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Fire Dynamics—A Primer

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Fire dynamics is the term chosen to represent the topics associated with fire behavior, including ignition, fire development, and fully developed fires. A review of pertinent information is undertaken to provide a useful brief primer. The dynamics of fire behavior in enclosures is considered, with emphasis on fundamentals, industrial fires, ignition, fire development, and fully developed fires. Appropriate details are given about related scientific topics (fuels, burning rates, heat transfer, and flashover and backdraft phenomena) and investigative techniques (experimental studies, fire modeling, and fire investigation). Clearly, an ambitious task, with an exhaustive array of topics being addressed, this review paper conveys appropriate information with pertinent referencing.

Introduction

FIRE development in buildings is an extremely important topic in fire protection engineering.[1–6] Fire spreading rates, amount and temperature of the smoke layer produced, evolution of toxic gases, and the amount of time available from the onset of fire for the safe departure of occupants are all topics of concern. Fire dynamics is the term chosen to represent the topics associated with fire behavior, including ignition, fire development, and fully developed fires. The scientific topics of chemistry, physics, aerodynamics, and heat transfer all play their part. Technical information about fuels, burning rates, fire spread, and flashover and backdraft phenomena is also relevant. Finally, aspects of experimental studies, fire modeling, and fire investigation are also strongly related to, and in fact, can be considered an integral part of, the subject of fire dynamics. The present document reviews pertinent information.

Simple empirical relationships have been developed to provide slide-rule estimates of fire growth,[7] and these provide guidelines. The surge in computer capability in the 1980s has led to several approaches that put the scientific and mathematical features on a firm foundation. Enclosure fire models (including so-called field and zone models) and special purpose models are available and discussed in Refs. 2 and 3. The improvement of fire modeling is assisted by experimental studies, and collectively this helps in understanding the actual behavior of fires in real-life situations. This includes the phenomena leading up to the occurrence of important events such as flashover and backdraft, and thus, how these events can be delayed or avoided completely. Additionally, understanding fire behavior assists in the evaluation of patterns of destruction left after the fire has been extinguished. This helps fire and arson investigators who examine and interpret postfire evidence to ascertain the origin and cause of fires.

Fundamentals

Definitions

Some useful definitions related to fire dynamic terminology are given next.

Accelerant: A substance of any type used to enhance the burning qualities of a material and to increase the spread and intensity of fire.

Area of origin: The localized area where a fire originated.

Backdraft: An instantaneous explosion of smoke blasting back through an opening.

Building: A relatively permanent walled and roofed structure that stands alone and separate from other structures.

Burn: To be on fire; to consume fuel during rapid-combustion; a geographical area over which a fire has passed; a fire in progress or under investigation; an injury caused by a fire's heat coming in contact with skin.

Burn pattern: Apparent and obvious design of burned material and the burning path of travel from a point of fire origin.

Combustion: An exothermic chemical reaction that produces heat, and generally light as well, in a variety of mediums; the burning process, causing loss of weight to a compound.

Conduction: This is transmission of heat from one object to another by contact. Fire may spread in this manner through solid wall boundaries.

Convection: This is the transmission of heat through a liquid or gas by means of the movement of the liquid or gas.

Crazing: Cracking of glass, such as windows and mirrors, from the heat of fire.

Fire: Rapid oxidation, with the evolution of heat and light; heat, fuel, oxygen, and interaction of all three.

Fire cause: Agency or circumstance that started a fire or set the stage for one to start; source of a fire's ignition.

Fire point: This is the lowest temperature at which a liquid when exposed momentarily to an ignition source and sufficient oxygen will give off sufficient vapors to continue to burn. This is usually a few degrees above the flash point.

Flame: Light given off by burning gases during the combustion process.

Flammable: Capable of burning and producing flames. In the context of liquid fuels, flammable and combustible liquids have special meanings.

Flash Point: This is the lowest temperature at which a flammable liquid when heated in the presence of sufficient oxygen will flash, but not continue to burn, in the presence of an ignition source.

Flashover: The rapid transition in fire behavior from localized burning of fuel to the involvement of all combustibles in the enclosure.

Fuel: Flammable substances available for a fire to consume.

Ignition source: Mechanism employed to initiate combustion.

Ignition temperature: This is the lowest temperature required to initiate or cause self-sustained combustion in the absence of a spark or flame for a flammable liquid or gas. This is also called the autoignition temperature, or self-ignition temperature.

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Incendiarism: Deliberate setting of a fire or fires by a human being.

Incendiary device: Contrivance designed and used to start a fire.

Indicator: Visual remains at a fire scene revealing the fire's progress and action.

Petroleum products: These products are frequently involved in fires and are generally referred to as hydrocarbons. These compounds range from components of gasoline as the lightest in weight, and include kerosene, fuel oil, etc., to the heaviest, asphalt.

Pyrolysis: The chemical decomposition of a substance through the action of heat. Fuel gases are evolved from solid fuels by pyrolysis.

Radiation: This is the transmission of heat by waves. When we stand in front of a fire we become warm by this process.

Rollover: Small, sporadic flashes of flame that appear in the smoke layer near ceiling level or at the top of open doorways or windows.

Short or short circuit: This is an electrical connection of low resistance or impedance, especially when accidental or unintended.

Smoke: Small particles of carbon, tarry particles, and condensed water vapor suspended in the atmosphere, resulting from the incomplete combustion of carbonaceous materials.

Spalling: Explosive pitting or chipping destruction of a surface, usually concrete, from intense heat buildup, commonly caused by the activation of an accelerant.

Splash pattern: Characteristic pattern left on a wall by an accelerant that has been splashed there, usually in the shape of an inverted V.

Spontaneous combustion: This is the act of burning from qualities inherent in the substance itself and not from any external cause. That is, combustion of a material initiated by an internal chemical or biological reaction producing enough heat to cause the material to ignite. This heat is generated by a slow oxidation process. It is most common in hay storage. Hay generates heat, and when improperly stored, can cause a fire.

Structure: A constructed object, usually a building standing free and above ground.

Trailer: Combustible material, such as rolled rags, blankets, and newspapers, or flammable liquid, used to spread fire from one point or area to other points or areas, often used in conjunction with an incendiary device.

Vapor pressure: The pressure exerted by a saturated vapor above its own liquid in a closed container. The vapor pressure is especially temperature dependent, higher temperatures producing higher vapor pressures with the possibility of vessel rupture.

Volatile: Changing into vapor quite readily at a fairly low temperature.

V pattern: Characteristic fire cone-shaped pattern left by fire on a wall, at or near its point of origin.

Chemistry and Physics of Fires

Chemistry is the science that deals with composition, structure, and properties of substance and the transformations that they undergo. Physics is the science that deals with matter and energy and their interactions in the fields of mechanics, acoustics, optics, heat, electricity, magnetism, radiation, atomic structure, and nuclear phenomena. Thus, whereas chemistry deals with how things are put together and what their composition is, physics deals with how things work in both normal and abnormal conditions. Rates of chemical reaction are determined by laws of both chemistry and physics, and the particular circumstances may be such that one or other of these laws takes precedence. Combustion is generally considered to be the science that deals with exothermic (heat releasing) chemical reactions, particularly where a fuel is involved as one of the chemical components. A fire is generally considered to be defined as follows:

Fire: The self-sustaining process of rapid oxidation of a fuel by an oxidizing agent along with the evolution of heat and light. Fire must maintain a very delicate balance to maintain combustion. There must be a number of things within the correct range of proportions. Lacking this, there will be no fire. There are two types of combustion we are concerned with:

1) Smoldering combustion: A type of combustion in which no flame is produced. This is illustrated by the fire triangle, whose three sides are oxygen, heat, and fuel.

2) Flaming combustion: A type of combustion with one additional feature illustrated by the fire tetrahedron with the three sides of the fire triangle, and one more side representing chemical chain reaction.

Carlson[8] and Wieder et al.[9] present basic ideas about fire behavior. Oxygen is often referred to as the uncontrollable side of the fire triangle. This is somewhat true when referring to a normal fire situation dealing only with the ambient atmosphere. In some cases, chemicals may be present that break down to give higher than normal oxygen content to the fire. This may intensify the fire. Under normal circumstances, the oxygen content of the air around us is ~21%. Air with at least 15–16% oxygen is necessary to support a free-burning flame-producing fire. Smoldering combustion can occur down to as low as 6% oxygen content. Remember that oxygen does not burn. The oxygen is the oxidizer. This side of the fire triangle supports the combustion.

Basics of Fire Behavior

A basic assumption in simplified approaches to a single room fire[10,11] is that there are only two spatially averaged temperatures: the upper- and the lower-layer gas temperatures. They both vary with time following ignition, as also does the optical density and thickness (distance down from the ceiling) of the upper smoke layer. Fire progression is as follows:

1) At the very start of a fire, the entire room is assumed to be at uniform ambient temperature.

2) As the fire progresses, the upper hot gas layer gets increasingly hotter and the layer extends progressively downward from the ceiling. This preflashover fire may be threatening to humans and important to the fire-spreading problem.

3) As the upper layer temperature reaches between about 400 and 600°C (752 and 1112°F), flashover occurs, the entire room contents become involved in the fire. Some authors quote that flashover occurs somewhere between 300 and 700°C (572 and 1292°F), this depending on the precise situation on which the experimental data were obtained (see Drysdale[12] for a review of the information). The upper hot layer is now down to near floor level.

4) Postflashover is particularly important. The temperature history after flashover is of prime importance in practice. The structural endurance of a building structure depends on the fire intensity (severity) after flashover.

5) After flashover, upper-layer gas temperatures have been found to be at most about 1452°C (2645°F), and to depend on several factors: burning-rate equivalence ratio, wall steady-state losses, wall transient losses, opening height effect, and combustion efficiency. These effects have been determined in terms of problem parameters, and values are deducible from figures given in Refs. 2, 3 and 13.

Industrial Fires

Industrial Fire Hazards

Cote and Linville[14] strived to describe many of the manufacturing processes used in industry, to identify the fire hazards associated with those processes, and to detail the methods used to control and eliminate them. They provide a basic reference book for those charged with protecting life and property in industry. They provide a broad introduction to the vast array of major industries and industrial processes, with emphasis on the fire hazards that accompany them. Information is presented about major industries and industrial processes, fire hazards associated with them are identified, and methods used to eliminate or control the hazards are explained. Litigation aspects associated with the reasons for the occurrence of fires—origin, cause, and responsibility—are addressed in several texts.[15,16]

Chemical Process Safety

Important technical fundamentals about chemical process safety, health, and loss prevention are addressed in Refs. 2, 3, 17, and 18. Identified are the many principles, guidelines, and calculations that are necessary for the safe design and operation of chemical plants, and analysis of failures. Numerous calculated examples and exercises illustrate how the principles are applied in practice. The coverage includes the following:

1) Fires and explosions can be prevented by the design of inerting, purging, and ventilation systems. Static electricity buildup (from flowing fluids) is computed.

2) Vessel overpressure protection is described. Relief systems protect process vessels from runaway reactions, external fires, etc. The latest two-phase flow-relief sizing procedures are included.

3) Hazards identification and risk assessment are determined by hazard and operability studies, fault trees, event trees, and other techniques. Accident probability is calculated.

4) Source models are described quantitatively. Various spill scenarios from accidents are formulated.

5) Dispersion modeling is illustrated. Calculations for areas affected by the accidental release of process materials are given.

Information is provided about latest process safety techniques to aid in the prevention and mitigation of catastrophic incidents.

Source Release Models

Chemical plant accidents often result in spills of toxic, flammable, and explosive materials. For example, material is released from holes and cracks in tanks and pipes, from leaks in flanges, pumps, and valves, and a large variety of other sources. Source models represent the material release process. They provide useful information for determining the consequences of an accident, including the rate of material release, the total quantity released, and the physical state of the material. Source models are constructed from fundamental or empirical equations representing the physico–chemical processes occurring during the release of materials.[17,18]

Several basic source models are available, each applicable to the particular release scenario: 1) flow of liquids through a hole, 2) flow of liquids through a hole in a tank, 3) flow of liquids through pipes, 4) flow of vapor through holes, 5) flow of vapor through pipes, 6) flashing liquids, and 7) liquid pool evaporation or boiling. Problem parameters come into play in determining the amount of release or rate of release. The purpose of the source model is to determine the form of material released (solid, liquid, or vapor); the total quantity of material released, and the rate at which it is released. This information is required for any quantitative dispersion model study, as now described.

Contaminant Dispersion Models

Dispersion models describe the airborne transport of materials away from the accident site. After a release, the airborne material is carried away by the wind in a characteristic plume or a puff. The maximum concentration occurs at the release point (which may or may not be at ground level). Concentrations downwind are less because of the turbulent mixing and dispersion of the substance with air. A wide variety of parameters affect atmospheric dispersion of toxic materials: 1) wind speed; 2) atmospheric stability; 3) ground conditions, buildings, water, trees; 4) height of the release above ground level; and 5) momentum and buoyancy of the initial material released.

Two types of vapor cloud dispersion models are commonly used: the plume and puff models. The plume model describes the steady-state concentration of material released from a continuous source. The puff model describes the temporal concentration of material from a single release of a fixed amount of material. Models are available that permit concentration (kg/m^3) and volumetric concentration percent (%) to be calculated at location (x, y, z) as a function of time (t) after initial release. It is important to determine if the mixture is within the flammability limits at a nearby ignition source, in the case of fuel release. Useful sources of information include Refs. 17–21. Sprays of liquid droplets and particles may be handled via computation of particle trajectories, including air resistance and wind effects.[22,23]

Ignition

Fuels

This side of the fire triangle is actually burned or reduced. Fuel comes in at least three physical states: solid, liquid, and gas.

1) Solid: Retains its shape and volume, is virtually incompressible, and does not flow.

2) Liquid: Assumes the shape of the portion of the container and does not expand to fill the container. Liquids are also virtually incompressible, and flow readily.

3) Gas: Gas assumes both shape and volume of container, is compressible, flows readily, and diffuses rapidly.

Solids and liquids do not burn. Only a vapor of a fuel will burn. A solid or liquid must be vaporized by being heated to its boiling point, which is the temperature at which vapor pressure equals the external pressure. Also, solids or liquids composed of fine particles vaporize faster than those composed of larger particles.

Physical Properties of Fuels

The following are some basic physical properties of fuel.

1) Flash point: The minimum temperature at which a liquid fuel gives off sufficient vapors to form an ignitable mixture with air near the surface. At this temperature vapors will flash but will not continue to burn.

2) Fire point: The temperature at which a liquid fuel will produce vapors sufficient to support combustion once ignited. The fire point is usually a few degrees above the flash point.

3) Ignition temperature: The minimum temperature to which a fuel in air must be heated to start self-sustained combustion independent of the heating source. This is also called the autoignition temperature, or self-ignition temperature.

4) Flammable or explosive limits: The percentage (usually by volume) of a substance in air that will burn once ignited. Most substances have both an upper (rich) and a lower (lean) flammable (explosive) limit. Either too much or too little fuel vapor in the air mixture can prevent burning. There is a wide range of fuels with different flammable limits, which may change with the weather, or the purity of the fuel. Higher temperatures and/or higher pressures generally increase the range over which a given fuel–air mixture is capable of being burned.

The water solubility, toxicity, and reactivity of the fuel must be considered in planning the extinguishment of a fire. The motion of a fuel in water or air may be predicted using its specific gravity or vapor density. Will it seek a low point on the ground or will it rise into the air? Will it sink or float on water?

1) Water solubility: A measure of how well a substance will mix with a given volume of water.

2) Toxicity: A measure of how poisonous a substance will be to a person of a given weight.

3) Reactivity: How a substance will react when combined with another substance.

4) Specific gravity: The weight of a solid or liquid compared with an equal volume of water.

5) Vapor density: The weight of a volume of gas compared with an equal volume of air.

Table 1 lists some of the basic properties of flammable liquids, gases, and solids, with further information available in Carroll.[41]

Heat Transfer

Heat is the third side of the fire triangle. Temperature is the measure of the molecular motion in matter. The faster the molecules move, the higher the temperature and the more energy is given off in the form of heat being transferred.

The law of heat flow states that heat will flow from a hot object to a cooler object. The greater the difference in the temperature between the two objects, the faster the heat will flow. The molecules do not actually move from one object to another. Only the kinetic energy of the motion of the molecules is transferred from object to object. Heat may be transferred in four ways (where the fourth item is actually a combination of the first three items):

1) Conduction: Heat conducted from one body to another through direct contact of the bodies or by contact with an intervening heat-conducting medium, like heating one end of a steel bar while holding the other end.

2) Radiation: Heat transmission by rays, such as the heat from the sun.

3) Convection: Heat transmission by the movement of air or liquid. As air is heated, it expands, becomes lighter, and rises, such as the air above a lighted match.

4) Direct flame contact: The direct application of flame to the object being heated, like touching a burning match.

Heat Source Groups

There are four basic heat source groups:

1) Electrical: Resistance heating, dielectric heating (pulsating dc current or high frequency ac); induction heating (current flow caused by a magnetic field); static electricity; electrical sparks.

2) Mechanical: Friction, compression, mechanical sparks.

3) Chemical: Heat of combustion (heat generated by oxidation), spontaneous heating (heating of an organic substance), heat of solution (combining of chemicals), heat of decomposition (heat released by the decomposition of a chemical composition).

4) Nuclear: Fission (breaking apart of atoms), fusion (the putting together of atoms to form new atoms).

Chemical Chain Reaction

This is the side that converts the fire triangle into a fire tetrahedron and produces flame. In combustion, this is the least understood of the proportions. A reaction involving the breaking down of chemical compounds into new compounds is believed to take place at the interface of the flame and the fuel. Parts of molecules called free radicals are left over from this reaction. It is the formation and movement of these radicals in forming the new compounds that produces flame.

Spontaneous Ignition (Self-Heating)

Some very reactive or pyrophoric materials have ignition temperatures below normal temperatures, and can ignite in air under certain circumstances. These materials include plutonium, uranium, thorium, zirconium, magnesium, hafnium, calcium, potassium, sodium, hydride of phosphorous, and hydride of silicon.

Many vegetable oils have oxidation rates, at normal temperatures sufficient to produce some heat. When the oxidation rate is increased by increasing the exposed surface area, e.g., oil-soaked rags, and the heat produced is confined (more rags piled on top), ignition can occur. Vegetable oils are particularly susceptible. Particular examples from high to low reactivity include: linseed, tung, hemp, poppyseed, sunflower seed, tobacco seed, soybean, corn, cottonseed, rape seed, and castor.

Biological action in moist, bulky, well-insulated piles of hay or grain can also produce heat sufficient for ignition. Also, note that, when stored at elevated temperatures in piles, the following materials can self-heat to their ignition temperatures: cellulosic fiberboard, glass fiber insulation, foam rubber, and polyurethane foam.

Fire Development

Several of the cited references address the topic of fire development, see, e.g., Refs. 9, 12, 24–27.

Classes of Fires

All fires are not alike. Fires can be placed into one of four classes, depending on what is burning or involved in the fire. These classes are as follows:

1) Class A: Involve normal combustibles (paper, wood, etc.).

2) Class B: Involve the flammable liquids (gasoline, fuel, oils, etc.). This class can be further broken down depending on the flash point of the liquids involved.

Class 1 flammable liquids: Flash point below 38°C (100°F), with vapor pressure not exceeding 275 kPa at 38°C (40 psia at 100°F).

Class 1A: Flash point below 23°C (73°F) with boiling point below 38°C (100°F).

Class 1B: Flash point below 23°C (73°F) with boiling point at or above 38°C (100°F).

Class 1C: Flash point above 23°C (73°F), but below 38°C (100°F).

Class 2 combustible liquids: Flash point at or above 38°C (100°F).

Class 2: Flash point at or above 38°C (100°F), but below 60°C (140°F).

Class 3A: Flash point at or above 60°C (140°F), but below 93°C (200°F).

Class 3B: Flash point at or above 93°C (200°F).

Class C: Fires involving energized electrical equipment, such as power poles, transformers, etc.

4) Class D: Fire involving the flammable metals group, such as titanium, phosphorus, etc.

When a fuel is burned, it is broken down and combined with the oxygen in the air to form new compounds. The elements that are burned are not destroyed in the burning process, only altered. These new compounds are called the products of combustion. The most common products of combustion from wood burning are water vapor, smoke (carbon particles), carbon monoxide (CO), carbon dioxide (CO_2), and two forms of energy: light (the flame) and heat (molecular motion).

Extension of the Fire

Extension describes the way a fire spreads within the fire building. There are three normal avenues of extension:

1) Vertical extension: This is fire movement in an upward direction. This is normally the first direction that a fire will go. This is the direction of least resistance because there is not only direct flame contact, radiation, and conduction transferring the heat, but also convection moving the heated gas upward via buoyancy.

2) Horizontal extension: This is fire movement in the same plane as the fire, in a sideways direction.

3) Downward extension: This is normally the last action that the fire will move. This type of extension is usually caused by falling embers or a structural collapse.

Phases of a Structural Fire

Fires in a single room environment are simply characterized by how much is burning and how furiously is it burning.

1) Growth period: Preflashover stage in which the average temperature is low and the fire is localized and in the vicinity of the origin.

Table 1 Properties of flammable liquids, gases, and solids

Name	Flash point, °F		Explosive limits in air, vol. %		Autoignition temperature, °F	Specific gravity (water = 1)	Vapor density (air = 1)	Melting point, °F	Boiling point, °F
	Closed cup	Open cup	Lower	Upper					
Acetone	0	15	2.1	13.0	1000	0.788	2.00	−137	134
Acetylene (air mixture)	Gas	Gas	2.5	81	571	0.621	0.91	—	−119
Asphalt (typical)	400+	535+	—	—	905	0.95–1.1	—	180–220	>700
Automotive gas (premium)	−50±	—	1.3–1.4	6.0–7.6	700	0.71–0.76	3.0–4.0	<−76	91
Automotive gas (regular)	−50±	—	1.3–1.4	6.0–7.6	700	0.70–0.75	3.0–4.0	<−76	91
Benzene	12	—	1.4	8.0	1044	0.885	2.77	42	176
Brake fluid (heavy duty)	—	220	—	—	—	—	—	—	—
Butane, n-	−76	Gas	1.9	8.5	761	0.584	2.06	−217	31
Butane, iso-	−117	Gas	1.8	8.4	864	0.563	2.06	−255	11
Camphor	150	200	0.6	3.5	871	0.999	5.24	345	399
Camphor oil (light)	117	125	—	—	—	—	—	—	347
Carnauba wax	540	595	—	—	840	0.96	—	14	595
Charcoal	—	—	—	—	—	3.51	—	>6300	7600
Coal tar oil	60–77	—	1.3	8.0	—	<1.0	—	—	—
Coal tar pitch	405	490	—	—	—	<1.0	—	—	—
Corn oil	490	490	000	000	740	0.92	—	14	—
Cottonseed oil (refined)	486	550	—	—	650	0.925	—	23–32	—
Creoaote oil	165	185	—	—	637	>1.0	—	—	392
Denatured alcohol, 95%	60	—	—	—	750	0.82	1.60	−60	175
Dry cleaning (naphtha)	100–110	—	0.8	5.0	440–500	0.8	—	<−50	300
Dry cleaning solvent naphtha, 140°F	138	—	0.8@302°F	—	451	—	—	—	<358
Ethyl alcohol	55	71	3.5	19	737	0.791	1.59	−173	173
Ethylene	−185	—	2.7	34	842	0.566	0.975	98	469
Fish oil	420	—	—	—	—	—	—	—	—
Formaldehyde gas	Gas	Gas	7	73	806	—	1.07	−134	−6
Fuel oil no. 1	114–185	—	0.6	5.6	445–560	0.78–0.85	—	—	340
Fuel oil no. 1-D	>100	—	1.3	6.0	350–625	<1.0	—	—	<590
Fuel oil no. 2	126–230	—	—	—	500–705	0.80–0.90	—	—	340
Fuel oil no. 2-D	>100	—	1.3	6.0	490–545	0.81	—	—	380
Fuel oil no. 4	154–240	—	1	5	505	0.84–0.98	—	—	425
Fuel oil no. 5	130–310	—	1	5	—	0.92–1.06	—	—	—
Fuel oil no. 6	150–430	—	1	5	765	0.92–1.07	—	—	—
Gas, natural, 103 Btu	Gas	Gas	3.8–6.5	13–17	>1000	—	0.61	—	—
Gasoline, aviation, commercial	−50±	—	1	6.0–7.6	800–880	0.70–0.71	3.0–4.0	<−76	108
Jet fuel, JP-4 referee	<34	—	—	—	—	0.785	—	<−76	144
Jet fuel, JP-5	105	—	0.6	4.6	400	0.82–0.835	—	<−40	370
Jet fuel, JP-6	127	—	—	—	500	—	—	—	250
Kerosene	110–130	—	0.6	5.6	440–560	0.81	4.5	—	350
Lacquer	0–80	—	—	—	—	—	—	—	—
Lard oil (commercial)	395	—	—	—	833	<1.0	—	28	—
Linseed oil (boiled)	403	—	—	—	—	—	—	—	—
Linseed oil (raw)	435	535	—	—	650	0.93	—	−2	600+
Lubricating oil (mineral)	—	275–500	—	—	500–700	0.83–0.90	—	—	680
Methane	Gas	Gas	5.3	13.9	999	—	0.554	−296	−259
Mineral spirits	100	110	0.77@212°F	6.0	475	0.80	3.9	—	300
Olive oil	>437	—	—	—	650	0.910	—	21	—
Paint liquid	0–80	—	—	—	—	—	—	—	—
Petroleum, crude	20–90	—	—	—	—	0.78–0.97	—	—	—
Propane	<−156	Gas	2.2	9.6	871	0.508	1.56	−306	−44
Rosin, gum	370	430	—	—	—	1.08	—	212–300	—
Rubber cement	<50	—	—	—	—	—	—	—	110
Soybean oil	250–600	—	—	—	833	0.9	—	10–25	—
Sulfur	405	440	—	—	450	2.046	—	234	832
Tallow	509	—	—	—	—	0.895	—	88–100	—
Transformer oil	—	295	—	—	—	0.9	—	—	—
Tung oil	552	—	—	—	855	0.936–0.943	—	88	—
Turpentine, spirits of	95	115	0.8	—	488	0.854–0.868	4.84	—	309
Varnish	10–80	—	—	—	—	—	—	—	—
Varnish shellac	40–70	—	—	—	—	—	—	—	—
Vegetable oil, hydrogenated	—	610	—	—	—	<1.0	—	—	—
Whiskey	82	—	—	—	—	—	—	—	—
Wines, high	60–80	—	—	—	—	—	—	—	—

2) Fully developed fire period: Postflashover stage in which all combustible items are involved and flames appear to fill the entire volume.

3) Decay period: Formally identified as that stage of the fire after the average temperature has reduced to 80% of its peak value.

It is to be noted that the occurrence of the fully developed fire is critical to important events. A person who has not escaped a compartment before flashover is unlikely to survive. There is now a severe threat to neighboring compartments or adjacent buildings, and structural damage will ensue.

Table 2 Major factors influencing fire growth

Realm	Approximate ranges of fire sizes	Major factors that influence growth
1 (Preburning)	Overheat to ignition.	Amount and duration of heat flux. Surface area receiving heat. Material ignitability.
2 (Initial burning)	Ignition to radiation point [10 in. (254 mm) high flame].	Fuel continuity. Material ignitability. Thickness. Surface roughness. Thermal inertia of the fuel.
3 (Vigorous burning)	Radiation point to enclosure point [10 in. to 5 ft high flame (254 mm to 1.5 m)].	Interior finish. Fuel continuity. Feedback. Material ignitability. Thermal inertia of the fuel. Proximity of flames to walls.
4 (Interactive burning)	Enclosure point to ceiling point [5 ft (1.5 m) high flame to flame touching ceiling].	Interior finish. Fuel arrangement. Feedback. Tallness of fuels. Proximity of flames to walls. Ceiling height. Room insulation. Size and location of openings. HVAC operation.
5 (Remote burning)	Ceiling point to full room involvement.	Fuel arrangement. Ceiling height. Length/width ratio. Room insulation. Size and location of openings. HVAC operations.

A sequence of events follow after ignition of furniture in a room, including events immediately after ignition, the plume–ceiling interaction, the ceiling jet–wall interaction, the fully enclosed space with developed growing upper layer, and further smoke filling. Cooper[28] elaborates at length about this fire development, and adjacent rooms may also participate (delivering fresh air and receiving smoke). But prior to this interdependent smoke-filling process of the two or more rooms, the event sequence of a one-room fire is still relevant to the early development within the fire room itself, especially when its doors and windows are essentially closed. Table 2 identifies major factors influencing fire growth.[2]

Five phases of a general fire are identified:

Phase 1. Incipient or beginning phase of the fire: oxygen content 20–21%, ceiling temperature ~100°F; products of combustion primarily water vapor, CO_2, SO_2, and smoldering start may last a few seconds to many hours before the fire breaks into flames, producing a large amount of smoke until flames appear, and progress rapidly after the flames start.

Phase 2. Flame-producing phase: oxygen content down to 15–19%; ceiling temperature ~1300°F; products of combustion primarily H_2O, H_2, CO_2, CO, and SO_2; and large quantities of dark gray smoke, rapid destruction, and the possibility of flashover (thermal radiation feedback from the ceiling and upper walls), which can make the entire room contents suddenly erupt into flame. (This radiation feedback gradually heats the contents of the fire area. When all of the combustibles in the space have become heated to their ignition temperature, simultaneous ignition occurs, and the flame area spreads.)

Phase 3. Smoldering: oxygen content <15%; ceiling temperature >1000°F; products of combustion H_2O, H_2, CO_2, CO, and SO_2; dense dark flammable smoke and gases; flammable fuel vapors distilled and collecting; little flaming combustion; and the possibility of backdraft (an explosion caused by the sudden introduction of oxygen into a highly heated very flammable atmosphere). [Visible indicators of imminent backdraft include little flame, high temperature, smoke under pressure (may puff or breathe, smoke color is very dark and dirty or yellow gray just prior to backdraft.)]

Phase 4. Steady-state, fully evolved fire condition, with a sufficient supply of air to feed oxygen to the fire and carry away the products of combustion.

Phase 5. Clear burning, high temperatures and complete combustion, with thermal columns. This normally occurs with high airspeeds at the base of the fire.

Burning Rates

Data are available for heat release rate vs time for many items, see, e.g., Refs. 3 and 29. Furniture calorimeter and cone calorimeter measurements are available, with data specifically for pools (liquid or plastic), cribs (regular array of sticks), wood pallets, upholstered furniture, mattresses, pillows, wardrobes (closets), television sets, Christmas trees, curtains (drapes), electric cable trays, trash bags and containers, and industrial rack-stored commodities.

Full-scale furniture calorimeter tests give useful information on the burning rates of many typical household items. Peak heating values are particularly useful to know, because in some cases, a triangular heat release rate vs time representation can be utilized for simplicity. Upholstered furniture, e.g., wood frame, with fire-retardant polyurethane padding and olefin cover fabric, show peak heat release rates as follows: F21 chair = 2100 kW at 260 s, F31 loveseat = 2886 kW at 230 s, and F32 sofa = 3120 kWat 215 s. The F number used here corresponds to the particular experiment performed.[29] Other useful data (to help characterize the heat energy output vs time) include peak heat release rate and the time of its occurrence from the start of ignition, for a variety of items: mattress and boxspring = 660 kW at 910 s; curtain, cotton, 1.87 kg = 240 kW at 175 s; wastepaper basket, 0.93 kg = 15 kW at 350 s; television, 39.8 kg = 290 kW at 670 s; cooking oil, corn, cottonseed, etc., 12-in. pan = 116 kW const; and Christmas tree, spruce, 7 kg = 650 kWat 350 s. The values help to visualize the differences between the items under burning conditions.

Of special concern in fire investigation and computer reconstruction of building fires is the use of accelerants. Liquid fuels are often preferred. They are used to accelerate the development of the fire, as indicated by temperature and spreading rates. On the practical investigative side, features often include low burns, high temperatures at low hidden locations, rapid house-fire development, and particular flame and smoke colors seen by witnesses. Burning rates of liquid pool fires are available in Ref. 3.

Radiant Ignition of Nearby Items

The preceding text has provided information about the burning rate (heat release rate vs time) of a single specified item in the burn room. What happens next? Either the item burns out without further damage to the surroundings, or one or more nearby items ignite and add fuel to the fire. This can be by direct flame contact (if the second item is sufficiently close) or, more usually, by radiant heat energy becoming sufficiently large on the surface of the second item. Direct flame contact requires time to pyrolyze the fuel and time to heat the gases produced to their ignition temperature. The radiant flux ignition problem is a very complicated issue and depends on many factors. The radiant energy comes from the flame above the first item, the upper layer and room surfaces, but simplifying assumptions are sometimes used. As the radiant energy flux rate increases from the first item to the second, often a simple criterion for ignition of the latter is used. A good approximation[3] is that the radiant heat flux (arriving on the surface of the second item) necessary to ignite the second item is the following:

1) 10 kW/m^2: Easily ignitable items, such as thin curtains or loose newsprint.

2) 20 kW/m^2: Normal items, such as upholstered furniture.

3) 40 kW/m^2: Difficult to ignite items, such as wood of 0.5 in. or greater thickness.

The peak mass loss rate of the first item (upholstered furniture) vs ignition distance capability is given in the documentation of Bukowski et al.[29] These data have been deduced from a variety of experimental results. As an example, note that an upholstered chair has a peak burning rate of about 80 gm/s (mass) or 2100 kW (energy), which is associated with the ignition of easy, normal, and difficult to burn items igniting at distances of 1.5, 1, and 0.5 m, respectively.

Flashover and Backdraft

Flashover and backdraft are two important events that may occur in the course of a fire.[6,12]

Flashover is characterized by the rapid transition in fire behavior from localized burning of fuel to the involvement of all combustibles in the enclosure. High radiation heat transfer levels from the original burning item, the flame and plume directly above it, and the hot smoke layer spreading across the ceiling are all considered to be responsible for the heating of the other items in the room, leading to their ignition. Warning signs are heat buildup and rollover (small, sporadic flashes of flame that appear near the ceiling level or at the top of open doorways or windows of smoke-filled rooms). Factors affecting flashover include room size, ceiling and wall conductivity and flammability, and the heat- and smoke-producing quality of room contents. Water cooling and venting of heat and smoke are considered to be ways of delaying or preventing flashover.

Backdraft is defined to be an instantaneous explosion of smoke blasting back through a door or window (a combustion explosion). Increased observation of backdrafts in recent years has resulted from buildings being more tightly sealed and better insulated, increased use of energy-efficient double-glazed windows, and more synthetic materials being used in furnishings. Backdrafts can occur when large quantities of CO build up as a result of incomplete combustion (and oxygen is then introduced), and when smoldering exists (during early and late stages of a fire's growth). Warning signs include thick smoke puffing and pushing out of windows and doors, reverse flow of smoke after venting, thick dark brown or black smoke indicating unburned gas buildup, and discoloration of window glass. Defensive operations include venting from above (to release hot smoke and gases upward), quenching the fire (resulting in lowering the temperature of the fire), and flanking the fire (standing aside to be out of the way of a direct explosion path).

Differences between flashover and backdraft phenomena can be briefly summarized as follows: Flashovers entail rapid combustion without explosion, are caused by heat buildup, and occur only in the early (growth) stage of a fire's growth. Backdrafts entail blast-blowing smoke, are caused by the introduction of air, and occur in early (growth) and late (decay) stages of a fire's growth.

Flashover Determination

Often the determination of whether or not flashover is expected is the single most important fire computation. This topic is addressed specifically in Drysdale[12] and Thomas et al.[30]

1) Simple approach: At flashover about 50% of fire output goes to heat losses, and the minimum fire heat release rate in kW is

$$\dot{q}_{f0} = 750 A_0 H_0^{1/2}$$

where A_0 is the window or door ventilation area (m^2) and H_0 is the height of opening (m).

2) Improved approach: Recent evaluation and comparison of improved estimates has led to an expression for the minimum fire heat release rate in kW at flashover as

$$\dot{q}_{f0} = 378 A_0 H_0^{1/2} + 7.8 A_w$$

where A_w is the total enclosure conducting wall surface area (m^2).

3) In practice it has been observed that flashover occurs when the upper room temperature of the smoke layer reaches between 300 and 700°C (572 and 1292°F). It depends on many factors, but a lower temperature should be used if one wishes to obtain a conservative safe estimate of the amount of time available before its occurrence.

Flashover is characterized by the following:

1) Temperatures reach ~500°C (932°F) to 600°C (1112°F) in the upper portions of the room.

2) Heat flux of from 25 kW/m^2 (7925 Btu/h ft^2) to 25 kW/m^2 (7925 Btu/h ft^2) occurs at floor level, with near-simultaneous ignition of combustibles not previously ignited.

3) The filling of almost the entire room volume with smoke and flames.

Generally, very high heat release rates occur after flashover, and (subject to oxygen availability) most ignitable items in the room burn, it gets very hot, and the windows break and melt. The open window permits more oxygen to be made available and thereby increases the severity of the fire.

Fully Developed Fires

Two cases arise: ventilation-limited (relatively small opening to permit only modest oxygen inflow) or not ventilation-limited (large opening permitted more than enough oxygen to flow in). Information, equations, and data are available in Refs. 2 and 3, from which calculations can be made. The following details are specific to typical house fires, burning typical contents.

Ventilation Limited Fires

If ventilation-limited (usual case), the heat release rate depends on the availability of oxygen:

$$m_{\text{fuel}} = K A_0 H_0^{1/2}, \qquad \dot{q} = (12{,}000) K A_0 H_0^{1/2}$$

where m_{fuel} is the burning rate of fuel (kg/s), K is the parameter generally between 0.09 and 0.12, A_0 is the area of opening (m^2), H_0 is the height of opening from top to bottom (m), and $\dot{q}$ is the heat release rate (kW).

Here, the net heat of combustion of typical room-burning objects has been taken as 12,000 kJ/kg. As an example, and taking $K = 0.12$, a window 1 m wide × 2 m high would permit, at most, a heat release rate of $\dot{q} = 4073$ kW, because of severely limited oxygen inflow.

Nonventilation Limited Fires

If not ventilation-limited, there is more than adequate oxygen available, and the heat release rate depends on the fuel burning rate. Then, a simple approach is to assume that typical household wood furniture burns to completion in 20 min at a uniform rate, so that a room fire load of 100 kg, for example, has a heat release rate of $\dot{q} = 1567$ kW, occurring during the 20-min postflashover period. Typical fire loads of ordinary combustibles in homes are[2] living room = 18.25 kg/m^2, family room = 12.64, bedroom = 20.12, dining room = 16.85, and kitchen = 14.98 (with standard deviations of about 25%). As an example: a living room of area 12 m^2 has about 219 kg of ordinary combustibles that could burn in 20 min at $\dot{q} = 3432$ kW, if enough air is available. This is a continuous high heat evolution rate.

Fire Control Methods

Fire requires a very delicate balance. Therefore, the extinguishment of a fire can be accomplished by the interruption of one of the sides of the fire tetrahedron or the fire triangle, depending on whether the fire is producing flame or only smoldering. The most common types of extinguishment are as follows:

1) Removal of the fuel: May be accomplished by pulling the fuel away or possibly turning off gas or liquid fuel flowing from a valve.

2) Temperature reduction: The most common method, accomplished by applying water to cool the fuel and atmosphere.

3) Dilution of the oxygen: Smothering the fire by either covering the fuel to shut out oxygen or by displacing the oxygen with something else, such as carbon dioxide.

4) Stopping the chain reaction: Applying extinguishing agents that work by either stopping or inhibiting the chemical chain reaction.

Fire Environment

Experimental Measurements

As an example of experimental work that has been able to assist in understanding fire behavior in structural fires, a house in Woodward, Oklahoma was selected (with appropriate permission) for a complete burn. Videotapes, slides, and internal temperatures were taken during the fire. The house was fully furnished with furniture and a large amount of old clothes in the closets and attic areas. Fire began in the kitchen with only natural combustibles being used. A waste basket with crumpled paper was first ignited. Fire spread rapidly to an adjacent dry Christmas tree (about 7 ft tall), and then ignition of a wooden shelf unit occurred.

Fire rapidly spread to the living room and west porch area (aided by the open door). Events were recorded on videotape and a sequence of about 200 slides over the ensuing burn. Additionally 8 *K*-type thermocouples with ceramic fiber insulated wires were strategically located in the building. Temperatures up to 2507°F (1375°C) could be measured with high accuracy and without damage to the wires or insulation. Important events were observed as follows: (all units of measure are in minutes): ignition = 0, flames on front porch = 5, porch roof falls = 16, lots of flame at west end, west roof area collapses, and attic venting = 30, roof and all windows show flames = 37, all of roof now collapsed and black smoke = 45, and most walls down = 56.

Complete details about this house burn, temperatures measured, and computerized reconstruction are available in Lilley.[31] Related work includes room fires and temperature measurements,[6] and a complete small house burn in Tulsa, Oklahoma.[32] Again, slides, videotape, and temperature measurements are available from these experiments.

Combustion Products

Inhalation of fire gases (toxic products of combustion) is the major cause of death in fires. There are three basic classes of toxicant gases: 1) asphyxiants (narcosis-producing toxicants), 2) irritants (may be sensory or pulmonary), and 3) toxicants exhibiting other or unusual specific toxicities. From all toxicants only carbon monoxide and hydrogen cyanide have been measured in sufficient concentrations in fire gases to cause significant acute toxic effects, depending on the concentration and exposure time. Table 3 summarizes the effect of common toxic products of combustion; also see Refs. 2, 3, and 16. Briefly, the common toxic gases of concern in fires from natural and man-made (plastic) fuels are carbon monoxide, carbon dioxide, hydrogen cyanide, hydrogen sulfide, sulfur dioxide, ammonia, hydrogen chloride, phosgene, acrolein, and oxides of nitrogen. The most important toxic gas is CO, which is produced in fires whenever oxygen is in short supply, resulting in incomplete combustion. Although CO is not the most toxic of gases in terms of the effects of a particular concentration, it is always one of the most abundant and, therefore, is the major threat in most fire atmospheres.

The toxicity of CO is primarily because of its affinity for the hemoglobin in blood, resulting in the formation of carboxyhemoglobin (COHb) and a decreased capacity of the blood to transport oxygen to body tissues (hypoxia). The CO content of blood can readily be measured and is expressed as percent COHb saturation. The actual blood COHb saturation levels associated with both incapacitation and death vary quite widely over the general population, and depend on many factors. In terms of CO concentrations required to reach hazardous COHb levels, a simple rule of thumb may be used. Any exposure in which the product of concentration (ppm) × time (minutes) exceeds ~35,000 ppm-min is likely to be dangerous. For example, a 10-min exposure to 3500 ppm of CO would be expected to be hazardous and possibly incapacitating to many people. At higher concentration levels, a lower product of ppm-min appears to be needed.

Fire Modeling

Mathematical Modeling

The mathematical modeling approach to simulating fire development in a multiroom building complements the experimental approach and/or postfire on-site investigations. Fire simulation models provide estimates of the amount and temperature of the smoke layer produced, the evolution of toxic gases, and the amount of time available from the onset of fire for the safe departure of occupants. Its results can be used to determine the key features of the fire evolution and the corresponding danger to occupants.

Table 3 Effects of common toxic products of combustion

Product of combustion	Exposure effect
CO	10,000 ppm exposure fatal within 1 min.
CO_2	70% concentration fatal within several minutes.
HCN	450 ppm causes death in 9 to 13 min (animal test results).
H_2S	400–700 ppm dangerous in 30 min.
SO_2	500 ppm exposure fatal in 10 min.
NH_3	1000 ppm exposure fatal in 10 min.
HCl	1500 ppm exposure fatal within several min.
$COCl_2$	25 ppm fatal within 30 min.
CH_2CHCHO	30–100 ppm fatal within 10 min.
NO_x	200 ppm fatal within 10 min.

Software is available with data, procedures, and computer programs, which simulate important time-dependent phenomena, involved in residential fires. Based on sound scientific and mathematical principles, predictions are made of the production of energy and mass (smoke and gases) by one or more burning objects in one room, based on small- or large-scale measurements. The buoyancy-driven transport of this energy and mass through a series of user-specified rooms and connections is then computed (doors, windows, cracks, etc.). The resulting temperatures, smoke optical densities, and gas concentrations (after accounting for heat transfer to surfaces and dilution by mixing with clean air) are linked to the problem of egress. The evacuation process of a set of occupants may be simulated, accounting for delays in notification, decision making, behavioral interactions, and inherent capabilities.

Empirical Temperature Assessment

Information is available[2] that provides simple, easy, quick, rule-of-thumb estimates of typical room fire temperature estimates. Focusing on the upper layer gas temperature, T_u, it has been found experimentally under preflashover conditions that

$$T_u = T_0[1 + 0.0236\dot{q}^{2/3}/(h_k A_w A_0 H_0^{1/2})^{1/3}]$$

where T_u is the upper layer gas temperature in degrees K (=°R/1.8), T_0 is the ambient temperature = 290 K (62°F), A_w is the total enclosure conducting wall surface area (m^2), A is the vent area (m^2), and h_k is the effective heat transfer coefficient for gypsum wall board walls during early stages of the fire.

After flashover, an empirical equation has been suggested[2] that gives the upper layer gas temperature to be less than 1725 K (1452°C, 3105°R, or 2645°F) via

$$T_u = T_0 + (1725 - T_0) \cdot \theta_1 \cdot \theta_2 \cdot \theta_3 \cdot \theta_4 \cdot \theta_5$$

where the θ multipliers (each <1) account for burning rate equivalence ratio, wall steady-state losses, wall transient losses, opening height effect, and combustion efficiency, and these values are deducible from figures given in Ref. 2.

Special-Purpose Models

These computer codes provide special-purpose analysis, such as structural fire resistance, prediction of response time of heat detectors and automatic sprinklers, egress design for building occupants, and the performance of smoke control and ventilation systems. These include the following:

1) ASCOS (analysis of smoke control system): for steady airflow analysis of smoke control systems.

2) DETACT-QS: for calculating the actuation time of thermal devices below unconfined ceilings.

3) EVACNET+ (evacuation network computer model): models emergency building evacuation.

4) FASBUS-II (fire analysis of steel building system): a finite element model designed to analyze the structural response of steel framed floors exposed to fire conditions.

5) FIRES-T3 (fire response of structures, thermal, 3-D version): a finite element computer model designed to analyze heat transfer through structural assembles.

6) FASTLite/FPETool (fire protection engineering tool): a collection of small computer codes related to fire protection.

Deterministic Models

Deterministic models represent the fire process by interrelated mathematical expressions based on principles of chemistry and physics. They are also called room fire models, computer fire models, and mathematical fire models. Deterministic models are subdivided into two categories:

1) Field models: These are not well-developed, they solve the fundamental partial differential equations of mass, momentum and energy at each point of a fine grid covering the solution domain.

2) Zone models: These are well-developed and solve the conservation equations for distinct regions or control volumes.

These are now described in greater detail.

Field Models

Field models of fire development in structures directly involve the fully three-dimensional time-dependent partial differential equations of conservation. Equations are solved for mass, momentum, energy, and species at each of the many points of a fine grid covering the entire volume of the interior of the structure. In this way, values are permitted to vary from point-to-point within each room, and from room-to-room. Thus, these models have the capability of very accurate solution of the equations, and hence, accurate simulation of the events. But mixing laws that are incorporated, etc., are in doubt and many fine phenomena are not addressed adequately in the mathematical models. Additionally, computational demands are very large, and correct simulation ultimately depends on the empirical specification of factors such as ignition, burning rates, fire spread, ventilation-limitation, etc. At this time, field models are not well developed for the simulation of structural fires, and zone methods are currently preferred.

Zone Models

Zone models solve the conservation equations for distinct regions (control volumes). A number of zone models exist, varying to some degree in the detailed treatment of fire phenomena. The dominant characteristic of this class of model is that it divides the room(s) into a hot upper layer and a cooler lower layer. The model calculations provide estimates of key conditions for each of the layers as a function of time. Zone modeling has proved to be a practical method for providing first-order estimates of fire processes in enclosures. A number of zone type enclosure fire models are in the public domain. These include the following:

1) ASET (available safe egress time): For calculating the temperature and position of the hot smoke layer in a single room with closed doors.

2) ASET-B: A compact version of ASET.

3) COMPF2: For calculating the characteristics of a post flashover fire in a single room based on fire-induced ventilation through a single door or window.

4) FAST (fire and smoke transport): A multiroom fire model to predict the conditions within a structure resulting from a user-specified fire.

5) HARVARD: Predicts the development of a fire and the resulting conditions within a room or multiple rooms, resulting from a user-specified fire.

6) OSU (Ohio State University compartment fire model): For calculating heat release rate, smoke-generation rate, and smoke and heat venting from a single compartment.

7) HAZARD-1: A generalized fire hazard assessment method for microcomputers using a version of FAST, with Version 1.2 allowing up to 15 rooms; multiple fires; heating, ventilating, and air-conditioning connections; and ceiling and floor venting.

One noteworthy multiroom zone-type computer program was code-named FAST (an acronym for fire and smoke transport). It is a multicompartment zone-type computer model to predict the temperature, heat transfer, and smoke hazard development in each compartment of a multiroom building, based on a description of the compartments and the type and location of the fire.[33,34] In a recent report,[35] predictions showed that FAST can approximate the test measurements closely for a small fire. Three test cases were simulated by FAST on a personal computer, and tabulated and graphic outputs are included. One-, three-, and five-room building fires were predicted with ramp heating rate and four different constant heat fires in all cases. Results were compared favorably with available experimental data from Cooper[36] and Cooper et al.[37]

The ASET-B computer code was used by Lilley[38] to investigate parameter effects on the rate of upper-layer temperature rise and upper-layer smoke height as functions of time. Recently, the HAZARD-1 computer code,[29] has been extensively used by Lilley,[31] and current work is involved with its application to the development and spread of fires in buildings. The latest microcomputer version of the code can handle buildings with up to 15 areas, multiple fires, HVAC connections, and ceiling and floor venting. This code is a generalized version of the earlier program, with user-friendly input and output, and a useful database of experimental properties to be used in the calculations. The latest version (Version 1.2) is described in Peacock et al.[39]

The software consists of data, procedures, and computer programs, which simulate important time-dependent phenomena involved in residential fires. The prediction procedures are based on sound scientific and mathematical principles, and include predictions of the production of energy and mass (smoke and gases) by one or more burning objects in one room, based on small- or large-scale measurements. The buoyancy-driven transport of this energy and mass through a series of user-specified rooms and connections (doors, windows, cracks, etc.) follows. The outcome is knowledge of the resulting temperatures, smoke optical densities, and gas concentrations after accounting for heat transfer to surfaces and dilution by mixing with clean air. The actions and fates of occupants are then considered. The evacuation process is established of a user-specified set of occupants accounting for delays in notification, decision making, behavioral interactions, and inherent capabilities. Prediction then ensues about the impact of the exposure of these occupants to the predicted room environments as they move through the building, in terms of the expected fatalities, and the time, location, and cause of each.

Fire Investigation

Fire and arson investigators examine and interpret postfire evidence to ascertain the origin and cause of fires.[5,8,25,40-44] Vehicle fires are discussed in Ref. 45. Electrical fires are considered in Ref. 46. Litigation aspects are addressed in Refs. 15 and 16.

Phenomena Associated with Fires

Witnesses to an in-progress fire will often have the opportunity to observe flames and smoke. The location, size, intensity, and material burning can be estimated from careful observations, with further information and tables given by Wieder et al.[9] For example, the color of smoke produced is related to the combustible that is being burned. Table 4 reveals the information. The flame color is related to local temperature, as shown in Table 5. Fire investigators also make use of knowledge about melted and puddled metal, the location of this evidence in relation to other factors can assist in locating the origin of the fire, and confirm deductions about the progress of the fire. Table 6 gives melting temperatures of various metals. Fire fighters, and on-scene fire investigators, will also gain further information by virtue of their sense of smell. Some odors are likely to be familiar. These include gasoline, kerosene, paint thinner, lacquers, turpentine, linseed oil, furniture polish, rubber insulation, natural gas, and manufactured gas. Other odors are more unusual, and include nitrocellulose = pungent, similar to camphor; phosphorus = wet match heads; carbon disulfide = rotten cabbage; gunpowder = burned firecrackers; sulfur candles = choking odor; ammonia = pungent; insect sprays = sweet or perfumed; and cyanide or hydrocynic acid gas = peach pits.

Table 4 Color of smoke produced by various combustibles

Combustible	Smoke color
Hay/vegetable compounds	White
Phosphorous	White
Benzene	White to gray
Nitrocellulose	Yellow to brownish yellow
Sulfur	Yellow to brownish yellow
Sulfuric acid, nitric acid, hydrochloric acid	Yellow to brownish yellow
Gunpowder	Yellow to brownish yellow
Chlorine gas	Greenish yellow
Wood	Gray to brown
Paper	Gray to brown
Cloth	Gray to brown
Iodine	Violet
Cooking oil	Brown
Naphtha	Brown to black
Lacquer thinner	Brownish black
Turpentine	Black to brown
Acetone	Black
Kerosene	Black
Gasoline	Black
Lubricating oil	Black
Rubber	Black
Tar	Black
Coal	Black
Foamed plastics	Black

Table 5 Flame color related to temperature

	Temperature	
Flame color	°F	°C
Faint red	900	480
Red (visible in daylight)	975	525
Blood red	1050	565
Dark cherry red	1175	635
Medium cherry red	1250	675
Cherry red	1365	740
Bright red	1550	845
Salmon red	1650	900
Orange	1725	940
Lemon	1825	995
Light yellow	1975	1080
White	2200	1205
Blue white	2250	1400

Table 6 Melting temperature of various metals

	Melting temperature	
Metal	°F	°C
Aluminum	1220	660
Brass	1570–1900	854–1037
Bronze	1290–1890	698–1032
Cast Iron	2000–2800	1093–1537
Chromium	2930	1610
Copper	1981	1082
Iron	2802	1538
Lead	621	327
Magnesium	1203	650
Nickel	2651	1455
Platinum	3224	1773
Silver	1761	960
Solder	361–482	182–250
Stainless steel	2462–2822	1350–1550
Steel	2552–2882	1400–1583
Tin	449	231
Zinc	786	418

Fire Facts

These fire facts will help determine the nature of the fire. If the fire has burned in ways differing from the norm, look for what made it burn in the unusual way. Campbell[47] goes into considerable detail about the origin and cause investigation, and how postfire investigation can assist in this determination. There are several fire facts to be aware of:

1) Fire language: Fire burns up and out. You also want to observe charring, soot and smoke deposits, what materials

were consumed, and the extent to which they were consumed, melting and distortion of the fire load, discoloration on metal, etc.

2) Least resistance: Fire follows the path of least resistance.

3) Depth of char: Measure it at a consistent height to show where the fire burned the hottest the longest. Depth of char varies widely and is dependent on such factors as rate of heating, length of heating, ventilation, type of fire load, moisture content, covering of the wood surface, and surface-to-mass ratio.

4) V-patterns: Always look for the original V patterns. Look for normal V patterns, inverted V patterns, hourglass patterns, and width of V patterns.

5) Holes in the floor.

6) Pour patterns: Recognize flammable or accelerant pour patterns.

7) Glass: Consider the fire effects on glass.

8) Fire load: The burn patterns on the furnishings may point to the point of origin.

9) Heat/smoke line: Pay attention to the heat/smoke line because it can show when the fire started by phases it indicates.

10) Underside burning: Look for burning on the underside of furniture or doors.

11) Containers: Look for containers of any kind where they shouldn't be.

12) Odors: Smell of flammables can give clues.

13) Trash: Unusual piles of trash, these may be records an arsonist wanted to destroy or fire load he planted.

14) Trailers: Look for trailers, consisting of flammable liquids, cloth, rags, rope, newspaper, towels or combinations of these items.

15) Multiple points of origin: These are especially important if they all appear to have original V patterns.

16) Liquids: Note the run down patterns.

17) Lack of personal effects.

18) Spalling of concrete.

19) Unusual items: Some of these may be part of an ignition device.

20) Annealing: Steel loses 90% of tensile strength at 1000°F.

21) Light bulbs: These tend to draw toward the point of origin or heat source; they warp at 900°F.

22) Steel Warp: I-beams and steel joists begin to warp.

23) Alligatoring: These are the char patterns on wood. The size of the blister on the wood will indicate the intensity of the heat.

24) Melting of metals: Examples are aluminum, copper, and steel, whose melting points are ~1200, 2000, and 2800°F, respectively (~650, 1100, and 1550°C, respectively).

Note that not one of these so-called languages of the fire may be sufficient in itself to show an incendiary fire, though some (pour patterns, multiple points of origin, and holes in the floor) may stand alone when accidental or providential causes are eliminated. Remember to look at the total scene. There has recently been controversy and discussion among investigators about the precise implications of observations of several of these items, including glass crazing, concrete spalling, and melted metals (temperatures reached in natural fires), see Refs. 25 and 41 for further information.

Evidence

Further evidence may be found from the following:

1) Floor: This will be the most productive area. Debris should be removed in layers to protect whatever might be found. Evidence of flammable liquids will be found in low places such as under carpets, in carpet pads, baseboards, and in well-traveled paths. Also, on top of standing water, not in it.

2) V Patterns: If not obscured, these provide direct evidence pointing to the origin of the fire, provided no rekindling has occurred.

3) First-in firefighters: They provide the best information as to what was burning and where, color of flames, color of smoke, etc. Many times, the pump operator or engineer gathers important information from bystanders and observes the crowd because of his stability on the fire ground.

4) Depth of char: Correctly measuring the depth of char is one way of evaluating fire spread. It does not establish specific burn times or heating intensity, but rather permits comparisons.

Indicators of Possible Incendiary Fires

Fire investigators must be especially aware of indicators of possible incendiary (deliberately set) fires. Major indicators include

1) Separate and seemingly unconnected fires.

2) Reaction of fire to water, e.g., does it flare up, do the flames reignite, or is there a film on top of the water where it may pool?

3) Obstacles are placed to hinder fire fighting, e.g., furniture placed in hard to maneuver places or automobile blocking a fire hydrant.

4) Conditions artificially created to assist fire spread, e.g., propped-open fire doors, punched holes in ceilings from floor to floor, or holes from wall-to-wall.

5) Uneven burning or localized heavy charring, e.g., burning or heavy charring in unusual open spaces when heat sources would not normally be found, or burning or charring underneath doors or any low horizontal surface.

6) Absence of items that would normally be found in a structure, e.g., clothing, furniture, appliances, personal affects, food; pets; or machinery and records in commercial properties.

7) Unusually intense heat generated by the fire may be an indication of an accelerant used to increase fire spread.

8) Tampering or damage to fire-prevention facilities, e.g., fire-alarm system not working, sprinkler system shut down, or burglar system damaged.

9) Streamers or trailers used to cause fire spread.

Conclusions

A review of pertinent information on fire dynamics was undertaken to provide a useful brief primer, with emphasis on fundamentals, industrial fires, ignition, fire development, and fully developed fires. Appropriate scientific details related to the main topic were given, concerning fuels, burning rates, heat transfer, and flashover and backdraft phenomena. Investigative aspects of experimental studies, fire modeling, and fire investigation were included to convey appropriate information with pertinent referencing about an exhaustive array of topics related to fire dynamics.

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