body clothing and socks were consumed early in the fire (Figures 7-23, 7-24, 7-25, and 7-26).

With the liquid applied to the upper body of the test mannequin, the resulting burn damage to the face and upper body of the mannequin proved to be identical with the actual injuries suffered by the deceased; both sets of photographs could be placed side by side and the injuries were seen to be identical (Figures 7-27 and 7-28). The injuries suffered by the deceased showed the fire had risen from beneath the face and affected the underchin area, lower portion of the upper lip, the nostrils and underside of the eyelids, and the lower lobes of the ears.

With these data and evidence the case was prepared for trial on the murder charges. After a conference with the Crown Prosecutor it was decided that further tests would be conducted in a kitchen-type configuration to test the validity of the actual scene configuration to validate the veracity of the testing and the theories

FIGURE 7-23 Test underway with flammable liquid at floor level only. *Courtesy of Ross Brogan, NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-24 Fire test with fire being extinguished. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-25 Fire damage to mannequin after fire test from floor-level pour. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-26 Fire test underway with flammable liquid on floor and on upper body and clothing. Note that dark coloring on clothing is liquid on upper body. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-27 Mannequin fully involved in test with liquid at floor and on upper body. The judge considered that this graphic photo might have upset jurors. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

FIGURE 7-28 Results of test showing fire damage/injury to mannequin that was compared with photographs of the actual victim. *Courtesy of Ross Brogan (ret.), NSW Fire Brigades, Greenacre, NSW, Australia.*

involved. The public housing authority was approached, and a vacant townhouse was obtained with a kitchen configuration similar to that of the actual incident scene. This configuration, rather than the open concrete room used in the initial tests, was thought to lend authenticity to the test results.

First, a 4-L (approximately 1-gal) container similar to the one found in the apartment was obtained and marked with graduations on the outside to show liquid levels, in approximately 250-mL increments. The container was filled with colored water and flung to try to give an indication of how much liquid was expelled with each throw when tested at differing liquid levels. The results of these tests were used to estimate the volume of liquid thrown onto the victim during the actual incident. These tests were videotaped and photographed, again for evidentiary purposes, and were later used in the court trial.

The fire tests were conducted using clothing identical with what the victim had been wearing, this time in the kitchen similar in configuration to the fire scene. Videotaped and photographed, these tests were again available for the trial as evidence. Again, the tests in which the liquid was applied to the upper body of the mannequin resulted in burn damage and injuries identical with those of the victim. The investigator and the prosecutor agreed that the theory proposed was valid and practical, having been tested by scientific methodology.

At the trial, after viewing the video evidence of the tests, the trial judge refused to allow the videos to be shown to the jury, stating that they appeared to be prejudicial to the defendant and a possible appeal point after the trial. However, the judge allowed the theory testing and results to be discussed during presentation of evidence. In all, the investigator spent five and a half days in the witness box presenting evidence in chief and under cross examination, and presenting evidence to establish his own credibility, the credibility of the hypothesis, and the validity of the tests that proved the story of the defendant to be false. The male was subsequently convicted of manslaughter.

It was interesting that during the cross-examination the defense attorney proposed a theory aligned with the fact that it was (the investigator had explained the scientific basis of ignition of flammable liquid vapor and not the actual liquid), in his words, "a spiderweb of vapor hanging in the air" that ignited and ignited the upper clothing of the deceased. This spiderweb theory was vigorously debated, with the scientific basis of the theory explained during the cross-examination, and ultimately dismissed, partly because a question from the jury indicated that a member of the jury had some scientific training and complained that the defense was using "junk science theories" to deceive the jury on something that was quite plainly a valid scientific theory proposed by the prosecution. The other factor was that if the "spiderweb of vapor" was hanging in the air, then the lower clothing was just as susceptible to ignition as the upper clothing. The jury found the defendant guilty.

This case provided courtesy of Inspector Ross Brogan (ret) AFSM, CFI—NSW Fire Brigades, Sydney, Australia.

CHAPTER REVIEW

Summary

In a fatal fire, the cause of death and the cause of the fire are independent but linked by circumstances. Each must be established, and only then can the link between them be determined.

Accidental fires can accompany deaths by accident, suicide, homicide, or even natural causes. Incendiary fires can be associated with homicide (as a direct cause of death or simply as part of the crime event) but also with accidental or natural-cause deaths. For a fire death investigation to be successful (i.e., accurate and defensible), the following guidelines must be observed.

- ***Treat the scene as a crime scene.*** Every fire with a death or major injury should be treated as a potential crime scene and not prejudged as accidental. The scene should be secured, preserved, documented, and searched by qualified personnel acting as a cooperative team.
- ***Document all critical features(as discussed in Chapter 4).*** Documentation includes accurate floor plans, with dimensions and major fuel packages included, and comprehensive photographic coverage. Photos must include presearch survey photos, photos during search and layering, and photos of all views of the body prior to removal, during removal, and during postmortem examination by a medical examiner. This documentation is essential to proper forensic fire scene reconstruction (as described in Chapter 4).
- ***Avoid moving the body.*** The body must not be moved until it has been properly examined by the fire investigator and the pathologist or coroner's representative and thoroughly documented by photos and diagrams. The debris under and within 0.9 m (3 ft) of the body should be carefully layered and sifted. All clothing or fragments should be preserved. Artifacts (jewelry, weapons, etc.) must be documented and collected.
- ***Assess the fuels.*** The fire investigator has to assess the fuels already at the scene (structure as well as furnishings), and the role fuels may or may not have played in ignition, flame spread, heat release rates, time of development, and creation of flashover conditions.
- ***Perform full forensic exams.*** Every fire death deserves a full forensic postmortem examination including toxicology and X-rays. Toxicology samples should be tested for alcohol and drugs, as well as COHb and HCN, and should include both blood and tissue. The clothing should remain with the body and be documented and evaluated in situ before removal, if possible, then properly preserved. The internal (liver) body temperature should be taken as soon as possible (preferably at the scene).
- ***Examine pets.*** Deceased pets should be X-rayed and necropsied. Injuries to living pets should be noted and documented. Blood from deceased pets should also be tested for COHb saturation and drugs.
- ***Examine living victims.*** Fire victims who are survivors, whether burned or not, should be visually examined during interviews and, when possible, be photographed. Blood samples should be taken from them for analysis later if needed. External clothing (pants, shoes, shirt) should be saved and properly preserved.
- ***Fully appreciate the fire environment.*** Pathologists and homicide detectives must appreciate the fire environment—temperatures, heat and its transfer, flames, and smoke—and the distribution of fire products and the variables in human response to those conditions. In best practice, the medical examiner and/or pathologist visits the scene and sees the body in situ to appreciate its conditions of exposure (to flame, heat, and smoke), the nature of debris, and its location and the position.
- ***Carry out forensic reconstructions.*** A full reconstruction may involve criminalistics evidence such as blood spatter, blood transfers, fingerprints, tool marks, shoe prints, and trace evidence. The criminalist should be part of the scene investigation team along with the homicide detective, fire investigator, and pathologist.

As we have seen, a death involving fire is not just a simple exposure to a static set of conditions at a single moment in time. Fire is a very complex event, and a fire death investigation is even more complex and challenging. A coalition of talents and knowledge working together as a team is the only way to get the right answers to the three big questions: What killed the victim? Was the fire accidental or deliberate? and How did those two events interact?

Problems

7.1. Discuss the common problems and pitfalls associated with fatal fire investigations. Compare them with a recent ongoing case in the national media. What parallels can you find?

7.2. Referring to Example 7-1, determine the visibility of the same fire in an enclosed hallway measuring 3 m × 15 m (9.84 ft × 49.2 ft) with a ceiling height of 2.5 m (8.2 ft).

7.3. Referring to Example 7-2, calculate the fractional incapacitating dose for a male, a child, and an infant in the same scenario.

7.4. Review the newspaper coverage of a recent fatal fire in your community. Determine who investigated it, what the conclusions were, and whether criminal charges resulted.

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