The Society of Fire Protection Engineers Series

Brian Meacham
Margaret McNamee *Editors*

Handbook of Fire and the Environment

Impacts and Mitigation

SFPE
Engineering A Fire Safe World

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Editors

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Foreword

Traditionally, fire loss has been measured based on direct losses such as number of fatalities and injuries as well as property loss. While these are key parameters when measuring the impact of fire, they do not provide a complete picture of how fire impacts society. Some studies on cost of fire also consider the indirect losses of fires, focusing on the economic impact of fires such as loss of production, business interruption, and job losses. However, fire also impacts the environment, and certain fire events might have the most catastrophic impacts with far reaching consequences. Yet this was rarely considered as we were missing the tools to quantify it.

How fires start, develop, and spread has been the focus of fire science research since the last century, in addition to understanding how we can best prevent this from happening. As our understanding of the basics of fire and fire protection has increased, the wider aspects of fire safety, such as human behavior and how to safely evacuate from fire, have received greater attention. The last decade has seen an increasing interest in sustainability in general and with that a rising awareness of the impact of fire and fire protection on the environment. In their opening chapter, the authors introduce environmental impact of fire as related "to any fire outcome which affects the physical, chemical, biological, cultural or socioeconomic components of the environ-ment."

This is the first book of its kind bringing together the information needed to understand how fires impact the environment as well as providing strategies to mitigate both fires and their environmental impact. It is a must read for anyone who wants to get the full picture of the impact of fire, and it is my sincere hope that this will generate an understanding that the cost of fire to society goes beyond the direct losses that are presently the focus of incident data collection.

It is not surprising that this book is brought to us by Margaret McNamee, a trailblazer throughout her career, focusing on the environmental impact of fire, and Brian Meacham, a globally recognized expert in fire risk and performance based design. Both editors have contributed significantly to fire science by expanding our understanding of the risk associated with fire and the need for a safe and fire-resilient built environment. The book includes contributions from world-leading subject matter experts ensuring that the information presented is the most up to date at the time of publishing.

I am thrilled that you have decided to read this book. I hope that you will find it informative as well as enjoyable and that it will inspire you to use the knowledge presented here in your work going forward.

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Preface

The environmental impact of fire is a broad topic. It includes physical, chemical, and biological impacts to the environment, and the cultural and socioeconomic impacts that result. It is common today to read about the carbon emissions from fire – particularly wildland fire – and the associated climate change impacts. However, there is also significant non-carbon contamination of the air by fire effluents distributed via the fire plume, contamination of soil and water from the deposition of products of effluents, and contamination from fire suppression agents and firefighting water runoff – especially as associated with the fires in the built environment. This handbook seeks to present an introduction of this broad topic.

It is anticipated that readers of this handbook will come from a wide range of backgrounds and levels of knowledge in the subject areas. As such, we chose not to develop a handbook that attempts to comprehensively treat all aspects of fire and their impact on the environment. Rather, we have taken an introductory approach that covers a broad spectrum of fire and environmental issues. We start with an introduction to fire, fire effluents, and the dispersion of fire effluents into the environment, we then present discussion on the impact of fire on the environment, and we end by presenting strategies for mitigating both fires and their environmental impacts. For those seeking more detailed treatments of the topics presented, we provide reference to numerous books, handbooks, articles, and reports and related resources in the reference list of each chapter.

Regardless of your background and level of knowledge in any of the areas covered, we trust that you find this handbook a useful resource to help broaden your understanding of fire impacts to the environment and steps that can be taken to prevent and mitigate them. As this integrative field of study expands, and interest grows, it is anticipated that future editions will build upon this first edition and become a living resource for understanding and addressing fire impacts on the environment.

Shrewsbury, MA, USA — Brian J. Meacham
Lund, Sweden — Margaret McNamee
July 2021

Terminology and Definitions

Abstract The focus of this handbook – fire and the environment – encompasses a broad set of scientific, engineering, and economic principles for which terminology and definitions may not be common and for some unknown. While it is easiest to understand the terminology within the context of its use, this chapter seeks to extract and consolidate a selection of the main terminology and definitions used within the handbook as a common resource for users.

Scope

It is not practicable to list every term and associated definition used in the handbook in this chapter. In some cases, the same or similar terms may be used differently from one chapter to another, and in most cases, they will be best understood in the context of the chapter in which they are used. However, there are some terms which are helpful to define as part of the overall context of fire and the environment. These are listed below. Where appropriate, references are provided.

Terminology that is chapter specific, is defined in the pertinent chapter.

Terminology and Definitions

Active Fire Protection Method(s) used to reduce or prevent the spread and effects of fire, heat, or smoke by virtue of detection and/or suppression of the fire and which requires a certain amount of motion and/or response to be activated [1]. Typically associated with fire protection within the built environment.

Acute Having a sudden occurrence or being of short duration. Fire is often considered an acute hazard since it occurs quickly and irregularly.

Building Element Integral part of a built environment, including floors, walls, beams, columns, doors, and penetrations (does not include contents) [1]. Building regulations often impose resistance to fire ratings for building elements as part of passive fire protection requirements. Contents of buildings are often not regulated, except in the case of hazardous materials.

Built Environment Individual or combinations of constructed structures, including buildings, civil engineering works (tunnels, bridges), and means of transportation (motor vehicles, marine vessels).

Buoyant Plume Convective updraft of fluid above a heat source [1]. The buoyant plume from a fire (fire plume) is the primary engine for the movement of smoke within an enclosure or in the open environment.

Chronic Persisting for a long time or consistently recurring. While fire is often considered an acute hazard or event, the impacts can be chronic in terms of persistence in the environment. This is particularly true for some fire effluents. In particular, some ecotoxicant species have chronic toxicological impact.

Combustion Exothermic reaction of a substance with an oxidizing agent [1].

Compartment (Enclosure) Space within building bounded by building elements (i.e., wall, floor, and ceiling) (Chaps. 6 and 10).

Controlled Burn Operational strategy where the application of firefighting media such as water or foam is restricted or avoided [1]. This term is often used in conjunction with burning of wildland as part of land management, as a means to mitigate larger wildland fires. However, it is also a tactic used by the fire service to "surround and contain" a built-environment fire that cannot be safely suppressed or extinguished.

Effluents (Fire) Emissions generated by the fire and discharged into the environment.

Emissions (Fire) The development and discharge of species into the environment (Chap. 5).

Emissions/Exposure Pathways The way in which effluents/emissions from fire and/or fire suppression reach the end receptor or recipient. These pathways are air, water, and soil, see Fig. 1 (Chap. 5).

Environmental Impact of Fire Broadly speaking, the environmental impact of fire relates to any fire outcome which affects the physical, chemical, biological, cultural, or socioeconomic components of the environment. Impacts can be direct or indirect. In addition to carbon emissions and the associated impact on climate change potential, direct impacts can include non-carbon contamination of the air by products of combustion distributed via the fire plume, contamination of soil and water from the deposition of products of combustion, and contamination from fire suppression agents and firefighting water runoff containing toxic products.

Environmental Impact of Fire Management Tree (EIFMT) Derived from the NFPA 550 Fire Safety Concepts Tree [2], the EIFMT is a decision tree–like structure which illustrates that to achieve the fire safety objective of "Manage Environmental Impact of Fire," one can either "prevent fire ignition" or "manage fire impact," with potential mitigation options presented under each branch, see Fig. 2 (Chap. 10) [2].

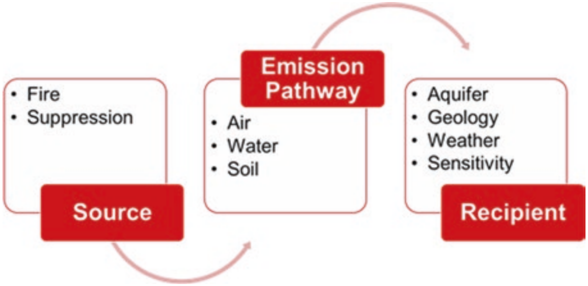


Fig. 1 Emissions/exposure pathways [Authors]

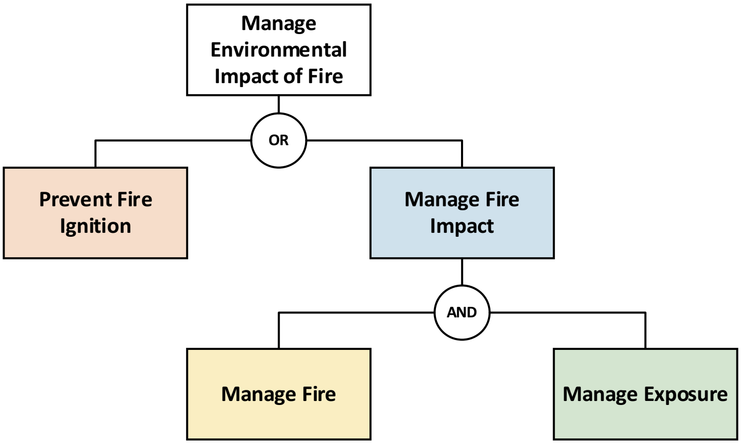


Fig. 2 Top branches of the Environmental Impact of Fire Management Tree. [Modified with permission of NFPA from NFPA 550, *Guide to the Fire Safety Concepts Tree*, 2017 edition. Copyright© 2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org]

Fire Process of combustion characterized by the emission of heat and fire effluent and usually accompanied by smoke, flame, or glow or a combination thereof [1].

Fire Effluent All gases and aerosols, including suspended particles, created by combustion or pyrolysis and emitted to the environment [1]. This term encompasses a variety of components, such as smoke, toxicants, particulate, and other substances produced during fires.

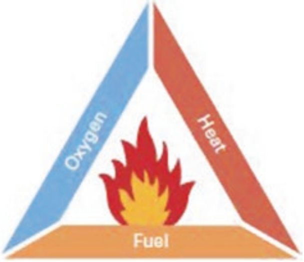
Fire-Fighting Chemicals (FFC) Substances, either natural or synthetic, which are used as additives aiming to improve the fire extinguishing effectiveness of water (Chap. 8).

Fire-Fighting Foams (FFF) A category of fire-fighting chemicals, which act either to reduce the surface tension of water used in firefighting through addition of a surfactant, which increases the ability of the water to penetrate into materials, thus allowing for improved wetting and more rapid and complete end to combustion (Class A foams), or which are formulated to develop a thermally stable cap or seal over the surface of flammable liquids, which excludes oxygen and prevents the release of flammable vapor which could ignite if a suitable fuel loading ratio is achieved (Class B foams) (Chap. 10) [3].

Fire Safety Concepts Tree (FSCT) A decision tree–like structure which illustrates that to achieve a stated fire safety objective, one can either "prevent fire ignition" or "manage fire impact," with potential mitigation options under each branch (Chap. 10) [2].

Fire Triangle A three-sided geometric figure that is intended to reflect the elements necessary for combustion: fuel, heat, and an oxidizing agent, see Fig. 3 (Chap. 3) [4].

Fig. 3 Fire Triangle [4]. (*Reprinted by permission of Pearson Education, Inc., New York, New York*)



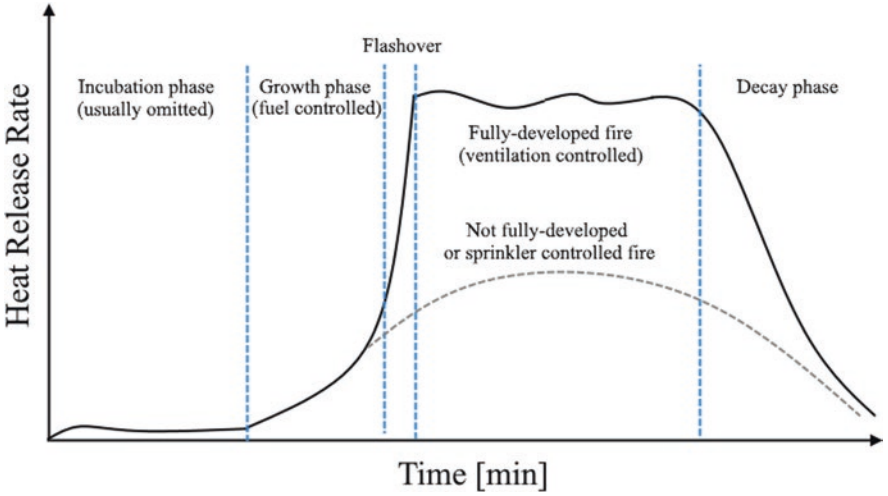


Fig. 4 Exemplar heat release rate curve within an enclosure (Chap. 4)

Heat Release Rate Rate of thermal energy production generated by combustion. [1] (Chaps. 3 and 4). Heat release rate (HRR) or rate of heat release (RHR) can be thought of as a measure of the "power" of a fire, and is generally expressed in kW or MW.

Heat Release Rate Curve A reflection of the phases (stages) of fire growth in terms of the power of the fire: incipient (incubation, smoldering), established burning, growth, fully developed (steady state), decay, and extinguishment. There are many representations of an HRR curve based on the fire phase of focus (e.g., rate of growth, peak heat release rate, impact of fire suppression, and burning duration), see, for example, Chaps. 3 and 4. One illustration of a HRR curve is shown in (Fig. 4).

Historically Significant Fires In the context of this book this refers to fires that have a significant potential to create an immediate and lasting impact on the environment. In Chap. 2, fires have been selected to be illustrative rather than exhaustive.

Major Accident Significant emission, fire, or explosion involving environmentally hazardous materials, resulting from uncontrolled developments in the course of the operation of any establishment, and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment.

Non-combustible Not capable of undergoing combustion under specified conditions [1].

Non-flammable Not capable of burning with a flame under specified conditions [1].

Passive Fire Protection System/Feature Approach used to reduce or prevent the spread and effects of fire, heat, or smoke by means of design and/or the appropriate use of materials and not requiring detection and/or activation upon detection (including the division of a space into compartments using materials with inherent fire resistance to fabricate walls, floors, doors, and other barriers) [1].

Product of Combustion Solid, liquid, and gaseous material resulting from combustion [1].

Reaction to Fire Response of a test specimen when it is exposed to fire under specified conditions in a fire test [1]. Building regulations generally require building elements to have some defined reaction to fire properties. The requirements can vary by building use and country.

Resistance to Fire (Fire Resistance) Ability of a test specimen to withstand fire or give protection from it for a period of time. Typical criteria used to assess fire resistance in a standard fire test are fire integrity, fire stability, and thermal insulation [1]. Building regulations generally require building elements to have some defined resistance to fire. The requirements can vary by building use and country.

Resilience The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events [5].

Resilient Design Designs which can resist and/or absorb and recover from extreme loading conditions with limited downtime and repair costs. (Adapted from [6])

Risk Possibility of an unwanted outcome in an uncertain situation, where the possibility of the unwanted outcome is a function of three factors: loss of or harm to something that is valued, the event or hazard that may occasion the loss or harm, and a judgment about the likelihood that the loss or harm will occur. ([7], as adapted from [8])

Smoke Visible part of a fire effluent [1].

Smoke Plume The extension of a buoyant plume of fire effluents as it reaches height and disperses horizontally, directed by wind or other means. Smoke plumes from wildland fires can stretch significant distances, in some cases being observable from satellites in space, and can result in deposition of fire effluents far from the sources of burning.

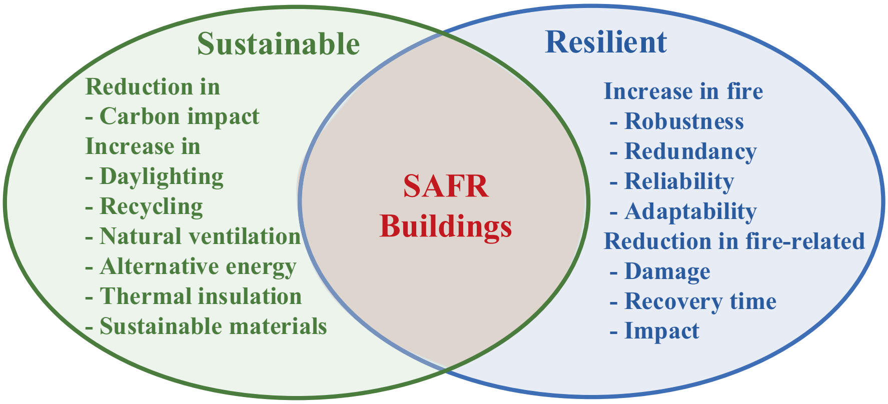


Fig. 5 Sustainable and fire resilient buildings (SAFR-B) concept. (Adapted from [11], Chap. 13)

Sustainability The principle of sustainability is based on a simple and long-recognized premise: everything that humans require for their survival and well-being depends, directly or indirectly, on the natural environment [9, 10].

Sustainability The ability to meet our present needs without compromising the ability of future generations to meet their needs [10].

Sustainable Design To reduce, or completely avoid, depletion of critical resources like energy, water, land, and raw materials, to prevent environmental degradation caused by facilities and infrastructure throughout their life cycle, and to create built environments that are livable, comfortable, safe, and productive [11].

Sustainable and Fire Resilient Buildings (SAFR-B) Buildings in which sustainable or "green" objectives do not conflict with fire safety objectives, and where the building is resilient to internal and external threats from fire, see Fig. 5 (Chap. 13) [12].

Sustainable and Fire Resilient Communities (SAFR-C) Communities in which sustainable urban planning and resilience to wildland and other large open fire events are addressed concurrently and not independently (Chap. 13) [12].

Sustainable and Fire Resilient Infrastructure (SAFR-I) Infrastructure components comprised of non-fossil fuel (sustainable) energy sources or materials and sustainable technologies that are at the same time resilient to fires resulting from technologies or that impinge upon the infrastructure from external fire events (Chap. 13) [12].

Wildland-Urban Interface (WUI) The region in which the built environment and wildland become intermixed, largely a result of constructions expanding into undeveloped areas. The WUI can be particularly challenging to protect depending on such factors as spacing of structures, construction materials, roadway widths, types and density of vegetation, and climatic condition.

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Most importantly, we want to acknowledge, thank, and express our deep appreciation to our respective partners and families for standing along with us, and supporting us, over the 4 years – pandemic and all – that it took to bring this work to fruition. Thank you for your sacrifices, patience, support, and love.

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July 2021

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Chapter 1
Introduction and Overview

Brian J. Meacham and Margaret McNamee

1.1 The Problem

Broadly speaking, environmental impacts of fire relate to any fire outcome which affects the physical, chemical, biological, cultural or socioeconomic components of the environment. Impacts can be direct or indirect. In addition to carbon emissions and the associated impact on climate change potential, direct impacts can include non-carbon contamination of the air by products of combustion distributed via the fire plume, contamination of soil and water from the deposition of products of combustion, and contamination from fire suppression agents and firefighting water run-off containing toxic products (Fig. 1.1).

These in turn can result in harm to ecosystems, wildlife and people, as well as cleanup and recovery costs. The impacts can be local (e.g., associated with a vehicle or small building fire), regional (e.g., as associated with a chemical facility fire or small wildland fire) or even global (e.g., as associated with a large wildland fire), with the magnitude of the impact being a function of the type and quantity of materials burning, size and duration of the fire, contributions from fire suppression and control agents and techniques, weather conditions, and environmental susceptibility in the impacted area (Fig. 1.2).

When considering environmental impacts of fire, several factors need to be considered, including the pollutants (contaminants) released by the fire and/or suppression material, the exposure pathway (direct impacts), the receptor susceptibility and

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Fig. 1.1 Aerial view of October 23, 2009 fire, Caribbean Petroleum Investigation. (Source: https://www.csb.gov/caribbean-petroleum-investigative-photos. Accessed July 2020)

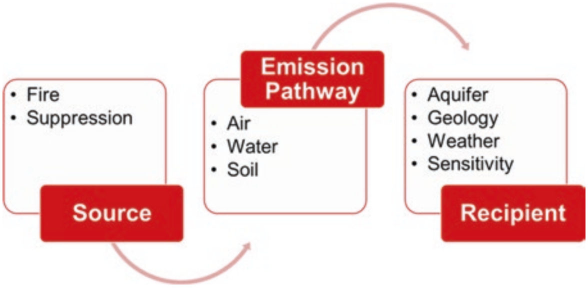

Fig. 1.2 Source to recipient pathways

secondary effects. Contamination of air, soil and water can result from several products of combustion or suppression, including metals, particulates, polycyclic aromatic hydrocarbons (PAHs), chlorinated dioxins and furans, brominated dioxins and furans, polychlorinated biphenyls and polyfluorinated compounds (Fig. 1.3).

The type, quantity and persistence of such substances are important in assessing impacts to various receptors. Some of these substances may not persist long after a fire (e.g., particulate may become diluted in the fire smoke plume as it spreads), while others may remain for some time, such as metals in soil or bioaccumulation of pollutants. In addition, some fire impacts can have long-term effects, other than

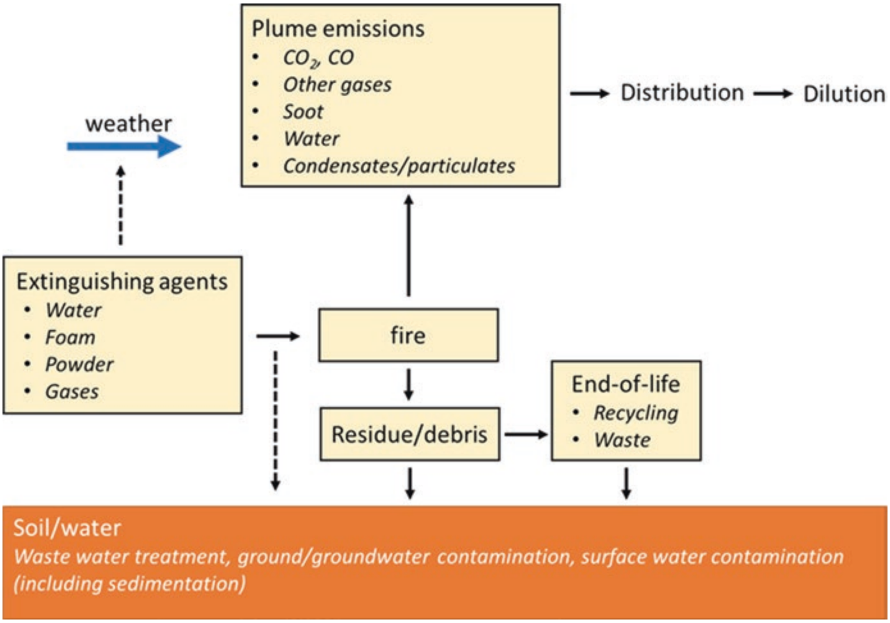

Fig. 1.3 Schematic representation of fire and impacts to the environment [1]. (Modified from ©2020, FPRF, permission pending)

from release of materials, such as loss of vegetation and subsequent erosion due to wildland fire, which can last from months to years (Table 1.1).

This handbook on Fire and the Environment: Impacts and Mitigations, aims for the first time to bring together into a single resource a comprehensive overview of the impacts that fire has on the environment, the range of tools available to assess the fire and its impacts, and the approaches that can be taken to reduce or mitigate the impact across the spectrum from individual facility fire to large area wildland fire. The topic of fire impacts on the environment is very broad, has been researched across numerous scientific disciplines, and across all scales. It is not possible to capture the full extent of this research and mitigation guidance in a single document, nor is that practicable for the user. Rather, the aim of this handbook is to present an introduction to the major topic areas and provide reference to in depth treatments of the various issues. It is expected that future editions will expand both in breadth and depth as the need arises and feedback from the users is obtained.

This handbook has been developed by experts in various areas of fire and its impact on the environment. It is structured to provide information on a topical basis along the progress of historical context, fundamentals on fire, dispersion and measurements of fire effluents, building fires, wildland fires, transportation fires, impacts of fire and firefighting in these areas, costs of environmental impact of fires, and physical and regulatory approaches to reduction and mitigation of fire impact.

Table 1.1 Connection between recipient, fire exposure and cost of the environmental impact of fires [1]

Recipient	Fire description	Impact radius	Exposure	Input data	Cost
Air	Deterministic description (e.g. statistics, fire specific data)	Plume modelling (local and global)	Gases, particulate emissions	Experimental Gaseous measurement in conjunction with real fires, e.g. satellite measurements	Inside scope of cost of environmental impact of fires Replacement Remediation/Decontamination Cost of loss of income due to loss of access to biotopes (to businesses or people) Societal cost for loss of access to biotopes Outside scope of cost of environmental impact of fires Loss of life Injury of people Long term irretrievable loss of environment
	Modelling (e.g. CFD, FEM, Zone, Wildland fire models)				
Water	Suppression method, potential to emit to the aquatic environment	Environmental Risk Assessment, transport models to surface water, ground water, assessment of contamination radius for soil (local and global)	Soluble organic compounds, particulate emissions	Experimental Water samples and measurements in conjunction with real fires, e.g. from rivers, lakes, and wells	
Soil	Suppression method, potential to emit to the soil		Deposition of solid waste close to the fire	Experimental Soil samples and measurements in conjunction with real fires	

1.2 Historically Significant Fires

Arguably, the environmental impact of fire only started to gain attention when the broader environmental protection movement began in the 1960s and 1970s. A key event was a fire – the 1969 burning of the Cuyahoga River in Cleveland, Ohio [2], which helped further the public's understand of the breadth of the damage being done to the environment by industrialization and became one of the events cited as helping to launch the formation of the US Environmental Protection Agency (US EPA).

As fire became understood as a source of impact on the environment, so too did impacts of firefighting. A benchmark example here was the 1986 high-profile fire at the Sandoz Ltd. warehouse near Basel, Switzerland [3]. The warehouse contained some 1250 tons of pesticides, solvents, dyes, and various raw and intermediate materials. After fire broke out, the fire service was on site for hours pouring water on the fire to control its spread. However, there was insufficient means to control the firefighting water runoff, and tons of hazardous and toxic materials contaminated the surrounding soil and flowed into the Rhine River. It is estimated that approximately 9 tons of pesticides and 130 kg of organic mercury compounds infiltrated the soil. The chemicals discharged into the Rhine River by the firefighting runoff resulted in large-scale kills of benthic organisms and fish, particularly eels and salmonids, with

Fig. 1.4 Smoke cloud from the Lac Megantic petroleum fire [4]. (Source: Wikipedia, 2013)

impacts observed as far away at the Netherlands. Of particular note was the eel kill, which spread from Schweizerhalle some 400 km downstream to Loreley (near Koblenz). In addition, other fish species were also severely affected, including grayling, brown trout, pike, and pikeperch, as well as typical food for the fish.

More recently, the environmental impacts of wildland fire have gained widespread attention. The extensive wildland fires in Australia, Europe and the Americas since 2017 have resulted in widespread damage (Fig. 1.4).

In Chap. 2, a selection of fires that have had a significant immediate and/or lasting impact on the environment, based on their size and scope, are overviewed. These include mainly large-scale events where information is available concerning interaction between the fire and the environment. The scope includes significant facilities, transportation and wildland fires.

1.3 Fire Fundamentals

The use of fire by humans is a major factor in the evolution of human invention and progress. However, uncontrolled fire has also resulted in significant disasters, from the leveling of cities to the devastation of forests. Chapter 3 provides an introduction to fire fundamentals, including combustion, preventing ignition, and extinguishing fires, from the perspective of the physics and chemistry that influence these processes.

The discussion begins with the 'fire tetrahedron', the sides of which are fuel, heat, an oxidizing agent, and an uninhibited chemical chain reaction, the components required for fire (combustion). From there, combustion reactions, basics of ignition, fuel properties and phases are presented. The mechanisms of heat transfer – conduction, convection and radiation – are then discussed, followed by fluid mechanics. The chapter rounds out by presenting fundamentals of fire in compartments and fires that burn in the open. Throughout the chapter, a number of references are provided to help those seeking more in-depth treatment of the topics covered (Fig. 1.5).

1.4 Fire and Smoke Modelling

Building on the fundamentals of fire, Chapter 4 provides a summary of knowledge and information underpinning the modelling of fires and release of pollutants to the atmosphere. With a focus on fire impacts on the environment, a particular focus is the pivotal role that wind phenomena take in the pollutant dispersion (Fig. 1.6).

The starting point is a history on computational modelling of fire in compartments, discussing how heat transfer and fluid mechanics drove research into the dynamics of fire in compartments, and how the advent of computer modelling allowed for the ready consolidation of knowledge into practical tools. It traces developments from simple one- and two-zone models into more elaborate computational fluid dynamics approaches. Next comes an overview of computational wind engineering and models developed to assist in that discipline, and how the fire and wind modeling can be coupled together.

Fig. 1.5 Fire tetrahedron [5]. (Reprinted by permission of Pearson Education, Inc., New York, New York)

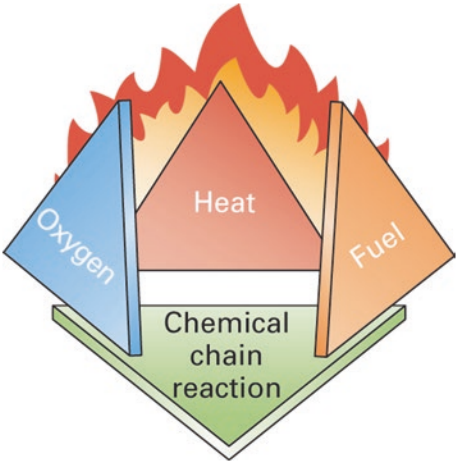

Fig. 1.6 Fire and smoke plume from exterior fire. (Source: https://www.csb.gov/barton-solvents-flammable-liquid-explosion-and-fire/, accessed June 2020)

From this start, a comprehensive exploration of computational fluid dynamics (CFD) frameworks is provided. How CFD modeling can be applied to fire and smoke modeling, for assessing environmental impacts, and some of the challenges faced are then presented.

1.5 Emission Measurements

An important aspect of evaluating the environmental impact of fire is the ability to measure the emissions from a fire. Chapter 5 begins with an overview of why it is important to measure fire effluents, as well as challenges faced in doing so. The types of effluents emitted, how they might travel to and disperse in air and water, and their duration and persistence is discussed (Fig. 1.7).

With this foundation, discussion of sampling requirements, methods and techniques is presented. Sections on emissions to air, water and land overview exposure pathways and sampling opportunities. This is followed by technologies for sampling in each type of environment. Throughout, reference is made to standards, guidelines and related resources which provide more detail on each aspect.

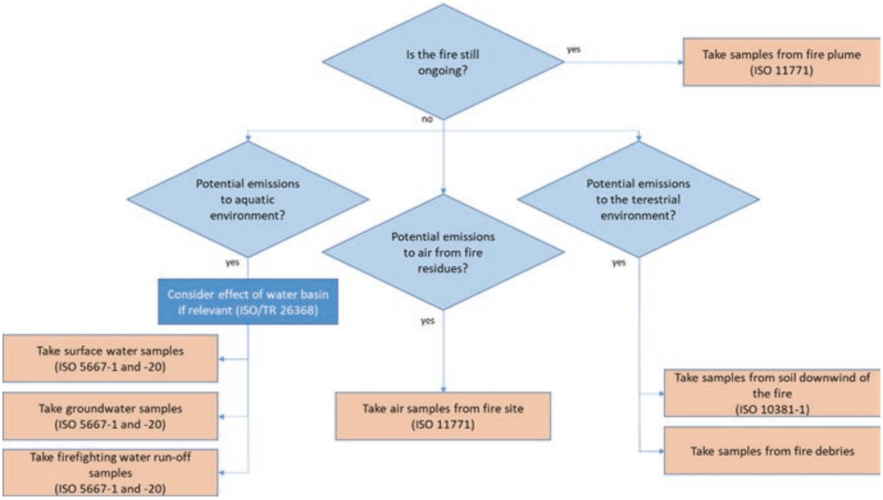

Fig. 1.7 Sampling options. (Adapted from ISO 26367-1 and ISO 26367-2)

1.6 Fires in Enclosures

To understand the environmental impact of fire from facilities, one needs to understand something about fires in enclosures and fire spread within buildings, as well as how fires in enclosures can be controlled. Chapter 6 provides an overview of important factors, several which are reflected in Fig. 1.8.

In any enclosure (single compartment to building of many compartments), the type and amount of fuel influences the amount of combustion product, which influences size and spread of the fire (see Chaps. 3 and 4) and the damage caused. Enclosure factors which influence the fire include the volume of compartment and size and number of ventilation openings. Factors such as fuel type, load and distribution, rate of heat release and smoke production, and effluents associated with enclosure fires are discussed.

There are also significant factors not directly related to the combustion process. Means to mitigate the fire (see also Chap. 10) include compartment construction and fire safety systems, including response time and tactics during fire suppression. When manual firefighting is needed, the time and tactics also result in contaminated runoff water, which may or may not have firefighting chemical additives (see Chap. 10), that can potentially pollute the ground water, soil and the community water handling system. The demolition of the building and its restoration, and in some cases restoration of the soil around the enclosure, have environmental effects as well, as does the environmental cost of rebuilding and replacement of the contents of the building.

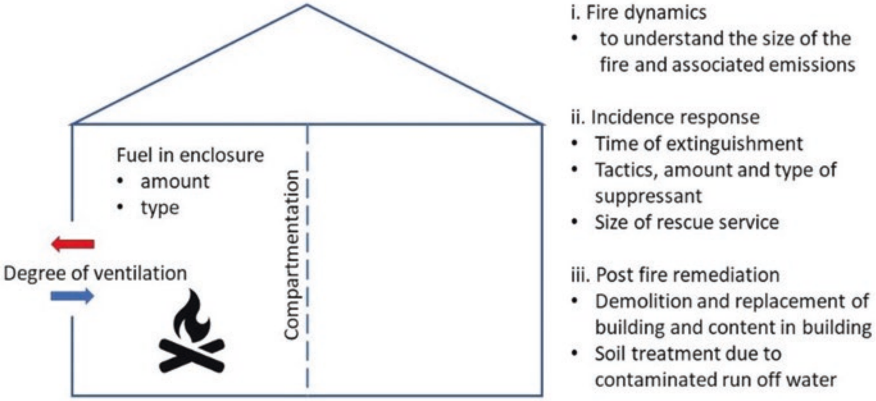

Fig. 1.8 Factors influencing environmental impact from enclosure fires

1.7 Wildland Fires

Wildfires, and their associated management activities, can have complex social, economic, and environmental impacts. Chapter 7 highlights some of the key impacts of wildfires, focusing on communities, biodiversity, water and soil and air quality. It then highlights the role of dynamic fire behaviors that lead to the most severe impacts.

A single wildfire can have wide-ranging effects on biodiversity. The effects of a single fire will depend on properties of the fire event such as fire behavior,

intensity and extent. This chapter discusses properties of wildfires, including how they are impacted by fuels, climate and weather conditions, and impacts to flora and fauna, water, soil and air quality that result (Fig. 1.9).

A discussion is also provided on the growing magnitude of wildfires and how climate change is influencing this. The chapter presents a case study from the 2009 fires in the Australian state of Victoria, and closes by describing the impacts of the 2019/20 fire season in south-eastern Australia as example of the extreme impact of wildland fire on people and the environment.

1.8 Firefighting Chemicals

In Chap. 8, firefighting chemicals (FFCs) are discussed, including chemical properties of classes of FFCs and potential impacts on the environment. A brief overview of the taxonomy of FFCs and a historical perspective on their development is provided. The mechanisms by which FFC function as fire suppressants is overviewed along with typical methods of application, with a focus on wildland fire suppression (Fig. 1.10).

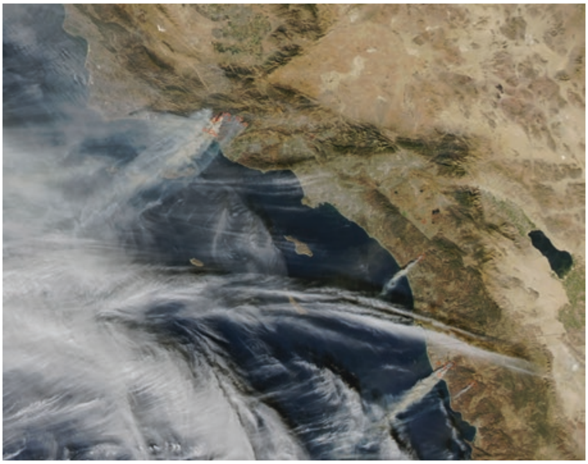

Fig. 1.9 California fires from space. (Source: NASA Goddard Photo and Video reproduced under license CC BY 2.0)

Fig. 1.10 FFC release at Grand Canyon National Park, Arizona, 2006. (Source: https://www.nps.gov/Media/photo/view.htm?id=03BA34D8-1DD8-B71B-0B485B3AFF136A6A)

A discussion on different types FFCs, based on short-term and long-term persistence is provided. The environmental impacts are then discussed, including aquatic and terrestrial. A brief discussion on human health impacts is also presented. This chapter closes by introducing trends towards more eco-friendly FFCs, which have become available in recent years.

1.9 Tools and Techniques for Impact Analysis

There exists a variety of methods that can be used to assess the environmental impacts of fire. Chapter 9 considers the types of environmental impacts that result from fire emissions, models for assessing the impact of these emissions and mitigation efforts to minimize these impacts (Fig. 1.11).

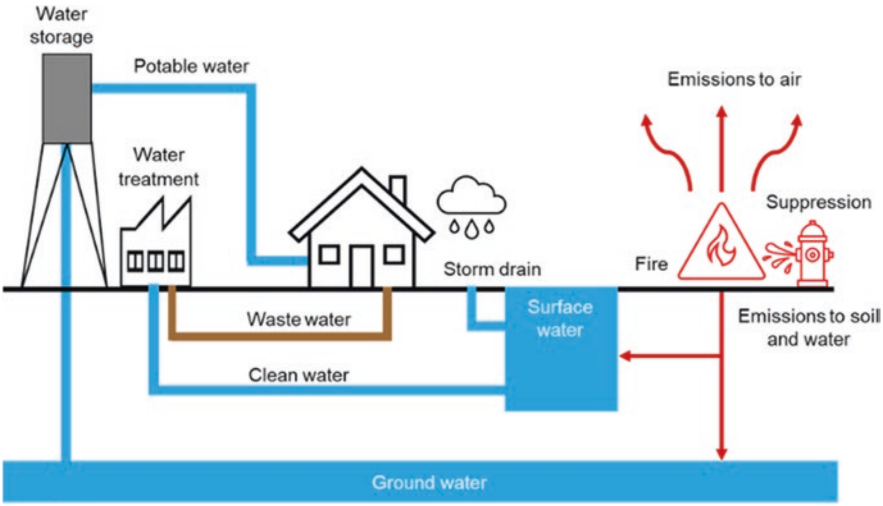

Fig. 1.11 Schematic overview of water cycle and access to it from a fire

The discussion begins with emissions and the pathways to environmental exposure – air, water and soil. Methods to represent the risk associated with the emissions is presented, followed by means to assess impacts.

Impact assessment methods that are addressed include benefit-cost analysis (BCA), life-cycle cost analysis (LCCA), life cycle assessment (LCA), and a selection of hybrid models.

1.10 Mitigation Strategies for Buildings

There are many fire protection systems and features that can be implemented as part of building fire mitigation strategies. These can be largely grouped into (1) means to prevent fire ignition, (2) means to manage the development and spread of fire and fire effluents, and (3) means to manage impacts to that which is exposed to the fire and its effects. These approaches are outlined in Chap. 10. These three approaches are reflected well in the Fire Safety Concepts Tree (FSCT) published by the National Fire Protection Association in the USA [6]. However, the focus of the FSCT is largely on people and property, and not the environment. As used in the context of environmental impacts, a modified structure is introduced in Chap. 10, called the *Environmental Impact of Fires Management Tree* (EIFMT), which places consideration of fire mitigation in buildings into an environmental protection context (Fig. 1.12).

Following the EIFMT structure, various approaches for mitigating fires and their effects are presented. This discussion is provided at an introductory level, for those

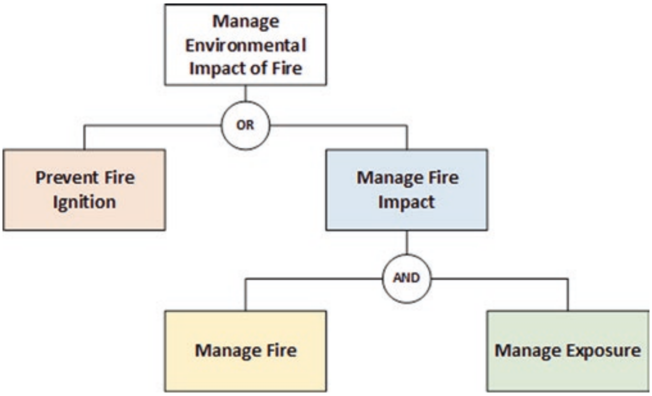

Fig. 1.12 Top branch of EIFMT.

Fig. 1.13 Structural firefighter training. (Photo: https://www.nps.gov/Media/photo/view.htm?id=A6CA1057-1DD8-B71B-0B8C1FF56E656EEA)

who may not be expert in fire protection design. It is placed within a context of common approaches identified within building and regulations, and provides overviews of various systems and technologies and how they can help mitigate fire's impact on the environment. The chapter also discusses the potential impacts of firefighting additives (see also Chap. 8) and runoff water, and strategies for addressing these issues (Fig. 1.13).

This chapter closes with a representative sampling of where one can find guidance in regulatory instruments (e.g., building and fire regulations, environmental regulations, and occupational health and safety regulations), consensus standards, standards and guidelines from the insurance industry, guidelines and codes of practice from professional associations and societies, and textbooks.

1.11 Mitigation Strategies for Waste Fires

Waste fires can ignite spontaneously, may be very long-lasting and difficult to extinguish, with potentially large emissions of smoke and water runoff. Large storage volumes, combined with a wide range of chemical components present, makes waste fires a potential environmental disaster. There are reports of landfill fires burning for days, months and even years.

Chapter 11 discusses large-scale waste handling and storage, focusing on four types of waste storage: (1) outdoor waste deposits or landfills without solid cover under the waste, (2) more controlled forms of waste storage at waste facilities, (3) indoor storage without collection of run-off water, and (4) indoor storage with collection of run-off water. This is illustrated graphically in Fig. 1.14.

Emissions from waster fires is then discussed, followed by fire mitigation strategies. This includes measures to limit the risk of large size fires and fire spread, including limiting the quantities of stored waste, providing separation, and monitoring the condition of the stored waste. Means of fire detection and different fire suppression strategies are also highlighted. The importance of addressing firefighting runoff water is also addressed.

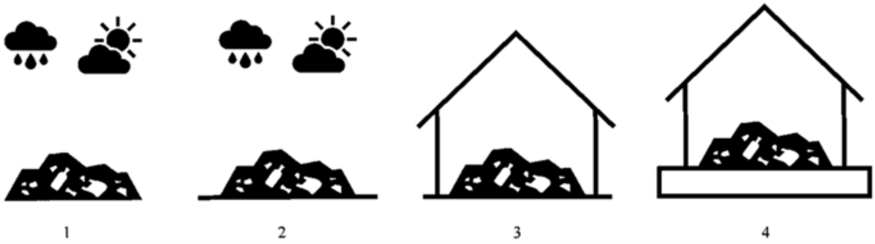

Fig. 1.14 Four forms of waste storage. (Based on [7], used with permission)

1.12 Mitigation Strategies for Wildland Fires and WUI

Climate change portends an increase in wildfire activity, including potential increases in terms of fire extent, severity and/or frequency. It is becoming increasingly important to consider ways to manage, and where possible, mitigate the impacts of wildland fire, in particular the wildland urban interface (WUI). At present, fuel management is the primary means for land and fire managers to reduce the risk from future fires, and there are multiple strategies of varying levels of effectiveness.

Chapter 12 reviews mitigation strategies for wildfire in the context of fuel management, with a primary focus on reducing the impacts to people and property. The range of fuel management strategies considered includes prescribed fire, mechanical treatments, grazing and landscaping. Fuel management is commonly broken down into three distinct but overlapping spatial scales: landscape treatments (i.e. broadscale fuel treatments); interface treatments (i.e. finer scale fuel treatments, predominantly undertaken at the wildland-urban interface, WUI); or home-owner/community scale actions (i.e. localised defendable space around individual properties. The known evidence-base for the efficacy of each strategy is discussed in terms of their influence on three key elements of wildfire risk: the likelihood of ignition; spread to the Wildland-Urban Interface, and impacts at the Wildland-Urban Interface (Fig. 1.15).

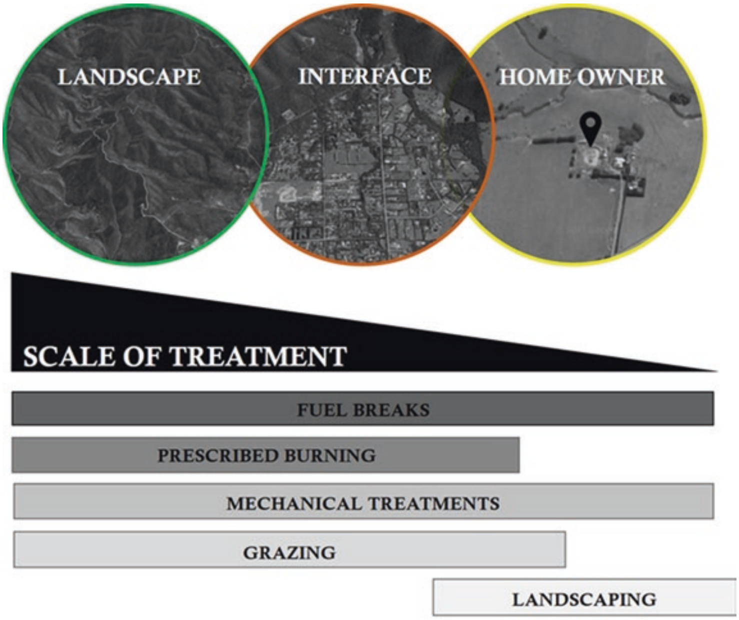

Fig. 1.15 Spatial scales of fuel management

Finally, Chap. 12 discusses fire risk mitigation strategies under the umbrella of a changing climate. It is noted that there is no single solution for addressing all stated objectives: fire managers need to consider where and when it is appropriate to apply the various fuel management actions in order to achieve the greatest risk reduction across a range of values, and whether the risk reduction benefit is outweighed by the harm it may do to human health or the conservation of biodiversity.

1.13 Sustainable and Fire Resilient Built Environment (SAFR-BE)

Sustainability and resilience are terms one often hears in discussions about the built environment at all levels – buildings, infrastructure and communities. While some use the terms interchangeably, they embody different concepts, which sometimes align, but in other cases, can result in competing objectives. Good building design should address both sustainability and resiliency concepts as part of a holistic approach. This is also true for planning of communities and critical infrastructure for all hazards.

To guide such integrated thinking and planning, it is important to develop a philosophy which embodies both sustainability and resiliency. In the context of fire, the need is for a sustainable and fire resilient (SAFR) approach (Fig. 1.16).

Chapter 13 provides a framing for sustainability and resiliency, and how it applies to buildings, infrastructure and communities, and what constitutes a sustainable and fire resilience built environment (SAFR-BE).

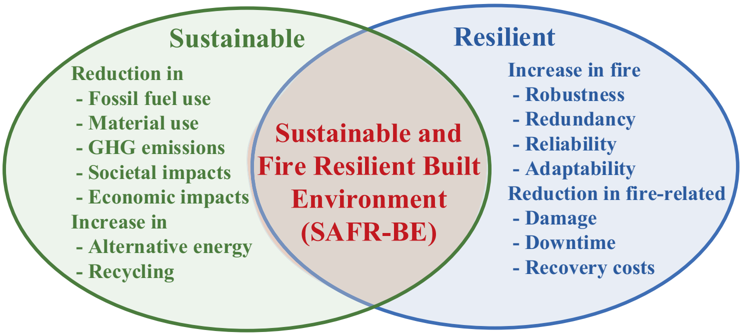

Fig. 1.16 Sustainable and Fire Resilient Built Environment (SAFR-BE) Concept

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Chapter 2
Historically Significant Fires

Margaret McNamee, Guy Marlair, and Benjamin Truchot

2.1 Introduction

Concern for the health of the natural environment is growing as human population grows and as new levels of contamination of scarce resources are revealed [1, 2]. Current efforts to improve the sustainability of buildings focus on increasing energy efficiency and reducing the embodied carbon [3]. This overlooks the fact that a fire event could reduce the overall sustainability of a building through the release of pollutants and the subsequent re-build. Most fires occurring in the built environment contribute to air contamination from the fire plume (whose deposition is likely to subsequently include land and water contamination), contamination from water runoff containing toxic products, and other environmental discharges or releases from burned materials. The environmental impact is, therefore, multifaceted including emissions to air, soil and water as discussed in more detail in Chap. 9.

In this chapter we define “historically significant” to include fires that have a significant potential to create an immediate and lasting impact on the environment. These include mainly large-scale events where information is available concerning interaction between the fire and the environment. The case can be made that the many small fires from the built environment, that provide the background “noise” to large scale events have a significant potential to impact the environment on an everyday basis. Therefore, annual emissions from typical fires in the built environment are included as one example in the table. Some of the material presented in this chapter has been modified from a report by the same authors [4].

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B. J. Meacham, M. McNamee (eds.), *Handbook of Fire and the Environment*,
The Society of Fire Protection Engineers Series,
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Table 2.1 contains data for the object burning in the chosen example, the ignition source, a summary of the fire load (burned) (qualitative or quantitative) and the environmental exposure, if known. The "environmental exposure" describes the recipient of fire emissions and the quantity of emissions if this information is available.

The remaining sections in this chapter are devoted to the presentation of more detailed information concerning the environmental impact of a selected number of fires. The sections are categorized based on the fuel characteristics rather than the impact categories. In many cases results are available for emissions to air, water or soil but not for all three. The results presented are based on what is available in the open literature or based on previously unpublished work by the authors.

Many different divisions could be made based on fuel. The authors have chosen to divide historical exampled in the following sections as follows:

1. Fossil fuel based products
2. Chemical products (manufacturing and storage)
3. Wildland (biomass) fires
4. Built environment

2.2 Fossil Fuel-Based Products

2.2.1 Buncefield

Early in the morning of the 11th December 2005 a large storage tank containing unleaded petrol was inadvertently overfilled and an aerosol cloud, containing a mixture of hydrocarbons and ice crystals, was released. The release was not immediately discovered, and it has been estimated that it was able to cover an area of between 160,000–300,000 m^2 before discovery. Ironically a firewater pump is thought to have caused the ignition as part of the initial response [65]. At the time of ignition, over 250,000 liters of petrol had escaped from the tank. The heavy combustible cloud was emitted from tank 912 in bund A, see Fig. 2.1. At the point of ignition, the cloud extended beyond the Hertforshire Oil Storage Ltd. (HOSL) site, across Buncefield Lane in the west, where it was discovered in the parking lot of Maryland Industrial Estate. In the ensuing fire, however, it is estimated that some 58,000 tons (ca 73 Mliters) of hydrocarbons were burned or approximately 75% or all the fuels stored at HOSL [66].

The weather conditions on the day of the incident were such that there was no wind and the atmospheric stability of Class F was estimated [67]. This led to the slow dispersion of the cloud and created stable conditions within the flammability limits of the gas. The fire that resulted from the ignition of the leaked fuel was the largest in peacetime UK and engulfed in the end some 20 fuel tanks on the HOSL and adjacent sites and burned for 5 days [65].

Table 2.1 Description of environmentally significant fires in modern history with a focus on the built environment (including manufacturing). Note that the list is illustrative rather than exhaustive

Fire incident (Name and Year)	Description	References
London, England, 1666	Object: City of London Source: Bakery fire Fuel load (burned): 13 200 houses, 87 parish churches, St Paul's Cathedral, and most of the buildings of the City authorities in central London. It is estimated to have destroyed the homes of 70,000 of the city's 80,000 inhabitants. Environmental exposure: Unknown	Garrioch [5]
Salzburg, Austria, 1982	Object: Chemical Warehouse Source: Welding/Hot works Fuel load (burned): 400 tons of fertilizers and pesticides Environmental exposure: Large gas cloud, dispersed due to favourable weather conditions	Christiansen et al. [6]
Woodkirk, UK, 1982	Object: Chemical Warehouse Source: Unknown Fuel load (burned): 1,5 Mlitres solutions based on paraquat and diquat, 20 tonns octyl phenol Environmental exposure: Herbicides entered the drains and were carried into a watercourse, polluting the surrounding area	Christiansen et al. [6]
Ipswich, UK, 1982	Object: Chemical Warehouse Source: Welding/Hot works Fuel load (burned): 1380 tons fertilizers Environmental exposure: Fire plume exposure to surrounding buildings, corrosion from nitrogen oxides	Christiansen et al. [6]
Basle, "Sandoz Fire", Switzerland, 1986	Object: Chemical Warehouse Source: Blowtorch incorrectly applied to shrinkwrap Fuel load (burned): 1 300 metric tons of agrochemical products and other chemicals Environmental exposure: Run-off water into Rhine river causing extensive contamination Comment: (a) A full special issue of Chemosphere has been released with all gathered information about lessons learnt from that disaster, notably in terms of air and water pollution (b) Corporate Environment protection strategy of SANDOZ was fully reviewed as the aftermath of this disaster and New guideline for plant safety n°28 entitled "Warehousing" was implemented within the group for the protection of the environment in case of a fire event	Capel et al. [7] Suter et al. [8] Giger [9] Vince [10]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
Nantes, France, 1987	Object: Chemical Warehouse Source: burning material among fertilizers or electrical fault Fuel load (burned): 1 450 tons fertilizers, 750 tons ammonium nitrate, 200 tons urea gas Environmental exposure: Extensive fire plume (estimated 25000 evacuated) Comment: as the aftermath of this event, French CA ordered a large-scale experiment perfomed by CERCHAR (former name of INERIS) to better uderstand self-sustained decomposition of NPK fertilisers and related thermal and toxic hazards	Christiansen et al. [6] Marlair and Cwiklinski [11]
Dayton, USA, 1987	Object: Paint Warehouse Source: spilt flammable liquid, ignited by spark from electric motor Fuel load (burned): full warehouse of paints (5,5 millions of liters) Environmental exposure: fire plume and minor exposure of nearby waterway	Copeland and Schaenman [12] Fischer and Varma [13]
Tours, France, 1988	Object: Manufacturer hazardous chemicals Source: Explosion and fire due to poor facilities maintenance Fuel load (burned): Chemical fire spread to flammable and toxic chemicals Environmental exposure: Fire plume zone some 30 km long and 12 km wide. Loire river polluted by toxic waste causing the death of some 15 ton fish and prompted decision to cut water supplies to Tours (pop. 155 000) for a week	Szarka [14] Marlair et al. [15]
Hagersville, Canada, 1990	Object: Tire storage Source: Arson, Molotov cocktail type device Fuel load (burned): estimated 14 million tires Environmental exposure: Toxic plume for 17 days. Evacuation approx. 4000, cost the province more than $10 million for a year-long clean up. It remains the worst environmental disaster in Ontario history	Schneider [16] Nolan [17]
Woking, UK, 1990	Object: Wood treatment installation Source: The fire started on a lindane storage Fuel load (burned): Several chemical products including lindane Environmental exposure: More than 30 t of lindane flew to the Bourne river (connected to the Thames) that was polluted over 80 km. Environmental cleaning evaluated to 150 000 £	Dowson et al. [18]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
Perth, Australia, 1991	Object: tanker Source: unkown Fuel load (burned): a large amount of petroleum Environmental exposure: toxic product atmospheric dispersion and petroleum spillage (2,9 million gallons crude oil) over the sea, more than 30 km^2	Nyt [19]
Bradford, UK, 1992	Object: Allied Colloid Source: Proximity of incompatible chemicals Fuel load (burned): Chemicals Environmental exposure: 16 000 m3 of contaminated run-off water	Hse [20] Marlair et al. [15]
Macassar, "Somerset West Fire", South Africa, 1995	Object: Sulfur stockpile Source: Grass fires over several days depleting water reserves Fuel load (burned): 15 700 ton sulfur Environmental exposure: Emission of estimated 14 000 ton SO_2 over a 20 h period. Thousands evacuated and long-term impact on people and agriculture up to 30 km from site Comment: at that time, the only industrial fire to our knowledge that killed some people (and likely also local fauna species specimen) at remote location from the fire	Batterman et al. [21] Jeebay [22]
Wilton, UK, 1996	Object: BASF Plant Source: Unconfirmed fault in fluorescent lighting Fuel load (burned): 10 000 tons polypropylene Environmental exposure: minor contamination through smoke plume	Carty [23] HSE [24]
Twin towers, USA, 2001	Object: World Trade Center, New York Source: Terrorist attack. Ignition through airplane impact Fuel load (burned): Building contents Environmental Exposure: minor contamination through smoke plume and dust cloud from collapse of buildings	Kean et al. [25]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
Cartagena, Escombras Valley, Spain, 2002	Object: Warehouse for fertilizer Source: Self-sustained decomposition process, no conclusion on the actual activating heat source that triggered the SSD phenomenon Fuel Load (burned): 15000 tons ammonium-nitrate based ternary fertilizer 15-15-15 Environmental Exposure: The smoke plume was entrained towards the sea. The cloud affected Cartagena, a city of 200,000 inhabitants and some 50 persons from the plant itself, 130 people from the various emergency services involved and 3500 people from the local population were affected, essentially by eye and throat irritation. The economic activity in the Valley was frozen during more than 24 h, while at risk population was ordered to stay confined. Limited air pollution occurred, as assessed from NOx measurement and post-event modelling exercise, and no significant water pollution was found due to appropriate fire water run-off containment	Baraza et al. [26]
Mishrag (near Mosul), Irak, 2003	Object: Al-MIshraq State Sulfur Plant, heap of sulfur extracted and refined from largest native sulfur deposit (500 million tons eq. elemental S) Source: believed to be arson Fuel load (burned): huge amounts of sulfur Environment exposure: 600 ktons SO_2 dense plume over 1 month affected a large area including nearby population, fauna and flora ; acute short term injuries in exposed military staff and population, including 2 deaths at least among the nearby residents, possibly also linked to long term adverse medical effects (incl. Bronchiolitis ; local wheat crop field polluted by fire and smoked resulted in US$40 million loss ; area affected by smoke plume ~100 sq km, reaching the Turkish city of Arbil Comment:This huge fire lasted almost 1 month and present significant similarities to the Somerset West sulfur fire in South Africa that occurred in 1995 ; the site has caught fire several times after ths major event, including in 2016 and 2019	Carn et al. [27] Baird et al. [28]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
Kolding, Denmark, 2004	Object: N.P.Johnsens Fire Works Factory Source: Fire works dropped by workers clearing a container Fuel load (burned): Large volume of fire works burned and exploded Environmental exposure: Approx. 355 houses reported damaged (176 rendered uninhabitable). Altogether, 2107 buildings were damaged by the explosion, with the cost of the damage rounding to an estimated € 100 million Comment: According to ARIA French database, and surprinsingly, environmental damage rated 0 out of 6 on European scale, while financial damage was rated the maximum value on the same scale (6/6). Fireworks fires are known to have to potential of significant soil pollution risk from heavy metal and related salts particles deposition	Beredskabsstyrelsen [29] ARIA [30] Agwu et al. [31]
Hemel Hempstead, UK, 2005	Object: Buncefield oil storage depot Source: Overfilling of Tank 912 due to faulty control gauges Fuel load (burned): 20 fuel tanks, millions of litres of fuel Environmental exposure: bunds for spill capture overflowed causing contamination of surrounding soil and waterways. Comment: in 2010, 5 companies ordered to pay £ 9.5 million for their responsabilities in this accident, including £1.3 million fine for pollution offense, a UK record for a single accident	Macdonald [32] Newton [33] Atkinson [34]
Lviv, Ukraine, 2007	Object: Train that carries yellow phosphorus Source: Train derailment with spontaneous igntion of phosphorus after carriage opening and phosphorus spillage Fuel load (burned): about 700 t of yellow phosphorus involved Environmental exposure: dispersion of highly toxic gases and ground pollution (fire reignition because of residual phosphorus 15 days after the first fire	Unian [35]
Quezon City, Philippines, 2011	Object: Informal Settlement Source: Unknown Fuel load (burned): Informal housing Environmental exposure: 20 000 homeless	Rini [36] Aap [37]
Iowa City, USA, 2012	Object: Tire landfill Source: Unknown Fuel load (burned): estimated 1,3 million tires Environmental exposure: Impact on Iowa City (pop 152 586 US 2010 census) through smoke exposure	Singh et al. [38]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
West (near Waco), USA, 2013	Object: Warehouse fertiliser storage Source: not known with certainty Fuel load (burned): seeds, woodframe buildings, as the aftermath of the fire event, mass explosion of some 50 tons AN-based fertilizers Environment exposure: many built infrastructures on a large area, including several schools and medical care for elderly people Comment: 15 fatalities incl. 14 firemen, and more than 260 injured , have lead to concentrate the analysis of the techncial understanding of the reasons for this incident, incl. the regulatory context gaps ; no information so far on damage to the environment, beyond destruction of many built infrastructures	Banks [39] Cbs [40]
Lac Megantic, Canada, 2013	Object: Petroleum fire in Lac Magantic downtown Source: Train derailment with petroleum spillage Fuel load (burned): 5 400 m3 of petroleum Environmental exposure: Petroleum flows to the lac Megantic and to the Chaudiere river. The decontamination cost is estimated to more than 150 M$	Galvez-Cloutier et al. [41] Saint-Laurent et al. [42]
São Francisco do Sul, Brazil, 2014	Object: Warehouse containing fertilisers imported from Russia some 20 days before the event Source: not actually evidenced by local investigation Fuel load (burned): SSD of 10,000 tons NK fertiliser Environment exposure: some 5000 tons of gases and smoke plume dispersed over a period of 3 days. Wind conveyed the plume towards the nearby harbor in parallel to a high traffic road where several sectors had been evacuated; more than 100 people treated for smoke inhalation, no reported death Comments: local investigator of that fire contacted INERIS to get some support in the analysis. From information collected, contamination of the fertiliser during transport may be one of the cause of the incident	Marlair [43]
Tianjin, China, 2015	Object: Port of Tianjin Source: First explosion in an overheated container of dry nitrocellulose. A second larger explosion occurred in container with 800 tonnes Ammonium nitrate leading to spread and burning over many days Fuel load (burned): Significant amounts of material across the port and surrounding facilities, e.g. >12 000cars, 300 building and 7 500 containers were damaged Environmental exposure: estimated 173 fatalities, 104 of which were firefighters. Significant environmental damage due to toxic chemicals stored in large quantities. In particular environmental damage is reported to be bound to the involvement of significant amounts of Sodium cyanide.	Zhang et al. [44] Chen et al. [45]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
Mishrag (near Mosul), Irak, 2016	Object: Al-MIshraq State Sulfur Plant, heap of sulfur extracted and refined from largest native sulfur deposit (500 million tons eq. elemental S) Source: deliberate ignition, as a warfare tactic by Daesh Fuel load (burned): huge sulfur stockpile Environment exposure: environmental impact mainly associated to huge SO_2 and H_2S releases, included casualties (2 deaths, > 1000 persons suffering breathing problems). SO_2 mass release of 161 kt over 6 days, estimated to correspond to minor volcanic eruptions	Björnham et al. [46] Rudaw [47]
Fort McMurray, Canada, 2016	Object: Horse River Wildfire Source: Unknown Fuel load (burned): 2 400 homes and businesses + 590 000 hectare wildland Environmental Exposure: total disruption of a community with mandatory evacuation of approximately 88 000 residents. An estimated insurance cost of USD 3.58 billion. Emissions to air, water and soil. Significant increase in mental health symptoms	Woolf [48] Brown et al. [49] Adams et al. [50]
London, UK, 2017	Object: Grenfell Tower Source: Combined refridgerator/freezer unit on 4th floor Fuel load (burned): 127 apartments in high-rise residential building Environmental exposure: Emissions to the soil have been posed as toxic and an enquiry is still underway	Gov.Uk [51]
Kemerovo, Russia, 2018	Object: Winter Cherry Shopping mall and entertainment complex Source: Ignited in fouth floor in childrens play rooms Fuel load (burned): four storeys of the shopping mall and entertainment center, 64 dead. Environmental exposure: no report of specific environmental exposure	San Francisco Chronicle [52] Interfax [53]
Fire SIAAP Achères, 2018	Object: fire in a wasterwater treatement plan on the clariflocculation process (process dedicated to particles capture) Source: unknown Fuel load (burned): wastewater treatment installation, some toxic product were involved in the fire as ferric chloride Environmental exposure: Strong reduction of the oxygen level in the Seine river with numerous fish death (more than 5 t, more 10 km of river concerned)	TR78 [54]

(continued)

Table 2.1 (continued)

Fire incident (Name and Year)	Description	References
Paris, France, 2019	Object: Notre Dame cathedral fire Source: The source of ignition is unkown but probably linked with renovation works that were in progress Fuel load (burned): The wood that consituted the frame of the cathedral (oak) Environmental Exposure: The cover was made of lead that was melt during the fire and then produced lead oxide that was partially dispersed with the fire smoke. More than 200 t of lead was present	Tiago Miguel [55] Tognet and Truchot [56] Date et al. [57]
Rouen, France, 2019	Object: Warehouse fire Source: Unknown, under investigation Fuel load (burned): Lubricant additives for the automotive industry Environmental Exposure: Environmental impact of that fire is under investigation	Perrin and Laurent [58]
Beirut, Lebanon, 2020	Object: Beirut Port Source: Unknown, under investigation Fuel load (burned): approx. 2 750 tons ammonium nitrate Environmental Exposure: At least 204 deaths, 6500 injuries, and US$15 billion in property damage, and leaving an estimated 300,000 people homeless	Gorriz [59] Wikipedia [60]
Cumulative small scale fires, every year	Object: Numerous structural fires Source: Variety of sources. Electrical and cooking are typically the main sources of ignition together with smokers materials (which is on the decline) Fuel load (burned): Combustible structural material and building contents Environmental Exposure: Emissions to air, water and soil to varying degrees depending on the size and duration of the fire. Estimates from Persson and Simonson put emissions from fires in Sweden on an annual basis to approximately 21 kton CO_2, 1 kton CO, 1 ton HCN, 42 ton NOx, 131 ton SO_2, 138 ton HCl and 1 kton particles for a population of 9 Million.	Persson and Simonson [61] Abraham et al. [62] Love et al. [63]

Note: In a recently published UNECE safety guideline about fire water run-off management [64], the reader may find some other fire incidents not included in the list that are analyzed in terms of water impact, brief data on environmental impact costs are also mentioned

Large quantities of water and firefighting foam were used to control the fire. The extinguishment activities for the main fire took approximately 60 h and required 786 kliters of concentrate with 53 Mliters of clean water [34]. Fuel, water and foam spilled from leaking bunds and formed a large pool of liquid to the east of Tank 12 (see Fig. 2.1). The foam used was a perfluorooctane sulphonate, PFOS, and emitted hydrocarbons included a mixture of species typical in petrol such as benzene and xylene. The firewater retention capacity was approximately 2.5 Mliters, which

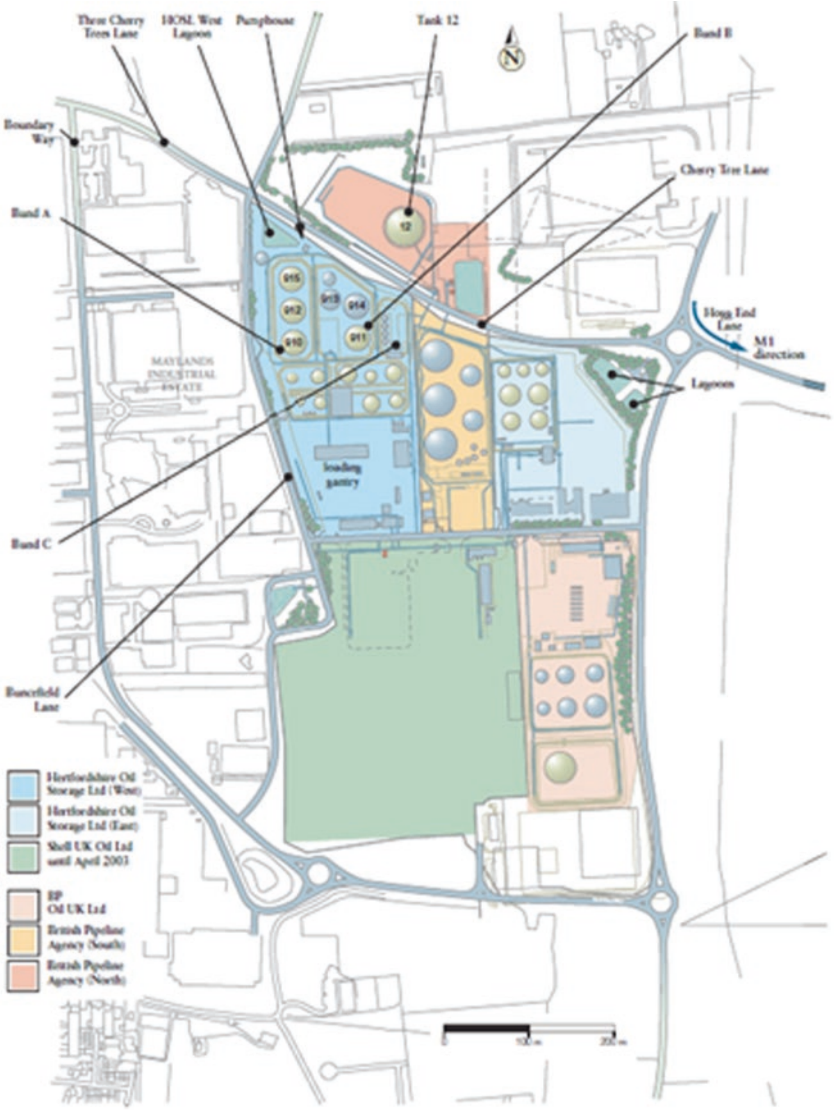

Fig. 2.1 Overview of the Hertfordshire Oil Storage Ltd. (HOSL) facility at Buncfield. (Source: © Crown 2021 copyright Defra via uk-air.defra.gov.uk, licensed under the Open Government Licence (OGL))

corresponded to <5% of the capacity needed, and a large amount of the water and foam applied was lost to local watercourses and ground water [34]. The emissions through firefighting activities were therefore able to enter the chalk stratum below the site and access an aquifer from which potable water is extracted for the region.

While initial findings did not indicate contamination of the drinking water supplies, it is expected that the water supply will need to be monitored for many years to come.

The fire plume from the event was significant. Vautard et al. [66] have estimated that approximately 37 tons of NO_x, 8250 tons of particulate matter <10 mm diameter (PM10) including 4950 tons of PM2.5, 1713 tons of CO and 101 tons of non-methane volatile organic compounds (VOC). Using a combination of satellite measurements and plume modelling Vautard et al. (2007) were able to ascertain that, due to the prevailing weather conditions, the impact of the fire plume was relatively mild on the surrounding environment. The fire plume was ejected high and the stable atmospheric conditions kept it locked at altitude until it could disperse. Therefore, the perturbation in concentrations of, e.g. particulates and NO_x, was negligible compared to background levels.

2.2.2 *Kuwait War Oil Field Fires*

In 1991, as a Gulf war major military action from the Iraqi forces, some 600 oil wells were set on fire over the Kuwait oil field using explosives, undoubtably creating the largest oil field fire that has ever occurred, see Fig. 2.2 [68]. In terms of duration of the event and subsequent environmental impact, the fires represent a massive source of pollution, making it one of the 10 worst manmade disasters of all time. This fire has attracted numerous investigations, and potential environmental concerns were even tentatively forecasted by some parties at a time of the event, announcing extremely gloomy potential environmental consequences, including in terms of regional ‘climate’ impact.

Post crisis assessment based on estimation of quantities of pollutants eventually released show much less environmental impact than expected. Due to complex interaction of various parameters that influenced burning processes and the subsequent chemically reactive fire plume, the emitted pollutant dispersion was affected by

Fig. 2.2 View of burning oil wells in Kuwait 1991. (Reproduced by permission of Bechtel https://www.bechtel.com/projects/kuwait-reconstruction/)

multiple dual scenarios, e.g. well-fire and oil-lake fire scenarios, as a result of the level of destruction of the oil wells and associated infrastructure. Estimation of major pollutant global amounts from these fires highly vary according to published sources. Table 2.2 is a compilation of lowest and highest estimates with most plausible values according to the Kuwait oil company. Early estimates of the overall number of damaged crude oil wells lied in the range 550 to 800, involving 9 out of 13 oil fields developed in Kuwait at that time [69, 70]. Post fire extinguishment reassessment concluded that at in the worst case 613 oil wells were on fire, while 76 were only gushing and 99 were simply damaged (without fire or gushing) during the Gulf war.

A number of studies have been performed on the overall combustion process of the oil fires and on the fate of pollutant emissions, see e.g. Sadiq, Mian [68] and Husain [69]. A joint initiative was conducted during the summer 1991 by the Kuweit Environmental Protection Department (KEPD) and Royal Saudi Air Force, together with a number of organizations that offered assistance (NASA, US EPA, Meteorology and Environmental Protection Administration (MEPA) to control the aftermath of the situation. This led to some additional qualitative observations of the various types of fire plumes associated to oil field and scenarios concerned. The fire plumes were categorized into three types, i.e. (i), black smoke plume from well fires, due to high content elemental carbon in the smoke, (ii), white smoke plume, accounting for up to one third of total plume lengths, whose color was primarily due to high salt content and different plume chemistry, and (iii) oil pool and lake fire plumes, also predominantly black but with a different composition compared to type (i) plumes and moving in a different manner in the atmosphere.

Additional data were also recorded from a number of direct sampling of pollutants (soot, CO, CO_2, NO_x, benzene, ozone…) by helicopter in the plume and nearby the plume, some 300 m to 400 m downwind the fire and all along the plume

Table 2.2 Key data regarding product releases during the Kuwait gulf war fire

Kuwait oil fire metrics	Estimation range	Most plausible order of magnitude
Number of oil pit on fires	550–800	
Overall burning rate (peak)	2–6 million barrels per day	4 million barrels per day (eg ~640 million liters/day)
Soot (5–10 wt % mass fraction of oil burnt)		< 4% wt
Soot emissions	3400 tons per day (as C)	3400 tons per day (as C)
SO_2 emissions	5500–22,400 tons per day	15,000–20,000 tons per day
CO_2 emissions	170,000–1,800,000 tons per day	7,000,000 tons per day
CO	252–10,300 tons per day	Nd
NO_x emissions		~ 550 tons/day (90% from gas combustion(*),

Compiled and adapted from [68, 69]
(*) data from Burgan oil field fire

direction at various distances from fire sources. It was observed notably that most of SO_2 emissions converted rapidly into sulfates, due to presence of metal traces and inorganic salts in the burning crudes. Detailed analysis of particles and soot (soot as carbon conversion ratio from total carbon in the crude, particle size distribution, submicronic particle fraction etc.) was also conducted. Concentrations of soot in overall particles was found rating some 20–25% in the black smoke plume while counting only 4% in the white smoke plumes. More detailed data were reported by Husain [69].

2.2.3 Lac Megantic

In 2013 on July the 6th, a train containing 72 wagons filled with petrol, derailed near Lake Megantic, Canada [41, 42]. Approximately 5700 m^3 of burning petroleum fuel spilled and propagated the fire through surface and underground installations. Firefighting lasted 2 days and more than 2000 people were evacuated. This fire had dramatic human consequences including 47 deaths and many casualties. Environmental impact mainly consisted of pollution of the Chaudiere River along 80 km where fish death was observed, fishing and swimming was forbidden and water extraction for human consumption was stopped for 2 months.

The atmospheric dispersion and resultant consequences were not discussed although a large smoke cloud was produced, see Fig. 2.3.

According to the total amount of petroleum, about 14,000 kg of CO_2 were produced during this accident. Such an approximation obviously depends on the real behaviour of the fire which can vary strongly from one point to another, but this provides a reasonable order of magnitude.

Such a fire highlights the properties of the smoke cloud that contains several kinds of gases, including combustion products but also a large quantity of nitrogen, and particles. It offers the opportunity to apply commonly used methods for impact modelling to highlight its limitation. Consequences should be distinguished between immediate toxicity and chronic consequences.

Regarding acute toxicity, the toxic gas concentration in the cloud is not significant, and the air dilution leads rapidly to a reduction of plume toxicity. However, the relevance of such approaches for very large fire could be discussed. Considering that a 30 m diameter pool surface, corresponding to a 700 m^2 pool, can be used to represent the Lac Megantic fire, it is possible to make some computation to evaluate consequences. This surface is probably not the maximum value reached during the fire but as the surface area increases the acute toxicity will decrease.

It is clear that such a huge fire is out of the scope of all existing analytical models. Evaluating consequences, however, requires one to make some assumptions and use some correlations as input of models. Since no more suitable relation is available, the Heskestad [72] correlation was used to described the smoke plume in the vicinity of the fire despite the fact that this is outside of the typical range of application for this correlation.

Fig. 2.3 Smoke cloud from the Lac Megantic petroleum fire [71]. (Source: Wikipedia [71])

Table 2.3 Main quantities for acute atmospheric dispersion source term [4]

Quantity	Physical value
Total HRR, Q_t	1700 MW
Convective HRR, Q_c	1100 MW
Height of emission, h	45 m
Total smoke mass flux, ϕ_t	5500 kg/s
Vertical velocity, v_h	15 m/s

Using Heskestad's [72] equations and considering that smoke is emitted to the atmosphere at a temperature of 250 °C, i.e. the temperature that corresponds to the threshold where the wind effect is no longer negligible, it is possible to evaluate the smoke composition, the height of fire plume and the vertical velocity. Knowing the composition of the products, the proportion of each acute toxic gas can be determined. If we assume a surface fire corresponding to 70,000 m^2 surface area and considering a combustion rate of 60 $g/m^2/s$ for the petrol with a heat of combustion of 40 MJ/kg, this gives the results presented in Table 2.3. More details of the calculations models can be found in McNamee et al. [4].

Based on a fuel than contain about 2% by mass of sulfur and nitrogen, the smoke composition, assuming that the molecular CO/CO_2 ratio is 0.25 at the height of emission, will be as described in Table 2.4.

The equivalent toxic threshold for such a mixture is about 16,214 ppm based on AEGL toxic thresholds. The computed consequences show that, even for such a fire, no acute toxicity is estimated near the ground, Fig. 2.4. On this figure, the smoke cloud was evaluated for different atmospheric stabilities as defined by Pasquill [67], from A for an unstable atmosphere boundary layer to F for a stable one, and different wind velocities, 2–10 m/s, measured 10 m above the ground. Figure 2.4 illustrates toxic calculations for the fire plume for a variety of combinations of stability class (A to F) and wind velocity (2–10 m/s).

While such results provide some information about human consequences of fire they also raise many questions. The two main issues with the calculations are: (1) The cloud dispersion was computed at a given time that corresponds to the maximum HRR. According to the equation that described the source term, while the maximum HRR gives the maximum smoke mass flow rate, it also corresponds to the more important emission rate and vertical velocity. As a consequence, it is not obvious to determine the worst situation regarding acute toxicity. An improvement for such a consequence evaluation should be to evaluate the HRR evolution versus time and to compute toxicity as a dose. This is however highly complex since evaluating the HRR evolution versus time imposes to consider firemen action into the HRR evaluation model. (2) The toxicity calculations assume a CO/CO_2 ratio of 0,25. Typically, the transformation rate of carbon into carbon monoxide and dioxide should be determined, but the CO/CO_2 ratio depends on the fire conditions, whether the fire is underventilated or not, for example. This is exactly the same for all hetero atoms that are present such as sulfur. The application of a global chemical mechanism hypothesis is used since full transformation mechanisms are complex to model.

Predicting the chronic potential impact due to dioxin, PAH or particles requires being able to model the fire dynamics the HRR and the corresponding physic characteristics but also the emission factor for all of those products. Such emission factors are highly complex and very little data exists. Furthermore, regarding particles, one of the key parameters is the particle diameter that is rarely measured. While some data are available for the global particle emission factor [73], very few publications provide information about particle diameter.

Table 2.4 Main quantities for acute atmospheric dispersion source term [4]

Gas	Mass fraction
CO_2	0.75%
CO	0.30%
SO_2	0,015%
HCN	0,012%
NO_2	0,012%
Air, entrained by the plume	98,92%

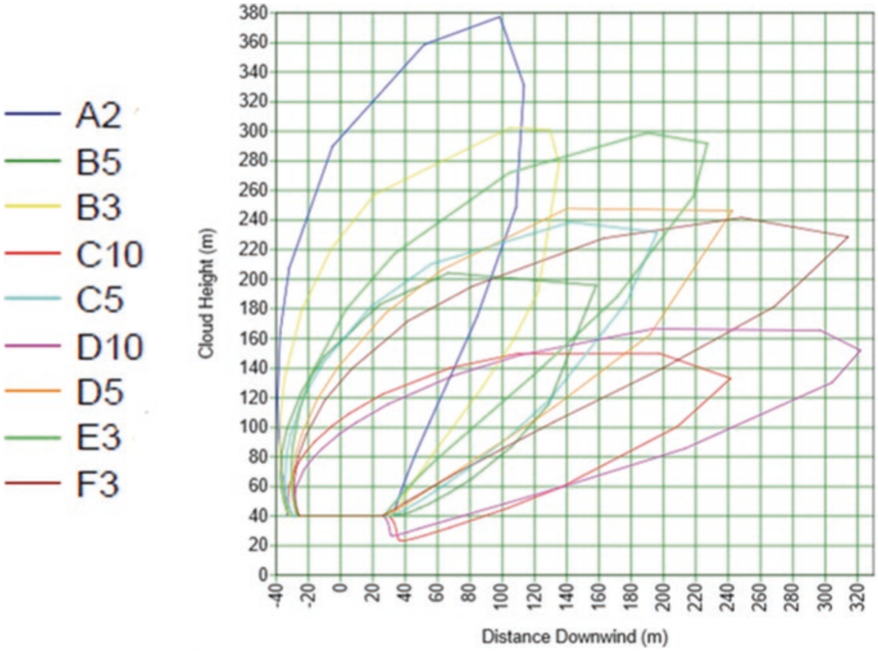

Fig. 2.4 Acute toxicity cloud computation for different wind profiles [4]. The legend denotes the atmospheric stability class (A to F) and wind spread (2–10 m/s)

Table 2.5 Estimation of particle drop distance [4]

Diameter [µm]	Re_p [−]	C_d [−]	Drop Speed [m/s]	Distance of dispersion
1	1.73E-01	1.39E+02	1.57E-04	> 500 km
15	2.60E+00	1.19E+01	2.74E-02	≈ 350 m
30	5.19E+00	6.77E+00	9.66E-02	≈ 1000 m
50	8.65E+00	4.61E+00	2.37E-01	< 400 m

Consequently, predicting this kind of impact using modelling is too complex and models should be coupled with analysis based on ground measurement [74]. A simplified calculation provides an illustration of these limitations. Considering particle emission, depending on the diameter, the deposit velocity can be evaluated using the Stokes law, i.e. the equilibrium between the gravity force and the drag force. Assuming that the particle density can be approximated by the carbon density, 2200 kg.m^3, Table 2.5 gives the estimated impact distance that corresponds to the required time for the particle to drop at its maximum drop velocity based on an emission at the Heskestad height computed above, e.g. 45 m for a wind velocity of 3 m/s. One should keep in mind that this evaluation, as all particle dispersion models, assumes that particles are emitted at the Heskestad height which could be a large overestimation in several situations. More details of the calculations models can be found in McNamee et al. [4].

So, while this aspect is the most critical in terms of environmental impact, its prediction still requires strong improvement to make it relevant. There is also many questions regarding the impact in terms of water toxicity and ecotoxicity that is virtually unpredictable since very little data exists regarding the pollutant transfer into water.

2.2.4 Tire Fire in Malmö

It has been estimated that each year automobiles produce 240–250 million waste tires in the US alone [75]. Fires in such waste facilities are an unfortunate recurring event all over the world. The potential environmental impact of such a fire is exemplified by an incident in the Swedish coastal city of Malmö in 2001. The tire facility was located in an industrial part of Malmö, close to the local harbor area. An equipment failure on September 22, 2001, led to the ignition of waste tires at the tire recycling facility in Malmö, Däck Rec. The waste storage was estimated to be approximately 6000 metric tons. The Fire and Rescue services were called to the scene and responded with all available resources. After unsuccessfully attempting to extinguish the fire for almost 24 h, the decision was taken to push the burning material into the harbor [76]. The unusual decision was made due to the proximity of the fire to central Malmö city, the third largest city in Sweden.

It is estimated that some 400 tons burning material were dumped into the harbor. No measurements were made concerning emissions in the harbor or to the city from the fire debris or the fire plume. Experimental data is, however, available for burning tires under conditions similar to those in the Malmö fire incident [77, 78]. If we assume the worst emissions case for burning tires in a pile as tested by Lönnermark [77] and the consumption of at least as much material as was dumped into the harbor, we can estimate emissions of PAH, dioxin and furan species from the fire in Malmö, see Table 2.6.

2.3 Chemical Products

2.3.1 Sandoz Fire

From the night of October 31 into November 1, 1986, a fire engulfed a Sandoz Ltd. warehouse at Schweizerhalle near Basel, Switzerland. The warehouse contained some 1250 tons of pesticides, solvents, dyes, and various raw and intermediate materials. The 90 m by 50 m warehouse was originally constructed to store machinery, and therefore lacked smoke detection and sprinkler systems and only contained one dividing wall. This contributed to late detection and poor containment of the fire. Given the amount of stored materials, considerable water was needed to control the fire. This was exacerbated by the need to control the fire from reaching a nearby

Table 2.6 Conservative estimate of PAH and dioxin/furan emissions from tire fire assuming emissions commensurate with Lönnermark [77] experiment T6 and a burned mass of 400 tons tires

Species	Yield	Emission
PAH	**mg/kg**	**kg**
Benzo(a)anthracene	6,6	2,64
Benzo(a)pyrene	5,9	2,36
Benzo(b)fluoranthene	6,6	2,64
Benzo(k)fluoranthene	1,5	0,6
Chrysene/Triphenylene	11	4,4
Dibenzo(a,h)anthracene	1,4	0,56
Indeno(1,2,3-cd)pyrene	4,6	1,84
PAH, total carcinogenic	**38**	**15,2**
Acenaphtene	8,1	3,24
Acenaphtylene	5,6	2,24
Anthracene	10	4
Benzo(ghi)perylene	11	4,4
Phenanthrene	34	13,6
Fluoranthene	15	6
Fluorene	9,8	3,92
Naphtalene	78	31,2
Pyrene	30	12
PAH, total others	**200**	**80**
Dioxins	**ng/kg**	**g**
2378 TCDD	2,2	0,88
12,378 PeCDD	4,3	1,72
123,478 HxCDD	2,8	1,12
123,678 HxCDD	10	4
123,789 HxCDD	13	5,2
1,234,678 HpCDD	33	13,2
OCDD	27	10,8
Furans	**ng/kg**	**g**
2378 TCDF	2	0,8
12,378 PeCDF	4,4	1,76
23,478 PeCDF	3,2	1,28
123,478 HxCDF	6,1	2,44
123,678 HxCDF	2,2	0,88
123,789 HxCDF	3,2	1,28
234,678 HxCDF	3	1,2
1,234,678 HpCDF	10	4
1,234,789 HpCDF	4,2	1,68
OCDF	9,3	3,72
TCDD-equivalent (I-TEQ) upper bound	**11**	**4,4**

warehouse containing phosgene, a highly poisonous gas. While almost all the stored materials were consumed by the fire, large quantities were introduced into the soil and groundwater at the site, into the Rhine River through runoff of the firefighting water, and into the atmosphere. Although the site was equipped with a sewer system that could be sealed off in the event of an oil spill, on the night of the fire the seals were not closed. However, even if the system had been sealed off, the firefighting water, estimated at between 10,000 and 15,000 m^3, would still have made its way into the Rhine, as much of the runoff was discharged into the Rhine via a drain designed for uncontaminated cooling water.

Approximately 9 tons of pesticides and 130 kg of organic mercury compounds infiltrated the soil. The pollutants could be detected at depths of up to 11 m. Remediation of the fire site and the contaminated soil took about 6 years, with 2700 tons of semi-combusted material being disposed of. The chemicals discharged into the Rhine River by the firefighting runoff resulted in large-scale kills of benthic organisms and fish, particularly eels and salmonids, with impacts observed as far away at the Netherlands. Of particular note was the eel kill, which spread from Schweizerhalle some 400 km downstream to Loreley (near Koblenz). In addition, other fish species were also severely affected, including grayling, brown trout, pike, and pikeperch, as well as typical food for the fish [15].

While the environmental impacts of the Sandoz event are well documented, the costs of those impacts are difficult to identify, and no comprehensive allocations were identified in this search. Although one resource identified some 100 Million Swiss francs in claims had been presented to Sandoz as of September 1987 [79], these largely reflect direct and indirect health and business losses, with valuation of the economic costs unclear.

2.3.2 West (SA) and Al-Mishraq (Iraq) Sulfur Fires

Two major industrial sites (one in South Africa in Western Cape Province (1995) and in Iraq, near the town of Mosul, experienced very large and long-lasting fires that have heavily impacted the environment, as a result of massive emission of SO_2 (and H_2S in the case of Al-Mishraq site) from elemental sulfur combustion. Figure 2.5 shows the smoke cloud resulting from the event taking place in Al-Mishraq. An estimation of SO_2 pollution was achieved for the fire that occurred in 2016 in the same place, see Fig. 2.6. It is interesting to mention that the data presented in Fig. 2.6 was obtained from a specific measurement technique using satellite data.

A full description of the West fire is given in Batterman et al. [21]. Before the fire, sulfur was stocked into three piles, 3 m high and about 200 × 130 m^2 each for a total mass of 15,710 kg of sulfur. During the day before the sulfur fire, several grass fires occur in the surrounding of the storage, before the sulfur ignited, melted and burnt. During firefighting operations, large amounts of water were applied using a helicopter as the closest fire hydrant was more than 1 km away.

Fig. 2.5 Satellite photograph of Al-Mishraq State Sulfur Plant October 22, 2016 (NASA Earth Observatory) [80]

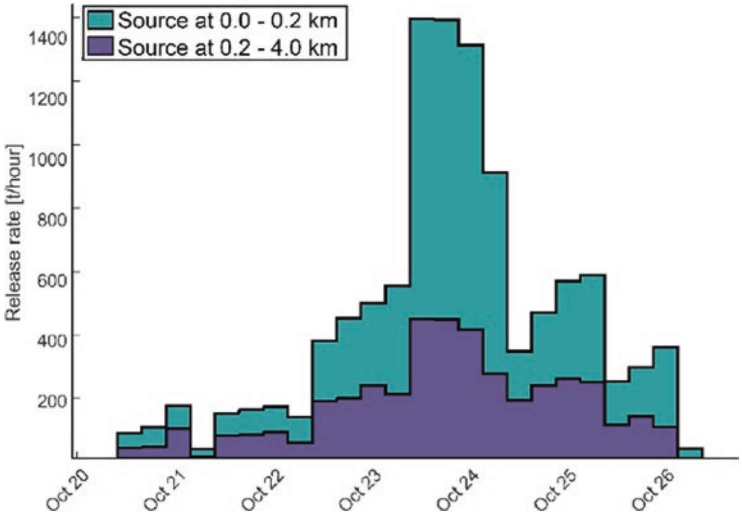

Fig. 2.6 Estimation of the SO_2 source term of pollution version time in the Al-Mishraq 2016 event. (Reproduced without changes from [46]). Published under the terms of the Creative Commons Attribution-NonCommercial-No Derivatives License (CC BY NC ND)

The fire lasted about 20 h and concerned 7250 kg of sulfur of the 15,710 kg that were stored. Some 10–15 deaths were reported following this accident, although very few data points are available regarding toxic concentration since only some measurement points were considered.

It should be noted that, according to the post analysis of that accident using the European scale of industrial accident, the environmental impact was set to 0, which means that all of corresponding criteria were 0, due to lack of data.

In Batterman et al. [21], some numerical simulations managed to predict sulfur concentrations in the surrounding of fire. The methodology used is similar to the one described in Chap. 4 of this report by first evaluating the source term of toxic gases, mainly SO_2, then using the characteristics of the source term, smoke total volume and temperature were computed to finally be introduced into a dispersion model. In the following paragraph, the main steps of the process as published are reported and discussed regarding recently available data.

The gas composition is assumed to be mainly SO_2. The mass flow rate of SO_2 production is computed considering the total mass burnt of sulfur, 7250 kg, and the fire duration, 21 h. To this end, the SO_2 mass flow rate is assumed to be constant, with the exception of the initial 2 h fire growth period, before the fire fighting become efficient, 10 h after its ignition. The surface of the fire is estimated to 25,000 m^2. Based on these hypotheses, the mass flow rate of SO_2 is evaluated to 185 kg/s. This source term is next coupled with different hypothesized temperature and emission parameters to compute the concentration distribution along the wind using the dispersion model.

Some points should be highlighted regarding this approach. First of all, the equivalent combustion velocity for the sulfur should be compared with existing data. According to the computed emission flow rate and the uncertainty of the real surface of the fire, the used combustion velocity, around 0,004 $g/m^2/s$ for a 25,000 m^2 fire, is in quite good accordance with experimental values, around 0,008 $g/m^2/s$.

Further, while sulfur is not soluble in water, SO_2 is. Therefore, during the firefighting activities, some sulfur might be caught by the water either in sulfur form, with dissolution; or as SO_2, in which case SO_2 dissociates into the ions sulfite, bisulfite and hydrogen and could induce eco-toxicity for organisms even though its persistence in the environment is weak.

One of key parameter for dispersion consists in the source term description. As described in the previous paragraph, this source term is composed of the concentration of toxic products and with thermo-kinetic parameters such as smoke temperature and vertical velocity. This fire typically illustrates the limit of the plume model since correlations such as the one published by Heskestad [72], are not applicable to model such a plume. Since the air entrainment phenomenon is governed by the fire characteristics, the specific combustion of sulfur should be with dealt specifically, as for many of real fire situations. This requires considering the chemical reaction through their representative equations, using the combustion velocity to evaluate the reaction rate and then computing the production rate and toxic gases and their temperature based on the release of chemical energy.

The global analysis of South African and Iraq fires also highlights a key issue when dealing with real fires, i.e. the information about the combustible product. While in South Africa, sulfur burned alone and produced only $SO_{2.}$ In Iraq, the sulfur was mixed with flammable liquid that led to H_2S emissions in addition to SO_2. This obviously has an impact on acute toxicity products, and also potentially is significant when dealing with the other aspect of the environmental impact.

2.3.3 Kolding Fireworks Fire

In the afternoon of the 3rd November 2004, workers for the N.P. Johnsens Fireworks factory were moving fireworks from a container to outside the container for further distribution. During relocation of specific fireworks objects to a pallet outside the storage container a packet of rockets was dropped and ignited. The ignited rockets spread the fire to other fireworks both inside and outside the container.

The Fire and Rescue Service (FRS) in the area was called to the scene to combat a "fire" and according to company policy, staff was evacuated. Initially, during the first phase of the incident, the FRS determined that the fire was under control. Problems due to that fact that the fire post was out of function caused all water supply to be through tank vehicles which restricted suppression activities. At approximately 15.30 the first explosion in a nearby container occurred causing an unexpected escalation of the incident and resulting in the death of one firefighter on the scene. Further explosions over a period of several hours caused the spread of the incident beyond the industrial site to nearby residential buildings [29]. The incident has been divided into three phases by the fire investigation as summarized in Table 2.7.

In total some 800 people were directly involved including approximately 350 firefighters, 150 police and 300 other services. In total, including hospital and other service personnel it is estimated that some 3000 professionals were involved in the response in some capacity. Costs for the response alone were estimated to 7 M€. In addition, 20 buildings were fully destroyed, some 350 buildings were heavily damaged (including approximately 10 small and medium sized enterprises). Further 760 homes, including approximately 2000 people were evacuated within a 1 km radius [81]. The facility at Kolding was permitted to store a maximum of 300 tons explosive material and the subsequent fire investigation indicated that the facility was close to this capacity, although it has been speculated that the facility was storing up to 8 times the allowed amount of fireworks. Before and after views of the seat of the fire in the industrial area of N.P. Johnsens are shown in Fig. 2.7.

The full fire emissions from the Kolding fire include many emissions from materials and buildings which are typical for residential areas and these are dealt with to a certain degree in later sections. What stands out in the Kolding incident is the burning and explosion of fireworks and the emissions that would be expected to be associated with such materials. Pyrotechnic compositions are challenging in many ways. We do not have as much information available concerning fire behaviour or emissions but some basic information is available in the literature [84, 85] or can be

Table 2.7 Summary of timing of the fireworks fire in Kolding, Denmark 2004 [29]

Timing	Description
Phase 1	**From alarm to first explosion**
3rd november, 2004, 14.02	Alarm received by dispatchers. Kolding Police, Incident leaders from local FRS and Falck Alarm notified. Incident leaders and a 7-man team of firefighters dispatched Fire in and around a 40 m container Personnel evacuated
14.32	Police on site note there is a risk that the fire in the 40 m container could spread to nearby 20 m containers.
14.45	Incident Commander decides that the response team is sufficient to control the fire (3 water lines and 7 water tanks)
15.15	Incident Commander determines the fire is under control as the fire intensity inside the container has fallen significantly. The plan is to turn the final suppression over to company personnel when the smoke production has been reduced further
Ca 15.25	Tank vehicles supplying two of the three water lines are empty and only one tank line is on the fire
Phase 2	**From first explosion to escalation**
15.25	An explosion unexpectedly occurs in the container. One firefighter is killed and several others injured
15.26	Incident Commander orders all personnel to fall back
15.30	The Incident Commander declares a state of emergency
15.32	Second explosion. All incident personnel leaves the area and for approx. 1 h there is no clear picture of incident development
15.55	Additional tank vehicles arrive from FRS Sydjylland and Kolding
16.10	FRS Fredericia arrives
16.15	FRS from Vejle arrives
16.25	Incident management is reorganized approx. 600 m from the incident site for safety reasons and additional personnel called in
Phase 3	**From escalation to extinction**
17.45	Additional three explosions. The Incident Management is divided into three teams, each with its own incident command with responsibility for the following areas: residential area, industrial area and Overby Road
	Incident response continues for the following 3 days with containment, evacuation, and suppression
7th November 2004, 13.30	Incident declared closed

gleaned from chemical composition. Table 2.8 gives a summary of significant products which might be emitted from the reaction of fireworks [84].

While there appears to be no publicly available data concerning emissions to the environment in Kolding, investigations after a similar fireworks incident in Enschede in 2000 [86] indicated excessive amounts of metals could be found in the environment long after the event.

Fig. 2.7 Before and after figures from the fire at N.P. Johnsens [82, 83]. Source: Reproduced with permission of Finn Hansen (photographer), retired from Kolding Fire and Rescue Services

Table 2.8 Summary of potential species produced from combustion of fireworks [84]

Phase	Examples of chemicals produced
Gaseous	CO, CO_2, H_2, H_2S, CH_4, COS, N_2, NO_x, O_2, SO_2, etc
Aerosols	Al_2O_3, $(NH_4)_2CO_3$, Sb_2P_2, $BaCO_3$, $BaSO_3$, Bi_2O_3, C (charcoal), CuO, Fe_2O_3, MgO, KCl, K_2O, K_2O_3, KNO_3, K_2SO_4, K_2S, K_2SO_3, $KCNS$, $SrCO_3$, $SrSO_4$, TiO, etc

2.4 Wildland (Biomass) Fire

Wildland fires create significant emissions to the environment through emissions to air, water and soil and by the environmental impact of firefighting activities. In recent years, increasing focus has been placed on the potential environmental impact of large scale forest fires in addition to the patent economic and societal losses. The development of an international technical specification on assessing the environmental impact of fires has created a starting point for the presentation of the environmental impact of fires [87]. The problem of the environmental impact of wildfires is a complex one with implications both globally (in terms of increased green house emissions) and locally (in terms of reduced biodiversity in a specific area) and the commiserate mitigation will be complex [88]. The scope of the problem will be illustrated by a specific case of fires in Sweden 2018.

2.4.1 Wildland Fires in Sweden

The summer of 2018 in Sweden was one of the hottest on record, but in contrast to other years with unusually hot weather the summer of 2018 had a very high fire risk for an extended period of time. From the end of May 2018, a series of wildland fires raged at a variety of locations across the country. On July 7, MSB Civil Contingencies Agency established a national center for incident management of the on-going and expected wildland fires in the country. Just over 1 week later (July 16), MSB requested support from the EU and neighboring countries in the Nordic region. Incident management of the ongoing wildland fire response was the largest combined response in the EU in modern time. By early August the majority of the international resources could leave Sweden and national efforts could be met mainly using Swedish resources. Finally on August 17, MSB could conclude the national response and return to routine operations under municipal leadership [89].

It is estimated that some 20,500 hectares of forestland was destroyed in the wildland fires, the largest area for any given year in Sweden in modern time, see Table 2.9 [90, 91]. In total, an assessment was made that the volume lost was equivalent to approximately 2,1 Mm^3 wood. If we assume a wood density in Sweden and Norway of 85 $\mathrm{mg/cm}^3$ [92] this corresponds to 180 kton wood burned in these fires. Blomqvist et al. [93] made some estimates of emissions yield for some common organic pollutants from wildland fires. Using these yields, the approximate emissions of dioxins, PAH and VOC from these wildland fires is given in Table 2.10.

The potential environmental impact of wildland fires is significantly more far-reaching than emissions to the environment and the undoubted toll of these. The impact on biodiversity and vulnerability of the environment after a wildland fire is also potentially significant and the subject of some study in modern time, see for example the work of Malcolm et al. [88].

2.5 Built Environment

Fires in the built environment often gain attention due to the fact that the majority of fire deaths occur in buildings, largely in homes. Emissions from buildings are often seen to be relatively minor compared to major industrial fires, and rightly so. This section, however, gives some insight into the fact that this may not be true in the case of particularly large or unusual buildings by using the example of the Notre Dame fire in Paris 2019. Further, while individual building fires may represent relatively small emissions, the cumulative impact of fire emissions from building fires

Table 2.9 Collation of number of fires and the commiserate area of forest involved in the fires of 2018 [90]

County	# fire	Burned forest (hectare)
Blekinge	7	10
Dalarna	29	3198
Gävleborg	28	8856
Halland	1	0
Jämtland	28	5233
Jönköping	1	0
Kalmar	14	45
Kronoberg	7	65
Norrbotten	40	1253
Skåne	1	1
Stockholm	14	12
Södermanland	2	1
Uppsala	14	27
Värmland	17	412
Västerbotten	25	422
Västernorrland	4	119
Västra Götaland	10	25
Örebro	13	77
Östergötland	14	16

Table 2.10 Estimated emissions from 2018 wildland fires in Sweden

Species	TCDD/F equivalent (TEQ)	PAH (BaP-equivalent)	VOC
Wildland fires (yield)	$0{,}002 \times 10^{-6}$ kg/kg	$0{,}1\text{–}1 \times 10^{-3}$ kg/kg	$1\text{–}20 \times 10^{-3}$ kg/kg
2018 wildland fires in Sweden	0,4 kg	18–180 ton	180–3600 ton

each year could be significant as illustrated by the assessment of all fire emissions in a typical year in Sweden using two different methods.

2.5.1 *Notre Dame*

In 2019, April the 15th, during significant renovation work, the Notre-Dame cathedral caught fire at approximately around 7:00 pm. Rapidly, a large amount of smoke was visible in the sky of Paris, and one could observe flames, see Fig. 2.8. In total, the fire lasted for approximately 15 h, including the 5 first hours of the fully developed fire.

Fig. 2.8 Smoke cloud and visible flame during the Notre-Dame fire [56]

While the environmental impact of such a large fire in a city centre is certainly a key aspect, the question exacerbated because the cover of the cathedral was made of hundreds of tons of lead on large oak beams. This fire is the equivalent of an area of close to 1700 m^2 of a large forest of such beams. The estimated peak heat release rate value was 2300 MW [56, 94]. The behaviour of lead in such a situation is quite complex having in mind the following properties:

- melting temperature is 327 °C;
- oxide formation occurs from 600 °C;
- boiling temperature is 1749 °C.

Considering this, it is clear than lead can flow after melting down to the ground and, if mixed with the extinction water, enter the surroundings. Further, oxides can be formed in the flaming zone and then be dispersed with the smoke plume.

Numerous analyses were conducted in the weeks and months after the fire, to evaluate the environmental impact of the fire due to the lead. Initially, soon after the fire, samples were taken in the air and in soil, not only on several sites in Paris, but also along the potential plume dispersion direction, dozens of kilometers from the fire. Such a fire highlights the difficulties of post-incident fire assessment in an urban environment, especially since lead was used for many years in various applications like paintings and fuels and some residual pollution should be present as a background level. A synthesis of official sampling can be found in a report developed by the Regional Health Agency (Agence Régionale de Santé ARS) [95]. A novel method to estimate the environmental impact was also undertaken by analyzing the honey production in the cloud dispersion area, a so called honey map in the direction of the fire plume [96]. Independent of what the real quantification of the environmental impact of the fire is, it is clear that most of the 450 tons of lead stayed in the vicinity of the cathedral, melting and flowing down in the debris [57].

To support sampling analysis, the atmospheric dispersion of the plume was modelled [56]. Such modelling includes two main steps. First the fire was modelled to determine the thermo-kinetic characteristics of the fire plume in the vicinity of the fire. Second the large-scale dispersion was modelled, taking into account the wind characteristics. As mentioned previously, lead was probably dispersed in smoke as an oxide. Therefore, one of the main aspects to evaluate from the dispersion distance was the characteristic diameter of lead oxide particles, several hypothesis were modelled to estimate this influence and work is still on-going.

Another important aspect still under study is the impact on the Seine river that flow in the vicinity of the cathedral due to the large amount of water that was used during the fire. To date, analysis of water characteristics has not indicated significant pollution of water due the fire.

2.5.2 House Fires

Building fires occur regularly in all countries around the world. The potential environmental impact of a single building fire will naturally depend on the type of building and its size and contents. A single house fire is unlikely to have a significant environmental impact or associated cost; but it is well established that a significant number of house fires occur any given year, meaning that the aggregate emissions from these individual fires are likely to be significant. Indeed, in the 1990s, Persson and Simonson [61] established that the overall emissions from fires in Sweden was of the same order of magnitude as emissions from heavy goods vehicle transport during the same time period.

The emission factors for a typical 1–2 family villa and a typical apartment are given in Table 2.11 for both Sweden and the US, using the methodology developed

Table 2.11 Fire emissions typical Swedish residential properties based on Persson et al. [97] and Abraham et al. [62]

Emission	Typical Swedish House ($120\ m^2$) [kg/object]			Typical US House (1350 sqf) [kg/object]	Typical Swedish Apartment ($80\ m^2$) [kg/object]		
	Structure	Interior	TOTAL		Structure	Interior	TOTAL
CO_2	15,803	7880	23,683	–	–	5245	5245
CO	600	312	912	445	–	208	208
NO_x	13	28	41	10,4	–	18	18
HCN	0,1	0,48	0,57	263	–	0,32	0,32
HCl	16	77	93	112	–	51	51
SO_2	193	–	193		42	–	42
Particulates	1331	89	1420	80	271	59	330
Formaldehyde				7,6			
Acrolein				33			
VOC				82			

Table 2.12 Residential fires (5 year average) classified according to the extent of the fire based on NFPA data [98, 99]

# residential fires(2007–2011 averages)	Spread beyond building of origin	Spread beyond room of origin	Beyond object but confined to room	Confined to object of origin
283,500	4%	21%	17%	58%

by Persson and Simonson [61] and by Abraham et al. [62]. Note that the emissions presented for a typical Swedish villa or apartment have been updated relative to those published in 1998 by returning to the original data [97]. It is clear from Table 2.11 that there are significant differences between the estimated emissions. This will also result in significant difference between estimates for the potential environmental impact of residential fires. More work is needed to establish which estimate is closer to the actual emission values.

The environmental impact of a single house fire is arguably small. Therefore, this analysis includes the calculation of the emissions expected from all house fires in the US based on an assumption concerning the number of fires in the US using published data from the NFPA [98, 99]. Table 2.12 contains a summary of fires a typical year based on these statistics.

Using the Swedish methodology the equivalent “Total burn” is calculated as:

$$\textit{Full House Equivalent} = \textit{Full house fire} + 30\% \times \textit{Medium house fire}$$

In terms of the US statistics, the first category (“spread beyond the building of origin”) is equated with a “Full house fire”, while the second category (“spread beyond the room of origin”) is equated to the category “Medium house fire”. In this case the Full House fire equivalent used to calculate the Swedish emissions is 29,200 House

Table 2.13 Emissions for a typical year based on the single house emissions multiplied by a full house equivalent

Emission	Annual emissions a typical year based on Swedish emissions data (29,200 Full House Equivalents) [metric ton]	Annual emissions a typical year based on US emissions data (20,700 Full House Equivalents) [metric ton]
CO_2	692 k	–
CO	26,6 k	9204
NO_x	1190	215
HCN	167	5440
HCl	2710	2320
SO_2	5630	
Particulates	41,5 k	1660
Formaldehyde		157
Acrolein		677
VOC		1690

fires a typical year. For the EPA fire emissions methodology the fire loss rate summarised across all fires is assumed to be 7,3%, which corresponds to a full house equivalent of 20,700 House fires a typical year. These numbers have been used to estimate annual emissions from House fires in the US a typical year, see Table 2.13.

As can be seen in Table 2.13, the estimates vary significantly depending on whether the Swedish or US-based emission factors are applied. This would indicate that even in cases where emission factors do exist there is a need to validate existing data to identify applicability and limitations.

2.6 Conclusion and Lessons Learned

This chapter has endeavored to give a flavor for emissions from fires by providing a list of historically significant fires and a selected number of more detailed case studies. While no such list of selected cases can be complete, they do give an indication of the potential magnitude of the environmental impact of fires. There is much to learn from the study of these events; both successes in their extinguishment and mitigation, and failures, provide significant opportunities to learn. Indeed, the evolution of fire regulation can often be seen in response to large scale incidents. This will no doubt continue into the future.

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Chapter 3
Fire Fundamentals

G. E. Gorbett and S. P. Kozhumal

3.1 Introduction

Fire is defined as "a rapid oxidation process, which is a chemical reaction that results in the evolution of heat and light in varying intensities" [1]. The use of combustion by humans is a major factor in the evolution of human invention and progress, however, uncontrolled combustion has also resulted in some of the world's greatest disasters. Effectively using combustion, preventing ignition, and extinguishing fires require an understanding of the physics and chemistry that influence it. This chapter summarizes the fundamentals of fire and combustion by integrating basic chemistry and physics concepts that will be further explained in detail in other chapters. Additionally, this chapter will provide references to resources for those wishing to delve deeper into any of the fire fundamentals.

3.1.1 Fire Triangle and Fire Tetrahedron

An easy model used to understand combustion is the fire triangle and fire tetrahedron. The fire triangle is a three-sided geometric figure that is intended to reflect the elements necessary for combustion (Fig. 3.1). The sides are fuel, heat, and an oxidizing agent (i.e. oxidant, oxidizer) of equal lengths to represent a triangle. A fourth side, the uninhibited chemical chain reaction, was added in the 1960s changing the model into a tetrahedron (Fig. 3.2). The sides of the model are drawn to be equal in length indicating that all four elements are necessary for combustion to commence.

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Fig. 3.1 Fire Triangle [4]. (Reprinted by permission of Pearson Education, Inc., New York, New York)

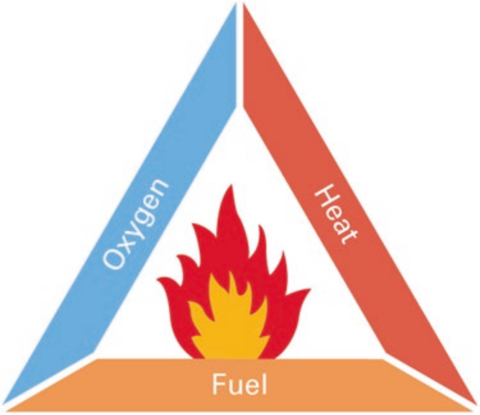
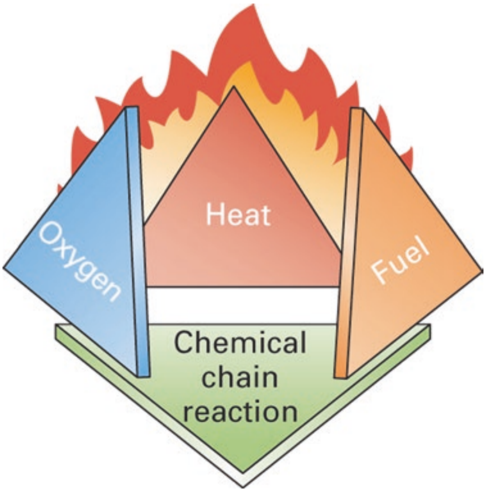


Fig. 3.2 Fire Tetrahedron [4]. (Reprinted by permission of Pearson Education, Inc., New York, New York)



Most commonly the model is used to teach firefighters about extinguishment, where if any of the sides are removed extinguishment of the fire occurs.

It can also be claimed that the fire tetrahedron is the keystone to understanding all of fire protection. Ignition requires all four sides in the correct concentrations, as such fire investigators must identify the first fuel, heat source, oxidizer, and how those elements came together to identify the cause of a fire [2]. Fire protection engineers often use the model as the foundation in designing systems for fire and life safety, conducting fire hazards analyses, and implementing performance-based designs [3]. Each side of the fire tetrahedron is introduced briefly below with further discussion later in the chapter.

Fuel is defined as “any material that will maintain combustion under specified environmental conditions” [5]. The majority of fuels are carbon-based (organic) and often contain other elements including hydrogen, oxygen, and nitrogen (e.g. wood, gasoline, propane, plastics). Combustible metals are examples of some non-carbon-based (inorganic) fuels that may also be encountered (e.g. magnesium, sodium, titanium, potassium). Fuels are often categorized according to their reactivity, hazards, or best agent for suppression.

Heat is defined as "a form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state" [6]. This side of the fire tetrahedron refers to the energy exposed to the fuel for production of sufficient quantity of vapors. Ignition may occur when a heat source can transfer sufficient energy to the fuel to support this production of vapors.

An oxidizing agent is defined as "any material that readily yields oxygen or other oxidizing gas, or that readily reacts to promote or initiate combustion of combustible materials" [7]. The oxidizer is related to the oxidation process that occurs during combustion. Oxidation is the loss of electrons during the chemical reaction, this loss of electrons and the overall reaction in combustion is rapid. The oxidizer in a combustion reaction is commonly oxygen from the air, but can also be found chemically bound within liquids and solids (e.g. hydrogen peroxide, ammonium nitrate).

The chemical chain reaction is referring to the series of reactions that are occurring internally in the combustion reaction, where the products of one reaction contribute to the reactants for the next reaction. For example, the complete combustion of methane (CH_4) is given as a simple balanced equation, such as:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

The arrow in the equation represents the overall combustion reaction, which in this example is a complete reaction which produces only carbon dioxide (CO_2) and water (H_2O). However, in reality, there are approximately thirty-two intermediate steps within this reaction chain [8]. When the chain reaction is interrupted for whatever reason (i.e. not enough oxygen or fuel) then incomplete combustion products are also produced in varying quantities. Energy is released during the reaction, known as the heat of combustion. Specifically, the combustion of methane releases a relatively constant ~50 kJ of energy for each gram of methane oxidized (50 kJ/g – heat of combustion).

3.1.2 Flammable Limits

Fuels generally must be in the gaseous or vapor state to enter into the combustion reaction, therefore, solid and liquid fuels must go through changes in order to enter into the combustion reaction. The chemistry and physics of phase changes and thermal decomposition of solids and liquids are discussed in the fuels section below. Once the fuel is in the correct state to enter the combustion reaction there are similar requirements for combustion to occur, regardless of the initial state of the fuel. Flaming combustion requires that there is an adequate mixture of gaseous fuel and oxygen. This range is typically expressed as a percentage of gaseous fuel to air by volume. Experimental tests are conducted for all fuel vapors to determine the percentage of fuel to air by volume that is required for combustion to occur. This range is known as the flammable limits or the flammable range (explosive range) for that particular fuel. The lowest percentage of fuel to air where combustion begins is known as the lower flammable limit (LFL), while the highest percentage of fuel to air where above which combustion can no longer be supported is known as the upper flammable limits (UFL). Methane gas, for example, is typically flammable between 5% and 15% of fuel to air.

The values obtained for flammable ranges are obtained through experimental testing done under controlled conditions with air (i.e. 20 °C, 1 atm, 21% oxygen in air). The flammable range results will alter when the temperature, pressure, or oxygen concentrations are changed. Specifically, elevated temperatures increase the flammability limits with significant changes occurring to the UFL [9]. Increasing oxygen concentrations increase the range, while decreasing oxygen concentrations narrow the range. Higher pressures imparted on fuel vapors generally increase the flammable range, while lower atmospheric pressures can significantly modify the combustibility of liquid fuels (Table 3.1).

3.1.3 Basics of Ignition

When the four sides of the fire tetrahedron are brought together in sufficient quantities ignition and combustion can begin. Ignition is defined as the "initiation of self-sustained combustion" [11]. Ignition is a complex topic that is dependent on many variables, many of which cannot be sufficiently covered in this chapter. The reader is encouraged to review Babrauskas' work on ignition for further details [10]. The majority of combustion reactions occur from flaming combustion. To summarize the tetrahedron for this type of combustion reaction would be to say that for ignition to occur there must be sufficient fuel available in the correct state (i.e. gas/vapor)

Table 3.1 Flammable Limits Data (Babrauskas [10])

	Flammable Limits (% By Volume in Air)	
Fuel	Lower	Upper
Acetylene gas	2.5	~100
Methane gas	5	15
Hydrogen gas	4	75
Ethane gas	3	12.4
Propane gas	2.1	9.5
n-Butane gas	1.8	8.4
Gasoline vapor	1	7
Fuel oil no. 2 vapor	0.52	4.09

Source: Babrauskas [10] Ignition Handbook mixed with sufficient oxygen from the air and the minimum ignition energy (MIE) is present.

A flammable mixture of fuel and air by itself does not cause combustion. The energy required to initiate the flaming combustion reaction can be defined or described through a variety of terms, including minimum ignition energy (MIE), ignition temperature, and autoignition temperature. Ignition will be discussed in more detail later in this chapter, but it is important to introduce the concept of minimum ignition energy here. Minimum ignition energy is defined as "the minimum amount of energy released at a point in a combustible mixture that causes flame propagation away from the point, under specified test conditions" [12]. In other words, when the flammable range is met, an amount of energy (MIE) is necessary to begin the combustion process. The MIE for common fuel gases is typically very low depending on the mixture, slightly fuel-rich level stoichiometry mixtures require the least energy to ignite. These MIE's are on the order of ~0.25–0.3 millijoules.

If the fuel was not within the correct state to begin with, then there is a bigger focus on the heat side of the tetrahedron and if the heat was competent enough to transition the fuel from one phase to another. There are many standardized tests and test apparatus that assist with identifying when a solid or liquid fuel has generated enough gases/vapors to ignite under given conditions. Here ignition will be summarized with a focus on the most common terms associated with flaming combustion.

Ignition temperature is defined as "the minimum temperature a substance should attain in order to ignite under specific test conditions" [13]. Typically, this is referring to the temperature that the material (i.e. solid or liquid) has to reach for it to be vaporizing or pyrolyzing at a sufficient rate to meet the flammable limits that when the MIE is present it ignites. Piloted ignition temperature is the temperature that the substance may ignite when the flammable limits are met and the MIE is introduced into the environment through a piloted ignition source (e.g. flame, spark). Autoignition temperature (also known as autogenous ignition temperature) describes the temperature at which oxidation reactions initiate within the fuel/air mixtures without a piloted ignition source introduced. The introduction of the MIE through a piloted ignition source or through chemical kinetics brought about by higher temperatures in the environment is the important distinction between these two ignition temperature concepts. Most common fuel gases have a MIE of 0.25 millijoules. This energy seems like an insignificant amount of energy, but it must be present in an area where the fuel/air mixture is within the flammable limits.

3.2 Fuel

As evidenced by the definition of fire, chemistry plays a major role in ignition and the combustion reaction. The fuel side of the fire tetrahedron focuses predominantly on those aspects of fire chemistry related to states of matter, phase changes, and thermal decomposition. Matter commonly exists in one of three states: solid, liquid, or gas. Fuels can begin in any of these states of matter, but generally must be in the gaseous or vapor state within the flammable limits to enter into the combustion reaction. This section first describes the chemistry and physics of changing states of matter most common for fires and then describes the specifics of fires progressing from each phase of fuel.

3.2.1 Phase Transition and Thermal Decomposition

The most common methods for fuels to transition into the gas phase are through a transition of phase or thermal decomposition. Below is a brief description of the physical and chemical changes that transpire for fires to occur. This sets the premise for discussing fires within each phase of the fuels. As a point for clarification, the term *gas* is used for matter that exists in the gaseous state at standard temperature and pressure, while the term *vapors* is intended for the gaseous state of liquids or solids.

Phase transition (or phase change) is the transition through the states of matter that are typically accomplished by changes in temperature or pressure. The transitions of phase that are most commonly encountered in fire include vaporization and melting. Vaporization is the transition of a liquid to a vapor, typically through boiling or evaporation. There is no chemical change to the material with this change, it is simply a physical change. An example is boiling water. The chemical structure of the liquid water remains the same chemical structure when the water boils and becomes steam. The process is reversible, in that the collected steam could be cooled down and condensed back to a pot of liquid water again. A similar process occurs with evaporated flammable liquids (e.g. gasoline). Melting is the transition of a solid to a liquid. Similar to vaporization, there is no chemical change to the chemical structure of the material, and it is a reversible process. For example, a block of ice can be heated up, melt, and become a liquid. That liquid can be cooled back down and become a block of ice. There is no chemical change to the water through this physical change.

Thermal decomposition is an irreversible chemical decomposition caused by heat. When heat is exposed to the material, the chemical structure of the material begins to decompose leaving behind material with a different chemical structure. Wood when sufficiently heated begins to decompose, releasing small chains of its chemical structure as a vapor. This change has thermally decomposed the wood, which is irreversible. The wood vapors cannot be cooled down and condensed to become wood again. A process known as pyrolysis will be discussed in more detail in the solid phase fuel section. This is a chemical decomposition or chemical change to the structure of the material. The energy needed to cause the molecular bonds to break down is known as the heat of gasification. Heat of gasification is commonly used to describe the amount of energy required to produce a unit mass of flammable vapor from a combustible that is initially at ambient temperatures [14].

Some of the fuels when encountered with heating may begin going through both a phase transition and thermal decomposition processes. A solid thermoplastic, such as polyvinyl chloride (PVC), when exposed to heat begins to melt and char. Melting is the transition of the PVC from a solid to liquid, but the charring of the material is chemically decomposing the material and changing its chemical structure.

3.2.2 *Fires from Gas Phase Fuels*

Gases are defined as matter where there is significant space between molecules. They do not have a defined shape nor volume because of weaker intermolecular forces. The molecules spread freely and typically fill their container.

A few properties of gases may assist in the understanding of gas dynamics, including density, specific gravity, and the ideal gas laws. First, the density of materials is an important property, as it describes the ratio of mass to volume within a given substance. Densities usually have units of kilograms per cubic meter (kg/m^3). Density differences allow one to identify if one gas will float or sink in another. If a gas is denser (i.e. having greater mass per volume) compared to another gas, then the tendency of the heavier gas is to sink. For example, propane gas has a density of 1.83 kg/m^3, while air has a density of 1.204 kg/m^3. This means that when there is a propane gas leak in a confined space filled with air, the tendency of the propane gas is to settle near the lowest point. A common way to compare the density of gases is through the concept of specific gravity. Specific gravity (s.g.) is the ratio of the density of the gas in question to that of a standard, air being the standard for gases. Thus, the specific gravity of air is 1.0 and propane gas is 1.52. Much of the vapors that evolve from liquids have a greater density than air (e.g. gasoline vapor s.g. is ~3.5). The concept of specific gravity is also used when comparing liquid densities, with water as the standard for comparison.

The combined gas laws and the ideal gas law are important to understand the behavior of many gases, specifically the relationship of pressure (P), volume (V), and temperature (T). The combined gas law is a combination of Boyle's Law, Charles Law, and Gay-Lussac's law. When Avogadro's law is added, the ideal gas law is derived. As combustion increases temperature of the gases, there is a direct influence to the volume expansion of those gases and ultimately the pressure if the expansion is restricted (i.e. container). The combined gas laws indicate that the ratio of pressure, volume, and temperature is a constant. This means that if the initial state is known for pressure, volume and temperature, then any second state can be determined with any change of the three variables.

$$\frac{PV}{T} = k \tag{3.1}$$

or

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \tag{3.1a}$$

Where P is the pressure (kPa), P_1 is the initial state pressure (kPa), P_2 the second state pressure (kPa), V is the volume (m^3), V_1 initial state volume (m^3), V_2 the second state volume (m^3), T is the temperature (K), T_1 initial state temperature (K), T_2 second state temperature (K) and *k* is constant.

Gases are in the correct phase to enter into a combustion reaction, therefore, there is no need for phase transition or thermal decomposition of the material. A mixture of the gas and oxygen within the flammable range is required before combustion can occur. A complete combustion reaction would only produce carbon dioxide and water. To accomplish a complete combustion reaction requires a stoichiometric mixture of the fuel gas and air or oxygen. Babrauskas [10] indicated that a stoichiometric mixture is one where the exact proper mixture (mass of each reactant) of chemicals enters into a chemical reaction where all reactants chemically change to yield a new product or products is the stoichiometric mixture [10]. A stoichiometric mixture is usually what is practiced when balancing chemical equations in high school chemistry classes. However, a perfect mixture of stoichiometric proportions is rarely attained.

In reality, there is limited oxygen to support a complete combustion reaction resulting in the production of incomplete combustion products (i.e. carbon monoxide, hydrogen cyanide). For example, the balanced chemical equation of a theoretical complete combustion of methane in oxygen was provided earlier. Combustion rarely occurs in pure oxygen and relies on air as the oxidizer, which air is composed of only ~21% oxygen (O2) and ~ 79% nitrogen (N2). To balance the chemical equation using air instead of oxygen results in the following chemical equation:

$$CH_4 + 2\left(O_2 + 3.76N_2\right) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

This is still a simplified version of the combustion reaction, because as you may recall the arrow here represents the chemical chain reaction. There are approximately thirty-two intermediate chemical reactions resulting in over fifty different species (molecules, atoms, or free radicals) that contribute to the next reaction. Thus, at any point where a lack of adequate reactants is mixed or available, the chemical reaction is affected resulting in products other than carbon dioxide and water. The result of incomplete combustion is commonly referred to as smoke, which includes unburned hydrocarbons, toxic gases (carbon monoxide, hydrogen cyanide), aerosols, and gaseous products (carbon dioxide, water). The unburned hydrocarbons if accumulated can become a flammable mixture and ignite (flameover and backdrafts).

Lower flammability limits are usually experimentally determined for pure gases, not mixtures. Most fuel gases, however, are not pure gases and are typically mixtures of gases of various percentages. The lower flammable limit of a mixture of gases can be calculated based on Le Chatelier's law:

$$L_m = \frac{100}{\Sigma \frac{P_i}{L_i}} \tag{3.2}$$

Where L_m is the lower flammable limit of the mixture of hydrocarbons in air, P_i is the percentage of composition of component i, and L_i is the lower flammable limit for i.

When a mixture of air and fuel gases are within the flammable range and the minimum energy is present for ignition to occur, a flame begins to propagate or spread through the gaseous medium. The propagating flame continues to spread through the mixture as long as the mixture is sufficient to sustain combustion. This flame spreads spherically outward through the mixture unless there are objects in its path that prevent its spread (i.e. walls, trees). A flammable mixture outside in the open atmosphere begins with the flame propagating through the flammable mixture. The heating of the gases involved in ignition and heating of surrounding gases causes a flame front to expand beyond the initial area where the proper mixture was originally located. The increase in volume of the gases is related to the temperature increases from the combustion reaction. An external event would allow the propagating flame to continue until all the fuel is exhausted. The propagation of flame through a gaseous medium without significant pressure increases is commonly known as a flash fire. A flammable mixture when ignited in enclosed atmospheres (e.g. building, container) begins flame propagation similarly to the external event. The major difference is that the components of the container or building act to confine the expanding gas to a definite volume. As the expansion of the gas volume is restricted, the pressure within the container begins to increase. If the expansion rate is faster or greater than what the confining structure can withstand, then the confining structure may fail. An explosion is defined as “the bursting or rupture of an enclosure or a container due to the development of internal pressure from a deflagration” [15].

3.2.3 Fires from Liquid Phase Fuels

Liquids are defined as matter that do not have a constant shape, but a nearly constant volume that assumes the shape of its container. Liquids have weaker intermolecular forces than solids and do not maintain a shape.

One effect of weaker intermolecular forces is that liquids have sufficient molecular motion where the molecules escape from the surface of the liquid in the form of a vapor. For example, when water is left in an open container the molecules leave the surface of the liquid as a vapor, and over time, all of the liquid water molecules have become vapor. It is said that the water has evaporated. As the molecules leave the surface of the liquid, pressure is created by this vapor. Stronger intermolecular forces of the material results in lower pressure caused by the vapor. Alternatively, weaker intermolecular forces of the material results in higher pressure caused by this vapor. A metric often reported for liquids, and some solids, is vapor pressure. Vapor pressure describes the pressure exerted by vapors leaving the material's surface. This pressure is determined by testing the material in a closed container where it is allowed to evaporate, but since it is in a closed container, the molecules are trapped above the surface of the material. After a period of time, the space above the material will become saturated with vapor and some of that vapor will condense back into the liquid state. An equilibrium state emerges over a period of time where the number of molecules leaving the surface are equal to the number of molecules returning to the liquid state. The pressure exerted by this vapor is known as the vapor pressure (Table 3.2).

The values for vapor pressure are recorded for specific temperature and pressure. Consider a liquid in an open container where the liquid temperature is being increased. The increase in the temperature of the liquid results in an increase in molecular motion, which in turn increases the number of molecules entering the vapor state resulting in an increase of the vapor pressure. The molecules entering into the vapor state have to overcome the pressure exerted on the surface of the liquid by the mass of air resting on its surface (i.e. atmospheric pressure). The boiling point of a liquid is the point where the vapor pressure exceeds the atmospheric pressure. A good example of this is the boiling point of water at different elevations. The boiling point of water at sea level is 100 °C where the atmospheric pressure ~ 101 kPa, but drops to ~91 °C at an elevation of 2440 meters (8000 feet) above sea level where the atmospheric pressure is ~75 kPa. The reason for the lower boiling point temperature of water is due to the loss of atmospheric pressure that the vapors need to overcome. Liquids with low boiling points possess comparatively high vapor pressures (e.g. gasoline vapor pressure ~ 53.7 kPa, boiling point ~95 °C). Liquids with high boiling points possess comparatively low vapor pressures (e.g. kerosene vapor pressure ~ 0.7 kPa, boiling point ~150 °C). Therefore, in an open container where the atmospheric pressure is not changing, an increase in the liquid temperature results in more molecules entering into the vapor state.

Now consider a closed container partially filled with liquid. Initially the pressure exerted on the liquid surface would be the mass of the air in the headspace above the liquid resting on its surface, roughly still atmospheric pressure. As the temperature of the liquid is increased and molecules begin to enter the vapor phase, the mass of the vapors combined with the mass of the air are now resting on the liquid's surface,

Table 3.2 Approximate Vapor Pressures for Common Liquids at Standard Temperature

Substance	Vapor Pressure (Pa)
Water	2400
Gasoline	37,000
Fuel oil no. 2	134
Methanol	17,000
Ethanol	8000

thus increasing the pressure on the liquid. For purposes of this example, let's call this a pseudo-atmospheric pressure. This change in pressure on top of the liquid's surface (i.e. pseudo-atmosphere) makes it more difficult for the molecules to enter into the vapor phase. If the temperature is still increasing and the pressure of the vapors are still greater than this pseudo-atmospheric pressure exerted on the surface, then more vapors will enter into the headspace of the container increasing the pressure exerted on the container. If and when the pressure caused by this vapor overcomes the container's structural integrity, a rapid release of the pseudo-atmospheric pressure on top of the surface occurs resulting in the rapid loss of pressure on the surface of the liquid. If the temperatures of the liquid are high enough, a rapid conversion of the liquid to the vapor state occurs resulting in a rapid expansion of volume. The pressure caused by this volume expansion can cause enough force to result in an explosion. This is commonly referred to as a Boiling Liquid Expanding Vapor Explosion (BLEVE), which is a mechanical explosion caused by the violent liquid to vapor expansion within the container brought about from the high liquid temperature and sudden release of the pseudo-atmospheric pressure.

Another time where the atmospheric pressure on a liquid may be worth noting is when there is a drop in atmospheric pressure (i.e. elevation changes in an airplane). The loss of atmospheric pressure on the liquid's surface permit the release of molecules in the vapor state at a faster rate. Thus, a liquid that does not release enough vapors to be ignitable at sea level may become ignitable when elevation changes occur (i.e., open container on an airplane).

The physical property of vapor pressure is important to understanding fires from liquid phase fuels because it is the vapors that ignite and burn, not the liquid. Vaporization of the liquid is the transition from the liquid to the vapor state. For ignition to occur, the vapors must evolve at a fast-enough rate to mix with the surrounding air to be within the flammable limits. Therefore, the temperature of the liquid, the vapor pressure of the liquid, and the pressure exerted on the surface of the liquid greatly influences the ability of this phase transition and reaching the flammable limits. As vapor pressure is a property that varies for each liquid, the temperature of the liquid necessary to produce sufficient quantity of vapors to be flammable will vary from liquid to liquid. Standardized tests were developed to better characterize the ignitability of liquids to provide a relative measure of the liquid's hazard. The most common test reported for liquid ignitability is known as the flash point. The flash point of a liquid is the lowest temperature of a liquid at which the liquid gives off vapors at a sufficient rate to support a momentary flame across its surface. These values are based on specific laboratory tests that have established environmental temperatures and pressures, typically 20 °C and 101 kPa. Liquids that produce vapors that can undergo combustion are considered ignitable liquids. Another common test for ignitable liquids is to determine the fire point of the liquid. The fire point is the temperature to which the liquid needs to be raised to produce sufficient vapors to sustain burning after the ignition source has been removed. The values obtained for flash points and fire points are typically reported in ranges due to the variety of testing conditions and apparatus.

One common method of characterizing a liquid's relative hazard is through the terminology that is used to classify it. Flammable liquid is a common name for liquids that have flash points under 37.8 °C, while combustible liquids are liquids with flash points over 37.8 °C. For example, gasoline is a flammable liquid with a flash point of approximately -45 °C, while kerosene is a combustible liquid with a flash point of approximately 50 °C (Figs. 3.3 and 3.4). Both flammable and combustible liquids are ignitable, the terminology are often just a means to achieve a relative idea of the hazards associated with the varying liquids. The classification of the liquid is typically done to regulate its use in certain environments and to assign appropriate levels of safety given the hazard associated with the liquid. Numerous government regulations and industry standards deal with the appropriate warnings and labeling associated with the variety of ignitable liquids. Therefore, there are numerous classification systems that one may encounter regarding the hazards associated with liquid ignitability.

Characteristics of liquids are relatively simple when dealing with a single material. Mixtures of liquids may complicate issues. In general, the flammability characteristics of mixtures typically follow the most volatile element or compound in the mixture. Although, at times, it may be important to recognize the physical properties of the materials mixing to better understand the flammability hazards. Liquid density describes the ratio of mass to volume (kg/m3) within the liquid. Density differences allow one to identify if a liquid or solid will float or sink in another liquid. If a liquid has greater mass per volume (i.e. mercury has a density of ~13,590 kg/m3) than another liquid (i.e. water has a density of ~1000 kg/m3) it will sink. The specific gravity is the ratio of density of a given liquid to that of water. The specific gravity of mercury would be ~13.6 and the specific gravity of water is 1.0. Many liquid petroleum ignitable liquids and oils are less dense than water, and as such many of these fuels will float on water (i.e. gasoline ~750 kg/m^3; kerosene ~800 kg/m^3; and diesel fuel 830 kg/m^3).

Other issues when dealing with mixtures of liquids is their ability or inability to mix. Materials that are miscible or soluble in another substance become part of the mixture but are not chemically combined; an example of this is salt in water. Salt

Fig. 3.3 Gasoline vapors ignited by an ignition source ~10 cm away from the liquid

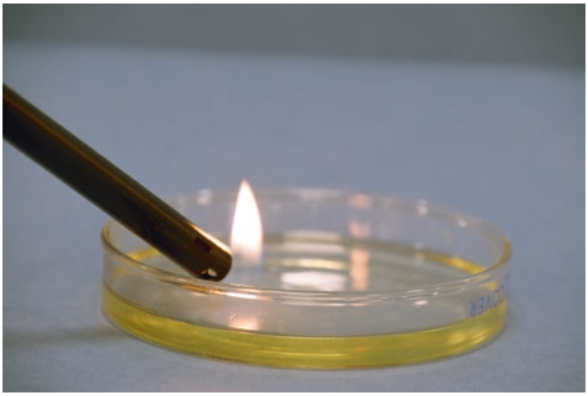


Fig. 3.4 Kerosene not ignited by flame touching liquid surface

water contains dissolved salt, but the solute (salt) can be separated from the solvent (water) without chemical change of either substance. The miscibility of liquids depends on their electrical polarity, usually referred to as polar or nonpolar solvents. Water and alcohols are examples of polar solvents, which means that water mixes with alcohols, each dissolving and diluting the other. Hydrocarbon petroleum liquids are examples of nonpolar solvents, which means they cannot mix with water. The oils or hydrocarbon petroleum liquid will separate out from the water. Extinguishment considerations must take in the consideration of whether or not the liquids are polar or nonpolar solvents. The ability of liquids mixing with other materials is an important consideration when dealing with environmental impact of runoff after fire suppression and its influence on local waterways.

Liquid fuels that have high flash points and high boiling point temperatures are not likely to ignite in normal atmospheric conditions. However, when ambient temperatures are increased or atmospheric pressures are decreased, those liquids typically classified as relatively safer become just as hazardous as other flammable liquids. An example of this would be the spilling of fuel oil number 2 (diesel fuel) on hot asphalt. The flash point for diesel fuel is typically ~48 °C, and rarely are temperatures of this magnitude found on Earth. However, dispersing the liquid in a thin film over a large surface area on hot asphalt during the summer, may allow the liquid to vaporize sufficient quantity of vapors to be ignitable should an ignition source providing the MIE be introduced.

Other times where combustible liquids may become hazardous under normal atmospheric conditions is when the surface area-to-mass ratio is increased (e.g. aerosols, wicking). Finely divided particles of liquid dispersed in air, known as aerosols, require less energy to be transferred into the smaller volume for the temperatures to be increased sufficiently for the liquid to convert to vapors quickly. These droplets require less energy to vaporize, therefore ignite easier and flames spread faster through the suspended drops. Wicks are commonly constructed from organic materials that allow the liquid from a bulk mass (e.g. a pool) to rise through thin tubes of the organic structure, commonly known as capillary action. As the combustible liquid rises through the wick, the surface area-to-mass ratio of the liquid increases. The droplet of the liquid now requires less energy to vaporize the liquid and ignite the fuel. This is commonly seen in kerosene heaters, kerosene lamps, and candles.

3.2.4 Fires from Solid Phase Fuels

Solids are defined as matter with definite shape and volume. Solids have strong intermolecular forces that allow them to maintain their shape and volume.

In general, solids do not burn directly. It is the vapor from the solid that is actually igniting and burning, similar to liquids. As heat is applied to a solid material, the temperature begins to increase within the material. If the heat is applied at a sufficient rate, the temperature begins to increase to a point where chemical bonds within the solid begin to breakdown. This thermal decomposition changes the chemical structure of the material by breaking the complex matrix of molecular bonds found in most solids into smaller chains of molecular bonds (i.e. lower molecular weight molecules). The smaller chains of molecules are released in the gaseous form (Figs. 3.5 and 3.6). A big difference between the transition discussed with liquids to vapors and thermal decomposition is that liquid fuels transition to gas without a change in their chemical structure, while solid fuels that undergo pyrolysis are forever chemically changed.

Most solids transition to gases through this type of chemical decomposition when exposed to elevated temperatures, which is known as pyrolysis (Figs. 3.5 and 3.6). Pyrolysis is defined as the chemical decomposition of a solid by the application of a heat source. Ignition only occurs when sufficient vapors are emitted to mix with the air to form a flammable mixture and the MIE is present from an ignition source. Absent the flammable limits being met, the material could pyrolyze for an extended duration without ignition. Therefore, the pyrolysis rate must meet or exceed the production rate of vapors to form a flammable mixture for ignition to occur. The rate of pyrolysis is dependent on exposure of the remaining solid to heat. To sustain combustion the heat returning to the fuel surface must exceed the heat that is lost into the fuel mass via conduction and that which is reflected off the fuel source.

Cellulosic fuels and thermoset plastics are good examples of solids that transition directly from a solid to gas and form char. Cellulosic materials are one of the more common fuels located inside and outside of homes, including wood, paper, and cotton (Fig. 3.5). These materials are composed of cellulose molecules, which consist of molecules of glucose ($C_6H_{12}O_6$) that are chemically bonded in long-chain polymers. Wood consists of 40 to 50% cellulose [16]. As wood is heated and the temperature increased sufficiently, both fuel and water molecules are emitted, leaving behind mostly a solid carbon residue (i.e. char). Char is defined a carbonaceous material that has been burned or pyrolyzed and has a blackened appearance. Solid organic compounds form a layer of char as the fuel is pyrolyzed. The layer of char that remains serves to insulate the material that has not yet pyrolyzed and the heat

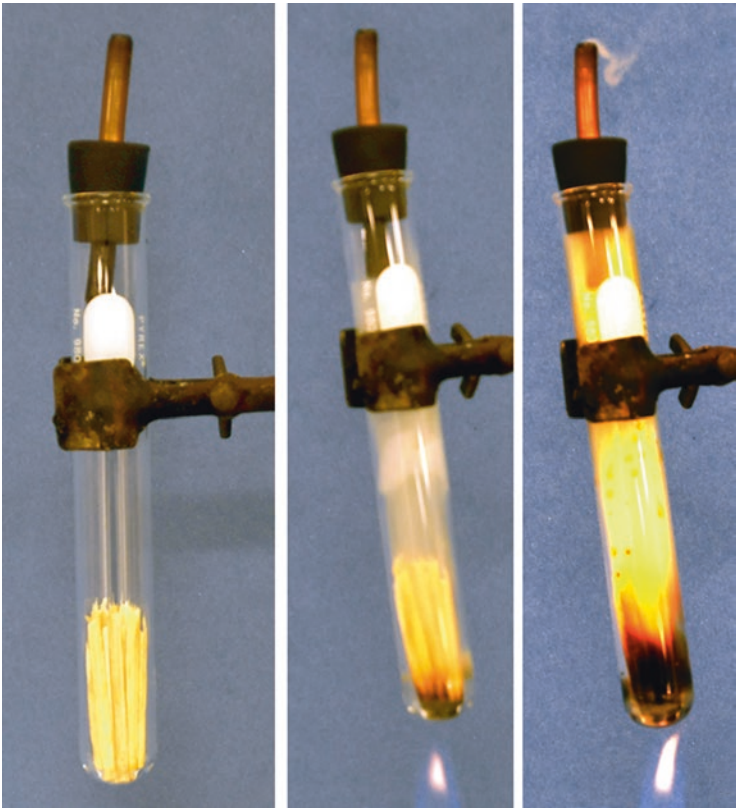


Fig. 3.5 Example of pyrolysis through the exposure of heat to pieces of wood in a test tube (left) before heating, (center) pyrolysis of the wood beginning and char forming, (right) vapors released through tube from pyrolysis of wood

source. Many solids have water in their structures, especially cellulosic fuels. As heat is exposed to these materials, a process called dehydration must take place first before the materials can be sufficiently heated for pyrolysis. Therefore, the burning characteristics of many solid fuels depend greatly on the amount of moisture contained within their structure, also known as the moisture content. The dryer the solid, the easier it is to ignite and the faster it burns. Thermosetting plastics are those plastics that have hardened into a defined shape during the manufacturing process (e.g. phenolics, epoxies). These types of plastics will behave similarly to wood when exposed to heating, including transitioning from solid to gas through pyrolysis without melting and the production of char (Fig. 3.7).

Other solids may melt and flow when exposed to heating, such as thermoplastics. Thermoplastics (e.g. acrylics, nylons, polystyrene) soften and melt prior to giving off vapors and igniting. This type of solid behaves similarly to a liquid fuel after melting and may transition from liquid to gas through vaporization. Most plastics burn rapidly and produce high heat release rates with significant smoke output.

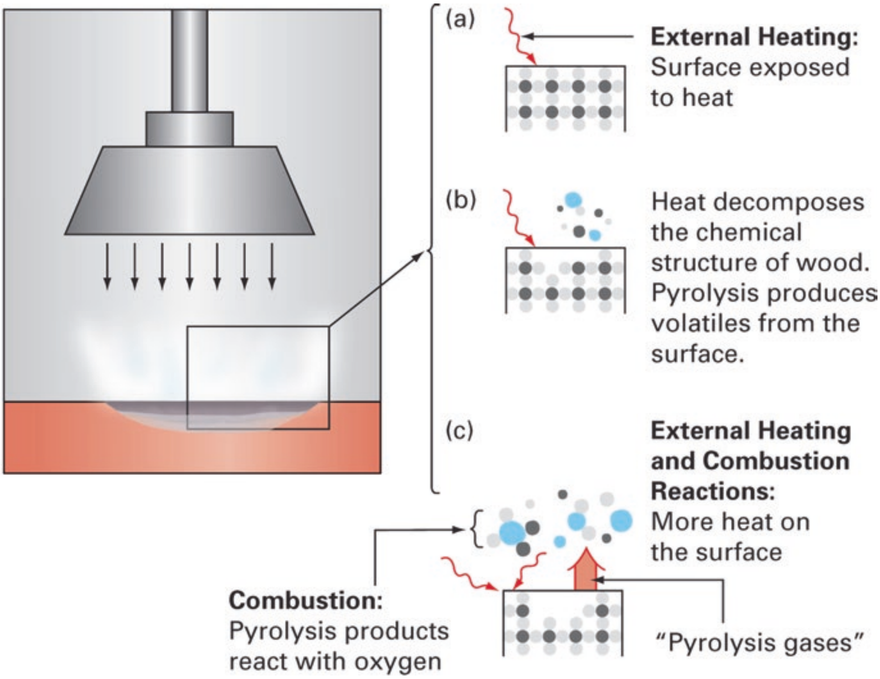


Fig. 3.6 Heat being conducted into a solid combustible resulting in pyrolysis [4]. (Reprinted by permission of Pearson Education, Inc., New York, New York)

Plastics are often formed into foams or expanded (or cellular) plastics for use in furniture, appliances, insulation, and packing materials (Fig. 3.8). Foams have a structure that is created with pockets of air throughout the fuel. The construction of this material greatly influences the ignition and burning characteristics of the plastic. Both the plastic with and without air pockets have similar ignition temperatures, however, the plastic that has air pockets interspersed throughout its structure will require substantially less energy to attain this temperature for ignition. A plastic with no pockets of air interspersed within its structure requires greater energy to increase the temperature of the solid mass to cause ignition because the molecules are tightly compact throughout the fuel and can conduct heat away from its surface more easily. Expanded plastic with pockets of air throughout its structure requires less energy to increase the temperature of the fuel to its ignition temperature because air is not a good conductor of heat and without this dissipation of heat from the surface, the temperature of the molecules near the heat source keeps increasing.

Expanded plastics in upholstered furniture (e.g. sofas, mattresses) has had major influences on fire development within compartments (Fig. 3.8). The plastics being used in today's furniture is easier to ignite, burns faster, and releases more heat and smoke than older furniture. Much of the furniture today still has wooden frames, but the majority of the materials used in the construction of furniture consists of plastics (e.g. polystyrene, polyurethane). The flexible polyurethane when exposed to fast

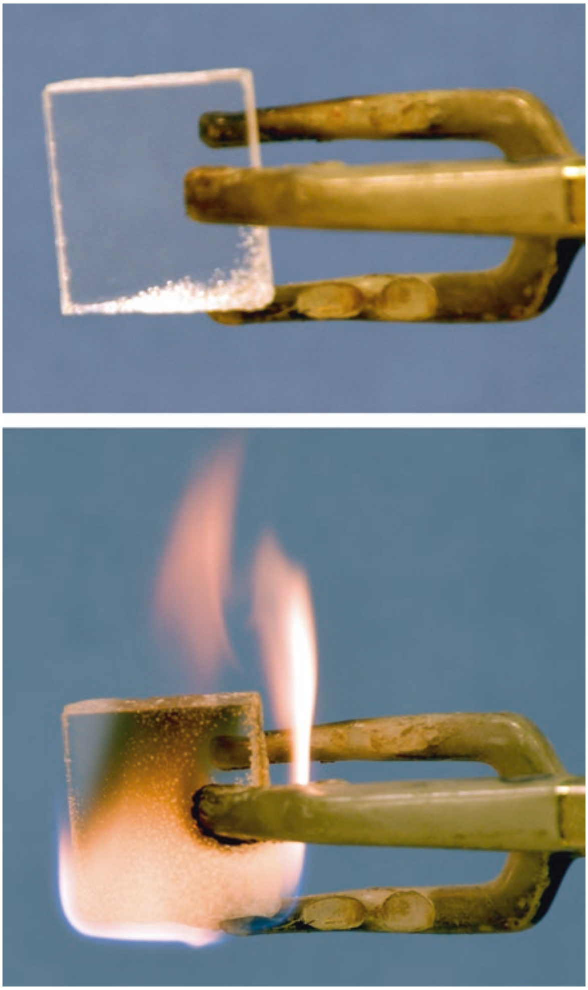


Fig. 3.7 Thermoset plastic exposed to heating (top) begin heating, (bottom) ignition and charring

Fig. 3.8 Polyurethane foam ignited and burning

rates of heating may melt and flow like a liquid, as well as release flammable vapors (Fig. 3.8). However, when exposed to slower rates of heating, flexible polyurethane may pyrolyze and char.

Regardless of the mechanism of how the solid transitions into a vapor, mass is lost from the solid when transitioning to a gas. A certain amount of energy had to enter the solid to cause the chemical decomposition of the molecular bonds, which is known as the heat of gasification (L_g). The heat of gasification is defined as the amount of energy that is required to produce a unit mass of flammable vapor from a combustible that is initially at ambient temperatures [14]. Heat of gasification is obtained experimentally and represents the amount of energy (kJ) required to produce a unit mass (g) of flammable vapors with units of kJ/g. The heat flux from the flame (Q''_F) minus the heat flux being lost through convection or re-radiation from the fuel surface (Q''_L) can be used under quasi-equilibrium conditions to predict the energy required for vaporization of liquid fuels ($m'' L_g$) (Fig. 3.9). Liquids have lower heats of gasification than solids because it requires less energy to convert liquids to a vapor than that required for solids. Consequently, lower heats of gasification also pose a greater flammability hazard.

Up to this point flaming combustion has been discussed where the fuel must gasify prior to combustion. There are two other types of combustion that occur with solids, including smoldering combustion and glowing combustion. Smoldering combustion is defined as "combustion without flame, usually with incandescence and smoke" [18]. This form of combustion is predominantly heated through the oxidation of a char layer. As such, those fuels that form char layers are susceptible to this form of combustion (i.e. wood, thermosetting plastics) and those fuels that cannot form a char layer do not smolder (i.e. thermoplastics). The oxidation reaction at the char layer is an exothermic process that releases heat and must be self-sustaining. Smoldering can transition to flaming combustion if there is enough

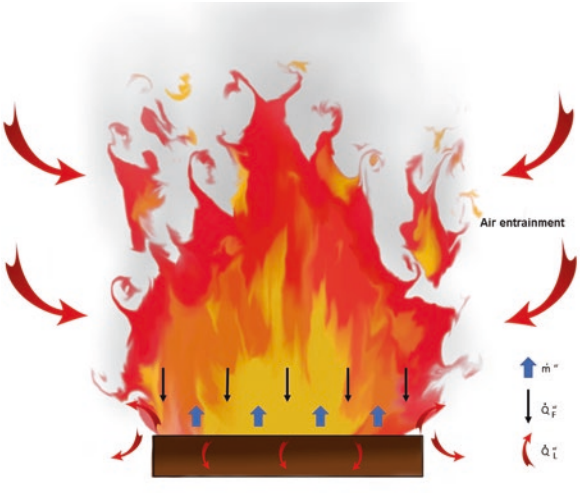


Fig. 3.9 Schematic representation of a burning surface, showing the heat and mass transfer process (illustration by Jennifer Taliaferro)

energy present to thermally decompose the material at a sufficient rate for the flammable limits to be met. Airflow into the fuel greatly influences the ability of the smoldering combustion to produce enough energy for this transition to occur. There are also some solids that may burn directly, known as a glowing form of combustion. This type of combustion gets its name from the "luminous burning of the solid material without a visible flame" [19]. Examples of glowing combustion include magnesium and charcoal (i.e. a form of carbon).

The surface area-to-mass ratio is an important concept when analyzing solid fuel ignition and flame spread. As the surface area increases and the mass of the fuel is lowered, through cutting, sanding, or shaving operations the hazards associated with the fuels increase. This is due to the fact that more surface area is being exposed at the same time to a heat source and there is less mass available to dissipate the heat throughout. A good example of this is when trying to ignite a wood log versus the shavings from the wood log. Both would have similar ignition temperatures required for ignition to occur, but the shaving or speck of saw dust is much easier to ignite because there is less energy required to raise this material to its ignition temperature. A major hazard can be associated with organic dusts because of this inherent ease of ignition by simply changing the fuel's physical characteristics (surface area-to-mass ratio).

Fire retardants are intended to reduce either ignitability or combustibility of a substance. Most often, fire retardants are chemical additives that are either added during the production of the materials or are sprayed onto the material after production. Fire retardants are usually used with solid fuels, especially in electronics, furniture, and flooring. The intent is for these to slow or prevent ignition, but often times ignition may still be able to occur depending on the duration of heat exposure. The benefits of fire retardants have been questioned by many, as several of these chemicals have been shown to propagate out of materials resulting in adverse health effects to animals and humans [20].

3.3 Heat

Heat is the third side of the fire tetrahedron. Heat transfer is one of the most important concepts to understand when dealing with combustion. Heat transfer (or heat) is defined as "thermal energy in transit due to a spatial temperature difference" [21]. In other words, heat is the transfer of energy based on a temperature difference between two objects or regions within a single object. This flow of thermal energy will only proceed from the high temperature region to a lower temperature region, never in reverse. If there is no temperature difference, then there is no exchange of thermal energy in the form of heat.

There is a distinction that is drawn within the definition of heat, which is that there is a difference between temperature and heat. This concept must be further explored to better understand the concept of heat transfer. First, in everyday language people often confuse these terms and as a result they become synonymous, however, they are different concepts. At the molecular level, molecules in a material are in constant motion of some form (i.e. rotational, vibrational, and translational). As matter absorbs energy, the movement of these molecules begins to increase, resulting in a temperature increase. A material's temperature is simply the measurement of the average kinetic energy (molecular motion) within the sample of matter. Greater molecular motion relates to higher temperatures, while lesser molecular motion relates to lower temperatures. There are various scales developed to measure this average molecular motion, including Celsius and Fahrenheit. The true thermodynamic scales (i.e. Kelvin and Rankine) identify absolute zero as the theoretical cessation of free molecular motion.

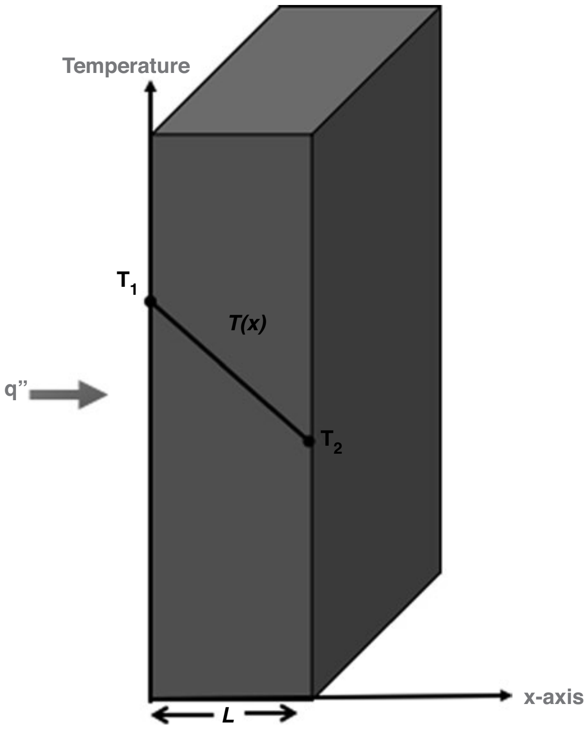
Heat is the amount of thermal energy that can be transferred due to a temperature difference. Heat deals with the transfer of energy, as such there are modes or processes in which the energy transfer can occur. The three modes of heat transfer commonly discussed are conduction, convection, and radiation. Conduction and convection require an intervening medium (e.g. solid, liquid, or gas), while radiation requires no intervening medium.

3.3.1 Conduction

Conduction is the heat transfer mode where energy is transferred through the direct contact through the excitation of molecules driven by a temperature difference. Molecules with higher temperatures are more energetic and when these molecules collide with slower moving molecules they begin to move faster, thereby increasing their temperature. This mode of heat transfer is most common in solids because of the proximity of molecules to each other resulting in easier direct molecular excitation. A good example is the conduction of energy through a metal pan when cooking, the entire metal pan increases in temperature as energy is transferred through the excitation of the molecules throughout. Conduction heat transfer also occurs in gases and liquids, although not as fast due to molecular proximity. Conduction heat transfer plays an important role in solid ignition, flame spread, activation of suppression and heat detection elements, and fire resistance.

The material's thermophysical properties that have the most influence on the speed of heat transfer via conduction is thermal conductivity, k (W/m-K), specific heat, c_p (J/g-K), and density, ρ (g/m^3). Thermal conductivity is a measure of the material's ability to conduct heat, determined by the rate of energy transfer through a given thickness of the material over a given area with a specific temperature difference. The property of thermal conductivity varies based on the material, material's structure, and is temperature dependent. The higher a material's thermal conductivity, the faster heat is able to conduct through it. It is easily possible to calculate one-dimensional heat transfer through a known material and thickness. The equation solves the rate at which energy is being transferred through the material using the thermal conductivity concept (Fig. 3.10). The rate equation for one-dimensional conduction heat transfer is known as Fourier's law (Eq. 3.3):

Fig. 3.10 One-dimensional heat transfer by conduction



$$\dot{q}'' = -k\frac{dT}{dx} \tag{3.3}$$

Where $\dot{q}''$ is the heat flux (W/m2), k is the thermal conductivity (W/m-K) and dT/dx the temperature gradient across the material (K/m).

Heat flux, $\dot{q}''$ (kW/m^2) is the heat transfer rate per unit area. Ignition is often reported as a minimum temperature the surface of the fuel must attain to produce sufficient vapors to be flammable (i.e. ignition temperature) or as the minimum heat flux or critical heat flux for ignition to occur. A good example of thinking about heat flux is a magnifying glass. Paper cannot be ignited by the sun. However, if one takes a magnifying glass and concentrates the heat transfer rate over a smaller area thereby increasing the heat flux to the paper, one can easily ignite paper.

The other thermophysical properties that influence conduction heat transfer are density and specific heat (Table 3.3). Density of the material deals with the compactness of the material, or the amount of mass per volume. In general, the denser a substance is, the greater influence molecular excitation has on nearby molecules and the transfer of energy is faster. Specific heat is the amount of energy that must go into a unit of material’s mass to raise its temperature. The ratio of the thermal conductivity to the heat capacity is known as the thermal diffusivity, $\propto$ (m^2/s), and is an important property for heat transfer analyses, which is calculated as Eq. 3.4.

Table 3.3 Flammability Parameters

Combustibles	L_g (kJ/g)	$\dot{Q}''_F$ (kW/m^2)	$\dot{Q}''_L$ (kW/m^2)	$\dot{m}''$ (g/m^2-s)
Polyethylene (solid)	2.32	32.6	26.3	14
Polycarbonate (solid)	2.07	51.9	74.1	25
Polypropylene (solid)	2.03	28.0	18.8	14
Wood (Douglas fir)	1.82	23.8	23.8	13
Polystyrene (solid)	1.76	61.5	50.2	35
Polyester	1.39	24.7	16.3	18

Source: Data determined by Khan, Tewarson, Chaos (2016) "Combustion Characteristics of Materials and Generation of Fire Products," Volume 1, Chapter 36, in SFPE Handbook of Fire Protection Engineering, Fifth Edition. New York, NY: Springer (USA)
Data determined by Khan, Tewarson and Chaos [17]

$$\propto = \frac{k}{\rho c_p} \tag{3.4}$$

Where $\propto$ is the thermal diffusivity (m^2/s), k is the thermal conductivity (W/m-K), ρ is the density (g/m^3) and c_p the specific heat (J/g-K).

Another way to look at thermal diffusivity is to consider it as a measurement that compares the ability of the material to conduct energy through it versus its ability to store the energy. When dealing with ignition of a fuel, it is common to see this rearranged and discussed as thermal inertia. Thermal inertia is defined as "the properties of a material that characterize its rate of surface temperature rise when exposed to heat; related to the product of the material's thermal conductivity, its density, and its specific heat" [22]. Thermal inertia of a material characterizes its ability to conduct energy away from its surface and through its mass, which is calculated as follows:

$$thermal\,inertia = k \cdot \rho \cdot c_p \tag{3.5}$$

Where k is the thermal conductivity (W/m-K), ρ is the density (g/m^3) and c_p the specific heat (J/g-K) (Table 3.4).

3.3.2 Convection

Convection is the transfer of energy through a circulating fluid to or from a solid object. As a reminder, a fluid is either a liquid or a gas. Heating water in a pot for cooking is an example of convection. Heat is transferred through the pot via conduction, but from the pot to the water via convection. A more pertinent example found with fire is the convection heat transfer that occurs from a flame or heated gases of a fire plume into wall lining surfaces during a fire inside a compartment. There are two energy transfer mechanisms that occur with convection. First, energy is

Table 3.4 Thermophysical Properties of common materials at Standard temperature

Material	Thermal Conductivity k (W/m-K)	Density ρ (kg/m^3)	Specific Heat c_p (J/kg-K)	Thermal Inertia $k\rho c_p$ (W^{2}s/m^{4}K^2)
Copper	387	8940	380	1.30×10^9
Steel	45.8	7850	460	1.65×10^8
Brick	0.69	1600	840	9.27×10^5
Concrete	1.4	2300	880	2.00×10^6
Glass	0.76	2700	840	1.72×10^6
Gypsum plaster	0.48	1440	840	5.81×10^5
Oak	0.17	800	2380	3.24×10^5
Yellow pine	0.14	640	2850	2.55×10^5
Polyurethane foam	0.034	20	1400	9.52×10^2
Air	0.026	1.1	1040	2.97×10^1

transferred through the conduction principles discussed above where excitation of molecules occurs through direct contact. Secondly, and more prominent in fire conditions is the bulk motion of the flowing fluid. In other words, as the fluid flows past a solid object in the presence of a temperature difference between the fluid and the solid object, energy is transferred by the bulk motion of the fluid (advection) and due to the molecular excitation of molecules bumping into each other (conduction). Meaning fluid properties can influence convection heat transfer via influencing the conduction principles that were discussed above. An example of this is when design engineers are unable to remove enough heat from a process through use of air or water, one solution may be to change the fluid thus influencing the conduction aspect of convection (e.g. using engine coolant in your vehicle radiator instead of water). In fire, the fluid that is being heated or transferring heat to other objects cannot be changed – it is typically air. Therefore, in fire the bulk motion of the fluid has a bigger impact on heat transfer. When the fluid flows over a surface, the manner or characteristics of how this flow proceeds over the surface will be either laminar or turbulent. Laminar flows are structured where the molecules generally flow in the similar motion and direction. Turbulent flows are chaotic moving in all three dimensions. The manner in which this fluid flows influences the rate of heat transfer. Turbulent flows have significantly higher rates of heat transfer.

Natural and forced convection are the two basic types that will be encountered. Natural convection is due to buoyancy forces. Buoyancy forces emerge due to the heated gases caused by combustion are now less dense than the surrounding air and because of gravity this heated gas rises. The primary mode of heat transfer during a combustion reaction is via convection. Approximately 70% of the energy liberated from a burning combustible is in the form of convection, which is an example of natural convection. Forced convection is typically associated with some mechanical means of increasing the convection process by applying a fan or some other external means of blowing air across a surface (i.e. wind). An example of forced convection is the introduction of a computer fan across a processor. Forced convection is a faster heat transfer mechanism because of the flow characteristics. Convection heat transfer can be calculated through the estimation of the convection heat transfer coefficient, h (W/m^2-K). These values are greatly dependent on the fluid condition (e.g. buoyant flow in air ~5–10 W/m^2-K, 35 m/s wind speed in air ~75 W/m^2-K). Convection heat flux can be calculated with Eqs. 3.6a and 3.6b:

$$\dot{q}'' = h\left(T_f - T_s\right) \tag{3.6a}$$

Or

$$\dot{q}'' = h\left(T_s - T_f\right) \tag{3.6b}$$

Where $\dot{q}''$ is the heat flux (W/m^2), h is the convection heat transfer coefficient (W/m^2-K), T_f is the temperature of fluid (°C or K) and T_s the temperature of solid (°C or K).

3.3.3 Radiation

Radiation is the transfer of energy through electromagnetic waves. All matter, regardless of its state (e.g. solid, liquid, gas), that is above absolute zero temperature can emit energy as thermal radiation. This mode of heat transfer does not require an intervening medium, meaning it does not require molecule to molecule interaction like conduction and convection. Radiant heat transfer can occur in a vacuum with the best example being the sun's energy transfer to the earth. The factors that influence radiant heat transfer are also witnessed when using the sun as an example. It is well known that if the distance from the earth to the sun was different, the earth's atmosphere would be significantly different. If the earth was closer to the sun, then the earth's temperature would most likely be too high for life and if the earth was further from the sun it would be too low. Thus, there is a relationship of distance to radiant heat transfer. Combine this with the knowledge that on a hot sunny day most people congregate under trees for shade or shielding from the sun's electromagnetic waves. The combination of distance and how the item being heated "sees" the emitter is combined as the view factor or configuration factor for radiant heat transfer. Greater heat transfer occurs when an object is closer and more directly in line with the emitter. Lesser radiant heat transfer occurs when an object is moved farther away and more off-angle from the emitter.

Radiant heat transfer typically accounts for ~30% of the heat liberated during a combustion reaction. This smaller fraction of heat transferred still accounts for a significant cause of flame spread and ignition of secondary fuels.

The thermal radiation emitted from a material is strongly dependent on its temperature. The mathematical relationship between the electromagnetic waves and its dependence on temperature was developed and derived into what is known as the

Stefan-Boltzmann constant. Additionally, the ability of the surface to emit energy compared to a perfect absorber or emitter of energy (i.e. blackbody) is known as the emissivity of the material. The value for emissivity ranges between 0 and 1, with 1 being a blackbody. The heat flux emitted from a surface can be calculated from these variables with the Eq. 3.7.

$$\dot{q}'' = \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right) \tag{3.7}$$

Where $\dot{q}''$ is the energy radiated per unit time per unit area (W/m^2), ε is the emissivity, σ is Stefan-Boltzmann constant, T_s the absolute temperature of body (K) and T_{sur} the absolute temperature of the surroundings (K).

An empirical correlation regularly used in fire protection is to assume that the fuel burning is a point source. The point source model, also known as the spherical approximation, is a simplification that allows one to evaluate the influence on ignition of secondary fuels, establishing safe distances, and various other fire protection design applications. This is done by dividing the radiative output of the heat release rate of the fire by the surface area of a sphere with a radius equal to the distance from the center of the fire. To simplify the calculation the angle from the point source to the target is assumed to be at 90-degrees, which is usually the worst-case scenario for radiant heat transfer. The point source model for radiant heat transfer can be calculated using Eq. 3.8.

$$\dot{q}''_{rad} = \frac{X_r\dot{Q}}{4\pi\left(d_\tau + 0.5D_p\right)^2} \tag{3.8}$$

Where $\dot{q}''_{rad}$ is the radiant heat flux to target (kW/m^2), X_r the radiative fraction of fire, $\dot{Q}$ the heat release rate (kW), D_p the diameter of pool fire (m), d_t the distance from flame edge to target (m).

There are also limitations on where the model itself is valid. The point source approximation is most accurate when $(\mathrm{d_t} + 0.5\mathrm{D_p})/\mathrm{D_p}$ is greater than 2.5 [23] and under predicts incident fluxes at small distances from the fire [24].

3.3.4 Competent Ignition Source

The concept of ignition is directly linked to heat transfer in several ways. First, as discussed above most solids and many liquids require heat for the phase transition to produce sufficient vapors to meet the flammable limits. Secondly, there has to be additional energy present for combustion to begin as the minimum ignition energy, either through a spark, flame, or energy from the environment. Ignition is covered later in this chapter, but it is important now to think of the concept of competency for ignition. A heat source must have sufficient energy and be present for a long enough duration for the phase transition to occur at a sufficient rate to produce vapors that meet the flammable limits. If a heat source is not capable of this, then it cannot be the ignition source for the given fuel and would be considered not a competent ignition source. This analysis is deeper than just identifying the temperature of a heat source versus the ignition temperature of the fuel, it must bring in concepts of the material properties, density, orientation, moisture content, surface area-to-mass ratio, geometry, various modes of heat transfer and duration of exposure. The analysis of ignition is only complete when one is able to understand the heat transfer components and how they are influenced.

3.4 Oxidizer

An oxidizer is a substance that oxidizes another substance. During the process of oxidation, the oxidizer gains electrons from the substance being oxidized. The most common oxidizer on the surface of the earth is oxygen and almost all fires involve oxygen. The composition of dry air, by volume, is approximately 78.08% nitrogen, 20.95% oxygen, 0.93% argon, and 0.04% other gases including carbon dioxide. Oxidizers like nitrates and chlorates can also readily supply oxygen. Materials like chlorine and fluorine are also strong oxidizers.

Oxygen is most commonly the limiting reagent in a combustion reaction. This becomes even more of a factor when fires are enclosed within a compartment or structure and air is not able to circulate. The rate of combustion will depend on the collision of fuel molecules with oxygen molecules. During combustion with limited air availability, the rate of collision of fuel molecules with oxygen molecules will decrease as the oxygen gets consumed. Thus, most flaming combustion requires around 16% of oxygen to sustain combustion. For the same reasons, the addition of oxygen to fire can increase the reaction rate of an oxygen-deficient fire (also known as under-ventilated or ventilation-controlled fire). The flammable limits, given in Sect. 3.1.2, are applicable only for reaction with air at standard temperature and pressure conditions. If we use pure oxygen as the oxidizer instead of air, fuels will become easier to ignite, flammable limits will expand, and the auto-ignition temperatures will decrease. Similar trends can be observed in oxygen-enriched environments (where the oxygen is more than 23.5% by volume). This is because when a fuel burns in air, nitrogen absorbs a part of the heat released by combustion and reduces the collision of fuel and oxygen molecules. Therefore, in the absence of nitrogen, the reaction rates and the product temperature can increase.

Most fires involve oxygen in the gas phase available in the air as the oxidizer. However, liquid and solid oxidizers are also available.

Liquid oxidizers: Oxygen, fluorine, and chlorine are gases at room temperature at atmospheric pressure. However, at high pressure, chlorine can be liquified even at room temperature. Oxygen and fluorine can be liquified at very low temperatures (otherwise known as cryogenic temperatures). Oxygen and fluorine condense into a liquid at −183 °C and − 188 °C, respectively. Liquified oxidizers are commonly used in propulsion. Oxidizers in the liquid phase are far more dangerous than those in the gaseous phase due to the much higher density (~ 1000 times). Therefore, oxidizers stored in the liquid phase, either at high pressure or at very low temperature, pose a higher risk for fire and explosion.

Solid oxidizers: Oxidizers can also be in the solid phase. Some of the common solid oxidizers are ammonium nitrate, potassium chlorate, potassium permanganate, and ammonium chlorate. The instant readiness for supplying a large mass of oxygen is the biggest advantage of solid oxidizers. Solid oxidizers can also be mixed with solid fuels to make solid propellants. However, these should only be processed and stored in well-conditioned environments due to the risk of explosion. Any solution of solid oxidizers may also aid the combustion process depending on the concentration of the oxidizer in the solution.

Recommended storage and handling practices for liquid and solid oxidizers can be found in [25].

3.5 Products of Combustion

Complete combustion of a hydrocarbon fuel with oxygen results in carbon dioxide (CO_2) and water vapor (H_2O). When the combustion happens in the air, the products also include nitrogen, argon, and other trace elements in the air. The complete combustion of hydrogen with oxygen is the cleanest a combustion can get, as it produces only water vapor. But in practical fires, combustion is never complete (Fig. 3.11). Therefore, combustion products also include carbon monoxide (CO), oxides of nitrogen and sulfur, partially burned hydrocarbons, particulate matter, and many other minor species. The maximum possible amount of water vapors the atmospheric air can contain is indicated by the saturation vapor pressure of water. Water

Fig. 3.11 Incomplete combustion products from a vehicle fire

has a fixed saturation vapor pressure for a given temperature below the boiling point at a given pressure. For instance, at a temperature of 20 °C and atmospheric pressure, the ambient air can only have a maximum of 2.3% water vapor by volume. Hence, the combustion has no lasting impact on the water vapor content in the atmosphere. Also, water vapor is not harmful to the environment. Therefore, combustion products are mostly analyzed after removing water vapor. Most of the remaining combustion products are harmful to the environment at varying extents. A brief summary of some of the common combustion products is discussed in this section.

Carbon Dioxide The biggest of the combustion products is carbon dioxide. Carbon dioxide is a colorless and non-flammable gas at standard atmospheric conditions. As its density is higher than that of dry air, it tends to stay low. Atmospheric air contains around 0.0391% $CO_{2.}$ A small increase in CO_2 levels in itself is not harmful to human beings. However, prolonged exposure to high CO_2 levels (above 10%, which is common during large enclosure fires) can even cause loss of consciousness. The total global CO_2 emission has increased from just 2 billion tons in 1900 to 36.5 billion tons in 2018. The increase in CO_2 emissions is largely responsible for the global warming [26].

Carbon Monoxide Carbon monoxide is a toxic, colorless, odorless, and flammable product of combustion. The rate of emission of CO will be higher in ventilation-controlled fires as oxygen is not sufficient for the complete oxidation of CO into $CO_{2.}$ Inhaling CO can cause many health problems and can be even fatal. During flashover in an enclosure fire, rate of pyrolysis rapidly increases causing a transition into a ventilation-controlled fire. At this stage, the CO emissions can significantly increase due to insufficient availability of oxygen for the complete combustion.

Oxides of Nitrogen Even though the air has vast amounts of nitrogen and oxygen, they rarely react under normal temperatures due to the strong triple bond between the two nitrogen atoms in a nitrogen molecule. However, the combustion of fuels containing nitrogen produces oxides of nitrogen, such as nitric oxide (NO) and nitrogen dioxide (NO_2). At very high temperatures, atmospheric nitrogen can also get oxidized thereby significantly increasing the emission of oxides of nitrogen. The rate of NO emissions is higher in ventilation-controlled fires. Fuel controlled fires tend to produce more NO_2. Oxides of nitrogen, commonly represented as NO_X, can cause many environmental problems (like acid rain) and health problems in human beings. They also contribute to global warming.

Hydrogen Cyanide Combustion of fuels containing carbon and nitrogen often leads to the production of hydrogen cyanide (HCN). Combustion or pyrolysis of most polymers, including widely used polyurethane, produce HCN. It’s a toxic substance and it boils at 25.4 °C. Thus, it can be commonly found in the liquid phase at room temperatures and in the gaseous phase in hot combustion products. Breathing air containing HCN can cause health problems and prolonged exposure to significant concentrations can even be fatal.

Oxides of Sulfur Combustion of fossil fuels or thermal decomposition of sulfur containing fuels can produce oxides of sulfur including sulfur monoxide, sulfur dioxide, and sulfur trioxide. They are common inorganic air pollutants. They can react with water causing acid rain.

Particulate Matter Combustion generally results in many organic and inorganic particulate matter along with gaseous combustion products. Unburned carbon particles and non-flammable components in the fuel are commonly present in combustion products. Certain particulate matter, especially with sizes below 10 microns, can cause health problems if inhaled.

Other Combustion Products Depending on the fuels involved, oxygen availability, and temperature, many more compounds can be present in the products of combustion. Burning of plastics and polyvinyl chloride (PVC) can produce hydrogen chloride (HCl), which is a strong acid. Many polymers, especially with synthetic coating, can produce hydrogen bromide (HBr) and hydrogen fluoride (HF). Combustion of fuels containing phosphorous can lead to the production of phosphorous pentoxide (P_2O_5). As bromine and phosphorous are commonly used in fire retardants, these toxic products are common. Combustion of wood, paper, and domestic waste often results in the production of propenal (commonly known as acrolein), formaldehyde, and ammonia in addition to the major combustion products. All these chemicals can cause health problems at different levels.

3.6 Fluid Flow

The increased temperature due to combustion results in the volume of gas intimate with the reaction to expand in volume. The expansion in gas volume results in a decrease in density, as the same mass is now over a larger volume. There now exists a density difference between this volume of gas heated by combustion and the surrounding air that was not heated. The difference in density creates a buoyancy force and the less dense gas will begin to rise due to gravity. Some of this gas is composed of a luminous body where the oxidation reaction is occurring, known as flames. Above the flame rises heated gases and smoke. The buoyant flow of the heated gases creates a difference in pressure at the location where the gas initially rose from. This pressure difference results in air from the surroundings to collapse into the location where the heated gases once were, this is known as air entrainment.

Flames are defined as “a body or stream of gaseous material involved in the combustion process and emitting radiant energy at specific wavelength bands determined by the combustion chemistry of the fuel, some portion of the emitted radiant energy is visible to the human eye” [27]. Oxygen is introduced into the combustion reaction in one of two ways, either diffusion or premixed. A diffusion flame is where oxygen is introduced into the combustion reaction from the surrounding air at the point where combustion is taking place. Oxygen from the air is diffused into the reaction and flaming combustion occurs at the point where the flammable limits and the MIE have been achieved. The interior of this reaction is the source where the fuel is being emitted, so this location is considered fuel-rich.

Flaming combustion does not occur on the interior of this flame because it lacks sufficient oxygen to form a flammable mixture. The location where the oxygen is diffused into the reaction is known as the flame sheet (Fig. 3.12). On the exterior of the flame sheet there is an abundant amount of oxygen and limited fuel, so this location is considered fuel-lean. Flaming combustion does not occur on the exterior of the flame sheet because it lacks sufficient fuel. A good example of a diffusion flame is a candle flame or a Bunsen burner with the air control vent at the base of the tube closed (Fig. 3.12). The placement of metal mesh into the flame easily demonstrates that the interior of the candle flame is void of flaming combustion and that only a small halo of a flame sheet wraps around the wick of the candle. Diffusion flames are characterized by incomplete combustion due to the reliance of the diffusion rate into the reaction. The incomplete combustion typically creates a flaming combustion region more visible to the human eye because more soot is released resulting in more colors emitted by the soot elevated in temperatures. Also, diffusion flames will all have similar temperatures (~1000 °C) regardless of the fuel burning. This is due in large part to the restriction of the diffusion rate of oxygen into the reaction, due to the presence of only 21% Oxygen within the air, and due to the presence of 79% of the air being composed of Nitrogen which is absorbing much of the heat during the combustion reaction.

Fig. 3.12 Diffusion flame from Bunsen burner with air control vent closed

The second way oxygen is introduced into the combustion reaction is prior to the point of combustion. If the fuel/air mixture is allowed to mix prior to entering into the combustion reaction the result is a premixed flame. Air or oxygen is introduced into the fuel stream prior to the combustion zone, which allows for better and more complete combustion. Premixed flames may occur in industrial applications where it is designed or if a fuel is permitted to leak into an area and mix with air prior to an ignition source is present or encountered (i.e. gas explosion). These flames are characterized by higher temperatures than diffusion flames. A good example of a premixed flame is a Bunsen burner with the air control vent at the base of the tube open (Fig. 3.13). Also, these flames will have less soot produced because of the more complete combustion reaction resulting in less visible flame to the human eye.

Flames can also be described based on the type of flow associated with the combustion zone. Laminar flames are characterized by a clearly defined combustion zone where lines separating combustion areas from noninvolved gases are distinct. This flow is usually considered quiescent with most molecules moving in one direction and a steady combustion region forming a simple geometric pattern. The steadiness of the combustion zone is typically because the fuel and air mixture are present in a configuration where air and fuel can mix in a constant location.

Faster rates of air can enter into the combustion reaction due to the size of the fire becoming larger. The combustion zone becomes less steady, as the mixing process of fuel and air begins to occur in whirls. The flaming combustion zone becomes more chaotic where no steady geometric pattern emerges. This type of flame is known as a turbulent diffusion flame. Friction between heated gases moving upward and cooler surrounding air results in turbulence. Moving flames and transient flaming may occur as the fuel/air mixture, combined with proper heat, is present for varying periods. Combustion only occurs where the fuel/air mixture meets the flammable limits and the MIE is present. As such, turbulence in larger fires forms swirling currents labeled eddies. The swirling currents entrain fresh air above the primary combustion zone.

Combustion results in the emergence of a flame plume, which includes a flaming combustion zone, heated gases and combustion products released above this zone, and cooler surrounding air entrained into the reaction location. The location from the base of the flame to the extent where ambient atmospheric conditions return is known as the fire plume. A flame plume is the only that region of the combustion zone that is visible due to the luminous body of burning gases. The height of the flame is a function of the heat release rate and the amount of air entrained into the perimeter of the flame. As the combustion zone gets larger both in height and diameter of fuel involved, the more air is entrained. The greater velocity of air results in more pulsating flame structures, however, there is typically a continuous flame that develops above which fluctuating flames will pulsate dependent on the entrained air and heat release rate of the fuel burning. Smoke and other products of combustion will rise in elevation, or follow the path of least resistance with wind or inside a compartment.

Fig. 3.13 Premixed flame from Bunsen burner with air control vent open

3.7 Heat Release Rate

The heat release rate (HRR) of a fuel burning is typically referred to as the single most important variable in a fire [28]. The size and speed of the fire are directly related to the hazards to life, property, and the environment, as well as what is needed to extinguish the fire. The formal definition of heat release rate is the "rate at which the heat energy is generated by burning" [29]. Another way to consider heat release rate is as the power of the fire, as it is detailing the amount of energy (kilojoules) over time (seconds) the fire is producing. The units for heat release rate are expressed as Watts (W). One Watt is equal to one Joule per second (J/s). Even small fires encountered will be more on the order of magnitude of 1000 Watts or 1 kilowatts (1000 J/s or 1 kJ/s). Typical fire sizes will be in kilowatts or Megawatts (1 million Watts). For example, a burning wastepaper basket has a HRR of 100 kW, a 1 m^2 pool of gasoline has a HRR of 2.5 MW, and burning 3 meter high wood pallets has a HRR of 7 MW.

Flame spread is often referred to as a series of piloted ignitions. Therefore, the faster a fuel burns, the faster heat is released resulting in a faster transfer back to the fuel's surface, which allows for the production of more fuel in a form capable of igniting. Once this fuel/air mixture is present, the flame serves as the piloted ignition source for the mixture. Once ignited more heat is released and a heat feedback loop is developed. This heat feedback loop influences the speed of ignition of other nearby fuels, as well as the production of smoke and products of combustion. In an enclosure fire, this may result in the incapacitation and deaths of occupants in very short order in the room of origin, as well as all within rooms connected. In external fires, this results in a conflagration that causes destruction to land, houses, and wildlife. The slower a fire grows, the easier it is to extinguish. Those fires that develop quickly or have a fast HRR become uncontrollable and cost billions of dollars a year to extinguish.

Several variables influence the power of the fire, including the heat of combustion (Δh_c), mass loss flux or burning flux ($\dot{m}''$), the surface area (A_f), and the combustion efficiency (χ). There are a few ways for determining the HRR of a fuel either estimating it by calculations or test the fuel item and measure its HRR. Calculating HRR is able to be completed for simple, two dimensional fires (i.e. ignitable liquid pool fires). However, more complex fuels such as upholstered furniture is more complicated and is typically best to conduct measurements through experimental testing rather than calculating it.

3.7.1 Calculating Heat Release Rates

The HRR can be calculated for simple fires with Eq. 3.9.

$$\dot{Q} = \chi_c \dot{m}'' A_f \Delta h_c \tag{3.9}$$

Where $\dot{Q}$ is the heat release rate (kW), χ_c the combustion efficiency, $\dot{m}''$ the mass loss flux (kg/m^2-s), A_f the surface area of fuel (m^2) and Δh_c the heat of combustion (kJ/kg).

The heat of combustion (Δh_c) is the amount of energy produced through the chemical reaction process for each unit of mass used within the reaction. The value of heat of combustion varies by fuel. The values range from 15,000 kJ/kg (cellulose) up to 50,000 kJ/kg (methane). It is experimentally measured under ideal conditions to obtain the maximum energy that can be emitted from a given fuel assuming complete reaction of the fuel. However, in practice, this theoretical value is never attained due to inefficiencies in the combustion reaction and heat losses. The range of values for different fuels greatly varied when measuring the amount of energy released when each mass of fuel was consumed within the reaction. As identified earlier, the combustion reaction is greatly inhibited when burning in air. Consequently, in the early 1900s it was identified that if the energy measured was determined for each unit mass of air or oxygen within air, the values of heat of combustion began to plateau regardless of the fuel used ($\Delta h_{c,air} \sim 3$ kJ/g; $\Delta h_{c,ox} \sim 13.1$ kJ/g). As such, an effective heat of combustion is the value that is used to account for burning in air with inefficiencies and oxygen consumption calorimetry is the basis for measuring the HRR of a fuel. The combustion reaction heat is emitted as either convection or radiation. The chemical heat of combustion is therefore broken into two components, the radiative energy (Δh_{rad}) and the convective energy (Δh_{con}). For a list of heats of combustion, refer to the work performed by Khan, Tewarson, and Chaos [24].

Complete combustion (100% efficiency) is never attained in actual fires. There are significant losses of heat to the atmosphere and inefficient diffusion of oxygen into the reaction to name a few reasons why complete combustion is not accomplished. The efficiency of a fuel burning is commonly referred to as the combustion efficiency, represented by the Greek letter chi, χ. A factor to account for the inefficiency is calculated into the HRR equation. It is a value that ranges from 0 to 1, with 0 being completely inefficient and 1 being 100% efficient. The limits of this range are impractical, therefore, most fuels fall within the middle of the range. The value can be estimated for well-ventilated conditions by dividing the effective heat of combustion by the theoretical heat of combustion. Drysdale [16] estimates that this value will be on the order of 0.3 to 0.4 for those materials with fire retardants added and is closer to 0.9 for fuels with chemically bound oxygen.

The loss of mass from the solid or liquid during the phase transition to the gaseous phase is directly related to the HRR. The faster the transition to a vapor, the faster the fuel/air mixture can form, reach an ignition source, and burn. This vaporization or pyrolysis rate is measured over a given area of the surface while burning, which becomes measured as the mass loss flux or burning flux ($\dot{m}''$). Typically, the mass loss rate is not constant and depends greatly on the orientation, surface area-to-mass ratio, and various other fire spread issues. Average mass loss fluxes are determined experimentally and are often a good place to start when estimating HRR.

The surface area of the fuel that is undergoing pyrolysis or vaporization influences the HRR. The larger the surface area emitting vapors increases the amount of vapors to mix with air, ignite, and burn. Several variables influence the exposed fuel's surface area, including orientation, surface area-to-mass ratio, geometry, density, texture, and thickness.

3.7.2 Measurement of Heat Release Rates

Complex fuels that consist of multiple materials over three-dimensional space (e.g. furniture) is better to determine the HRR through experiments, rather than through calculations. Most materials, being constructed of more than one material, it is common to find thousands of fire tests done and reported on every year. Testing of the fuels are conducted in laboratories around the world that measure the mass loss rate from the fuel and capture the gases emitted via an exhaust hood and ductwork. The principle of oxygen consumption calorimetry is applied during the test, looking at the amount of oxygen that was used within the reaction as a means to determine the energy released during combustion. The data from these tests are often reported through tables of peak HRR for various fuels and HRR graphs. Tables usually only list the maximum or peak HRR attained through the testing for the fuel. HRR graphs better illustrate the growth of the fire, speed to reach the peak HRR, peak HRR, and the time it takes for the fire to decay.

Similar fuels may have different HRR curves due to a variety of factors, including orientation, method of ignition, and material properties. For example, if two wood furniture items are tested, one with a high moisture content ignited at a single point versus the other with lower moisture content ignited over a larger surface area.

Despite being essentially the same material, the second wood item would have a significantly faster HRR growth rate and most likely a higher peak HRR due to the lower moisture content and method of ignition.

The best approach for determining the heat release rate of a 3-dimensional object is to experimentally test the fuel through oxygen consumption calorimetry [30]. As the fuel burns a heat release rate curve is developed. The curve maps out the release of energy over the duration of the fuel burning. The x-axis of the graph is in time, typically seconds. The y-axis of the graph is heat release rate, typically kilowatts or Megawatts. For example, the heat release rate graph for a polyurethane foam chair is shown below (Fig. 3.14). The curve follows a path similar to an exponential growth curve and reaches a peak heat release rate of 2000 kilowatts at approximately 400 seconds.

3.7.3 Application of Heat Release Rates

The heat release rate of fires for simple 2-dimensional pool fuels can be derived by calculating potential energy of the fuel and the surface area exposed to air. The heat release rate of a pool fire can be calculated through using Eq. 3.10.

$$\dot{Q} = \chi_c \dot{m}'' A_f \Delta h_c \quad (3.10)$$

Where $\dot{Q}$ is the heat release rate (kW), χ_c the combustion efficiency, $\dot{m}''$ the mass loss flux (kg/m^2-s), A_f the surface area of fuel (m^2) and Δh_c is the heat of combustion (kJ/kg).

For example, a gasoline pool fire with a 3 meter diameter (Area of 7.07 m^2), a heat of combustion of 43,700 kJ/kg, a mass loss flux of 0.055 kg/m^2-s, and assuming a combustion efficiency of 70% (0.7) would result in a heat release rate of ~11,895 kJ/s or 11,895 kW.

Flame height, velocity, and temperatures of the fire plume have been shown experimentally to be related to the heat release rate of the fire. There are several simple empirical correlations that have been developed through experimental testing to apply heat release rate curves and simple calculations to determine the flame height. As an example, below is Heskestad's correlation:

$$H_f = 0.23\dot{Q}^{0.4} - 1.02D \quad (3.11)$$

Where $\dot{Q}$ is the heat release rate (kW), H_f the flame height (m) and D the diameter of the fire (m).

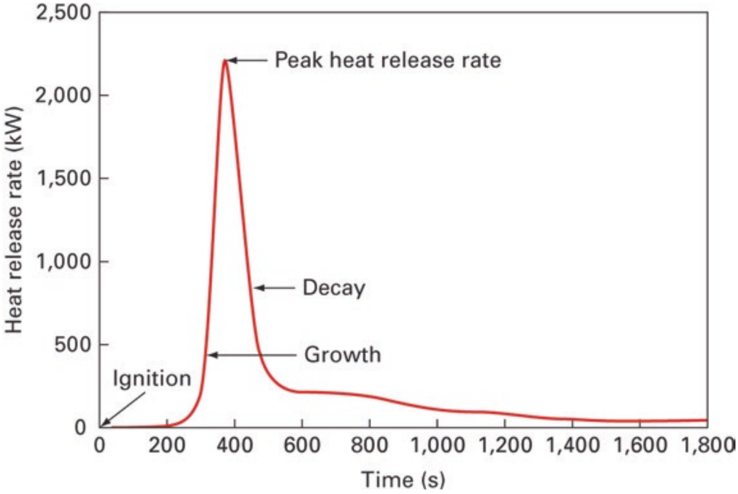


Fig. 3.14 Example of a heat release rate graph [4]. (Reprinted by permission of Pearson Education, Inc., New York, New York)

3.8 Enclosure Fires

The physics of how a fire develops inside an enclosure or compartment (e.g. a room in a house) is relatively similar. The development of a fire from ignition through the decay phase of a fire in an enclosure is described briefly here. Other textbooks have more exhaustive discussions on enclosure fires [31–33].

The early stages of a fire in cellulosic fuels may begin as smoldering combustion that may transition between smoldering and flaming combustion for some time before flaming combustion becomes self-supporting. The self-supporting combustion comes when heat feedback is at a sufficient rate to maintain a constant supply of gases/vapors that can mix with air for combustion to occur. This is referred to as established burning, which simply serves as a benchmark that the fire will not transition back to smoldering combustion for organic fuels. It is often reported to be between 20–50 kW for most residential structure fires and upholstered furniture [16, 34].

Once a sustained flame has been established, then the growth phase of the fire begins (Fig. 3.15). The heat release rate of the fire is the controlling factor in the speed of this growth phase. A fuel that is easy to ignite typically has a fast flame spread and associated heat release rate. The ease of ignition comes in the form of the type of material, the orientation of the fuel, surface area-to-mass ratio, and ignition source. The arrangement of fuels can influence the speed at which secondary fuels become involved and begin adding to the overall fire in this space. The controlling factor in the early stages of the fire growth is the amount of fuel available in a physical state capable of supporting combustion, commonly known as a fuel-controlled fire. A fuel-controlled fire is one that is being restricted by the amount of available fuel in the correct state to burn yet has sufficient supply of oxygen to support combustion. This means that the heat release rate, smoke production, temperatures within the compartment, and ignition of secondary fuels are all being controlled by the available fuel at this point. As the fire spreads across the fuel's surface and possibly involving secondary fuels, the heat release rate increases. If sufficient fuel is available close in proximity, then the fire will continue to grow.

A plume is formed during this combustion reaction, which results in the release of combustion products in a steady stream of heated gases, carbon dioxide, water, carbon monoxide, and smoke. The smoke and gases of the plume are elevated in temperature and thus less dense than the surrounding air allowing the fluid to move vertically in elevation within the compartment (Fig. 3.16). The upward moving gases and smoke are commonly referred to as a fire plume. As the heat release rate increases, the fire plume can rise high enough to begin intersecting with the ceiling and walls within the compartment. As a reminder that fluids follow the path of least resistance, and the walls and ceiling boundaries of the compartment are more restrictive than the buoyant flow of gases.

The ceiling and walls within the compartment redirect the buoyant flow of gases from the fire plume. The redirection of the fire plume by the ceiling forces the gases to begin flowing in all directions away from its centerline. This redirection by the ceiling is often referred to as the ceiling jet (Fig. 3.17). Not all fires have sufficient heat release rates to develop a plume to intersect the ceiling, especially in tall rooms (i.e. atriums). However, when a ceiling jet does form it creates other hazards within the developing enclosure fire. The velocity and temperatures of ceiling jets have been well studied within fire protection as a means to help identify best practices for detection and activation of automatic fire protection systems (e.g. heat detectors,

Fig. 3.15 Ignition of a couch inside an enclosure

smoke detectors, sprinklers). All of this technology mounted to the ceiling of compartment stems from designs focusing on using the ceiling jet as a means of early detection and notification.

The ceiling jet, or redirection of the fire plume, will continue spreading laterally under the ceiling until temperatures within the plume lower significantly or until another obstruction redirects its flow (Figs. 3.16 and 3.17). Walls in a compartment serve to redirect this ceiling jet to form what is known as an upper layer. The upper layer is where a collection of gases is being constrained by the walls and ceiling of the compartment. This gas layer is elevated in temperature and is composed of heated gases and particulate matter, it begins to transfer heat via convection into the lining surfaces of the room as well as radiantly heat other surfaces and contents within the room. As the fire continues burning and more smoke is being pumped into this upper layer it begins to descend from the ceiling into the lower portions of the compartment. At this point within the development of the enclosure fire, convection is the primary heat transfer mechanism from the fire to the compartment. However, as this layer begins to descend and temperatures of the gas layer increase, as well as temperatures of the wall and ceiling linings increase, the radiant heat transfer from the upper layer begins to increase substantially (Fig. 3.18).

Thermal radiation from the bottom of the upper layer and from the lining materials begins to heat up the contents and items in the lower layer (i.e. furniture, flooring). As the layer descends further, the radiant heat transfer to these materials increase substantially. The radiant flux imposed onto these surfaces may eventually

Fig. 3.16 Plume and ceiling jet formation from burning couch

Fig. 3.17 Redirection of the plume by the ceiling and walls creating an upper layer within the enclosure fire

pyrolyze the fuels sufficiently to cause them to ignite. Since this descending upper layer is relatively uniform in temperature, in smaller compartments, and since the layer is descending at the same level throughout the compartment most fuels within the lower layer are receiving similar heat fluxes. The majority of these fuels in the lower layer will have similar ignition temperatures or critical heat fluxes. So when the radiant flux is overwhelming one object in the lower layer, it is likely overwhelming all of the objects in the lower layer due to the relatively similar temperatures and depth of the layer throughout the compartment. The almost simultaneous ignition of the fuels in the lower layer is known as flashover. Flashover is defined as "a transitional phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperatures more or less simultaneously and fire spreads rapidly through the space resulting in full room involvement or total involvement of the compartment or enclosed area" [35].

During this development of the upper layer, there is a lower layer that remains in the lower portions of the room that remain at relatively cooler conditions. As the heated gases are rising in the buoyant fire plume, the cooler air from this lower layer is being pulled into the fire plume to replace what has risen. This is called air entrainment and serves as the source of oxygen into the combustion reaction. In a fuel-controlled stage of the fire, there is sufficient oxygen available for combustion to continue. However, if a fire is developing in a compartment without sufficient openings or the size of the fire is overwhelming the available access to oxygen through openings then the fire can transition into a ventilation-controlled fire. A

Fig. 3.18 Upper layer formation and flame spreading along couch

ventilation-controlled fire is one where combustion is influenced by the lack of oxygen. The heat release rate, temperatures, and smoke production will all begin to be controlled by the available oxygen into the compartment. If the compartment is left alone during this stage of the fire, the heat release rate curve and temperature profile within the compartment resemble a quasi-equilibrium state. A flashover is a quick transition from a fuel-controlled fire to a ventilation-controlled fire.

An enclosure fire that transitions into a ventilation-controlled fire is one that will continue until the fuel is all exhausted with the HRR and temperature regulated by the openings (Figs. 3.19 and 3.20). Another possibility is if there is a significant lack of oxygen, the fire may vitiate and extinguish because of the lack of oxygen. If, however, during this vitiation of the fire a new opening is introduced or a larger opening occurs through breaking of windows, opening of doors, or burn through a wall then the fire can begin to increase in HRR and temperature again. Sometimes this increase can have explosive effects, commonly referred to as a backdraft. A backdraft is a ventilation limited fire leading to the production of large amounts of unburned pyrolysis products that when an opening is suddenly introduced, the inflowing air forms a gravity current. This gravity current of cooler air mixes with the outflowing unburned pyrolysis products, creating a combustible mixture of gases in some part of the enclosure. When this mixture encounters an ignition source, the mixture ignites resulting in an extremely rapid burning of gases and pyrolysis products are forced out through the opening creating a large fireball outside of the compartment with associated increases in pressure.

A fully involved compartment fire can result if adequate fuel and oxygen are available over the duration of the fire (Fig. 3.20). Flashover is a quick transition to a fully involved fire, commonly known as a full-room involvement fire. A fully involved single room, residential compartment fire is on the order of 10–15

Fig. 3.19 Radiant ignition of fuels throughout the compartment beginning the transition to a fully involved enclosure fire

Fig. 3.20 Fully involved enclosure fire

Megawatts, which relates to a significant production of greenhouse gases issuing into the atmosphere.

3.9 External Fires

External fires are those that happen in open environments in the abundance of air. They have certain characteristics significantly different from enclosure fires due to the increased oxygen availability and wider length scales. The physics of small-scale external fires are similar to the early stages of enclosure fires which are fuel-controlled. At this early stage, fire spread is largely due to the heat transfer through convection. As the fire grows, the increase in temperature causes a rapid increase in radiative heat transfer and fire spread. At this stage, in an enclosure fire, the fire transitions to ventilation-controlled fire. In other words, fire growth is limited by the availability of oxygen. However, in an external fire, the fire continues to be fuel-controlled with radiation as the dominant mode of heat transfer and the fire grows if more fuel is available. This increases the gas temperature and the rate of preheating of the nearby fuel elements. Which, in turn, results in accelerated pyrolysis producing more fuel vapors. The fuel vapors then mix with oxygen entrained from the surrounding air and react releasing more energy. Thus, the fire grows.

Large-scale external fires can cause serious threats to human lives, properties, wildlife, and the environment. Wildland fire is the largest class of external fires. A wildland is an area where development is non-existent except powerlines and transportation facilities. If any structure is present, they're widely scattered (Wildland, 2020). A wildland fire may be a wildfire- which has unplanned ignition like lightning or volcanos- or a prescribed fire- which has planned ignition (Wildfire, 2020). Though this classification may have legal merits, the fire dynamics after the initial fire growth stage are similar for both classes of wildland fires. Wildfires happen naturally without human interference burning large areas of forests. Over a long period, plants grow back restoring a similar ecosystem it had before the fire.

In an already warming environment, the intensity of wildfires can increase making long-lasting changes to the wildland. In many regions, wildfire caused long-term disturbance on soil thereby preventing the restoration of the wildlife [36]. In addition, many endangered species can go extinct due to large wildfires. The CO_2 emissions from wildfires is also a threat to mankind. Greenhouse gas emissions from wildfire are tracked separately considering it as a part of the natural carbon cycle. There is not enough data over a large enough time scale to establish whether wildfires have significantly changed due to human interference [37]. In 2019, major wildfires are reported from the western US, Amazon forests, and Australia. The fires in Australia in 2019–2020 alone are likely to have contributed 900 million metric tons of greenhouse gases, nearly doubling the total annual greenhouse emissions from the country based on multiple reports of early estimates [38]. Only very limited knowledge is obtained on the impact of global warming on the intensity and frequency of wildfires or the impact of wildfires on global warming.

These wildfires can significantly influence the wind due to the upward flow of hot combustion products and entrainment of the cold surrounding air. This can even change the local weather depending on the scale and intensity of the wildland fire. This causes a complex feedback loop between local weather and wildland fire, which has not been sufficiently explored scientifically. These factors call for more serious attention to wildfires, though we are more used to safely neglecting wildfire as a natural process. There is a significant difference in opinion, even among the scientific community, on whether an attempt should be made at suppressing wildfires or just let it burn naturally.

Problems become far more significant when wildland fire reaches the Wildland-Urban Interface (WUI). When it comes to WUI fires, there is an overwhelming consensus that it is a growing global crisis that needs to be addressed. WUI is where human beings meet wildland. They can be either intermix communities, where houses and wildland vegetation intermingle, or interface communities, where built environment abut wildland vegetation. In the United States, 9.4% of the land area and 39.5% of the houses fall under WUI and these numbers are on the rise [39]. Stopping all wildfires is not a feasible or convenient option. Even preventing the small fraction of wildfires (typically 2% to 3%) that reach WUI communities is extremely challenging. The frequency of WUI fires is increasing thereby increasing the cost of fire suppression. Federal spending on fire suppression alone in the US exceeded $ 3 billion in 2018 [40].

The fire spread from wildland into WUI can be because of direct flame contact, high radiative heat flux, or embers. Imposing stricter standards for distance from vegetation to buildings can prevent direct flame contact from wildland fire. This can also significantly reduce the radiative heat flux. However, embers can travel many kilometers in the presence of favorable weather and topography. This makes the prevention of WUI fires extremely challenging.

Drylands, which are characterized by scarcity of water, are more prone to wildland fires in the presence of favorable fuel distribution, weather, topography, and an ignition source. 41% of the global land area is considered to be drylands. The degree of aridity, or deficiency of moisture, can increase the rate of wildland fire spread. Figure 3.21 shows the average aridity of all drylands on the surface of the earth. The aridity levels are increasing since 1970 due to human-caused increase in temperature across the western continental US. This increase is related to the recent increase in wildfires in the region [41]. The change in aridity levels and increase wildfires over the last few decades are significant even though the period of recorded data is very small compared to the history of wildfires.

The fire spread during wildland and WUI fires depend on the fuel, weather, and topography.

Fuel The degree of flammability of a fuel depends on the chemical composition of the fuel, moisture content, size, and density. Most live vegetation has high moisture content. During a fire, a significant part of the heat flux from the fire will get absorbed for the vaporization of the moisture content. This will reduce the rate of pyrolysis and combustion. The chemical composition of different fuels in a wildland or WUI is complex. However, they have a large mass of hydrocarbons that can burn in the presence of oxygen and a suitable ignition source. Another important factor is the density of fuel distribution. When the fuel elements are closer to each other, fire can spread easily due to convective heat transfer from direct flame contact.

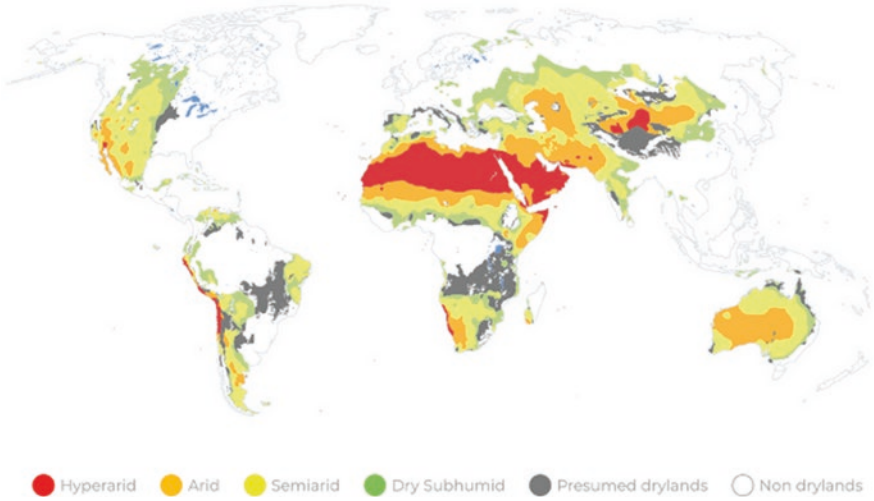


Fig. 3.21 Aridity map of drylands on earth from the Food and Agriculture Organization of the United Nations. (© FAO 2019 Trees, forests and land use in drylands: the first global assessment, p2, http://www.fao.org/dryland-assessment/en/, accessed June 2021)

When the fuel elements are spread apart, fire spread will require much higher radiative heat flux. The size of the fuel element is also a major factor. Thinner fuel elements, like small branches and leaves of trees, catch fire easily due to high surface area to mass ratio thereby accelerating fire spread. Thick tree trunks are not easily ignited but they can burn for a longer duration.

Weather Weather conditions also significantly impact wildland and WUI fires. Higher humidity will decrease fire spread by absorbing part of the heat released by the fire. A higher atmospheric temperature will increase the rate of fire spread as the amount of energy required for ignition decreases. Wind usually increases the rate of fire spread by supplying more oxygen for the reaction. Wind can help in partial premixing of fuel vapors, formed by pyrolysis of vegetation, with oxygen. Wind also aides in transporting embers. However, extreme winds in the early stages of fire growth can extinguish the fire. It's interesting that most of the WUI in the US is near the east coast; however, most of the WUI fires are reported near the west coast. This is due to the difference in the weather. Eastern US stays relatively moist and western US faces more droughts and warmer winds casing easier ignition and fire spread as evident from the aridity levels shown in Fig. 3.21.

Topography Topographical features like elevation, slope, and aspect can impact wildland fire spread. The elevation is generally expressed as the height from the sea level. Higher elevations tend to be colder and dryer. The slope is the gradient or incline of the land (Fig. 3.22). A demonstration to illustrate the impact slope has on flame spread can be done by taking two identical channels filled with fuel (e.g. fire

Fig. 3.22 Small scale demonstration of the influence of slope in a fire spreading uphill versus downhill (left) two identical channels filled with fire paste, (center) ignition at top and bottom 0 s, (right) flame spread downwards has only involved 1/10th of the fuel, while spread upwards has involved all of the fuel 20 s

paste) igniting one channel at the top of the fuel and the other at the base. The flame spreads upwards (concurrent flow) much faster than it does downwards (counterflow) due to the natural buoyant flow and convection heat transfer preheating fuels (Fig. 3.22). Fires spread faster uphill when compared with fire spread downhill or through a flat surface. When a fire spreads uphill, the hot combustion products move upward due to buoyancy, thereby preheating or even igniting the fuel elements above. Aspect is the direction of the slope. The amount of solar heat flux on an area depends on the aspect of the area. The presence of valleys can also significantly impact fire spread, as it channels the flow of air and combustion products. The presence of canyons, which are deep narrow valleys with steep sides, can cause accelerated fire spread. Due to fire, the gas temperature increases and the density decreases. This causes an expansion of the combustion products. As a canyon limits the space for this expansion, the hot combustion products tend to accelerate causing faster fire spread.

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Chapter 4
Fire and Smoke Modelling

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4.1 Introduction

4.1.1 Computer Models in Fire Engineering

The Fire Safety Engineering (FSE), also known as Fire Protection Engineering, is a discipline intertwined between civil, environment and material engineering, strongly influenced by thermodynamics and social sciences. FSE aims to solve principal problems related to fires, to limit their consequences to the individuals, society, economy and environment. In a performance-based approach to the FSE [1, 2], various computer-based modelling tools are used to predict the outcomes of a fire in terms of the flow of the heat and mass inside buildings. With the increasing care about the environmental impact of fires, we try to expand our modelling, to provide an insight not only to the conditions inside buildings (and safety to their occupants) but also to the environment in which the smoke release takes place (and safety of society), Fig. 4.1. This chapter aims to summarize the knowledge related to the modelling of fires and release of pollutants to the atmosphere, highlighting the principal role that wind action takes in the pollutant dispersion.

Efforts to predict and quantify the consequences of fires with computer models were numerous in modern history. The first example is the empirical model of the smoke flow in thermal plumes of smoke, referred to as the axisymmetric plume. The first models date to 1950s [3, 4], and considerable effort was made to develop more sophisticated models in 1970s and 80s [5, 6]. The plume models were reviewed by

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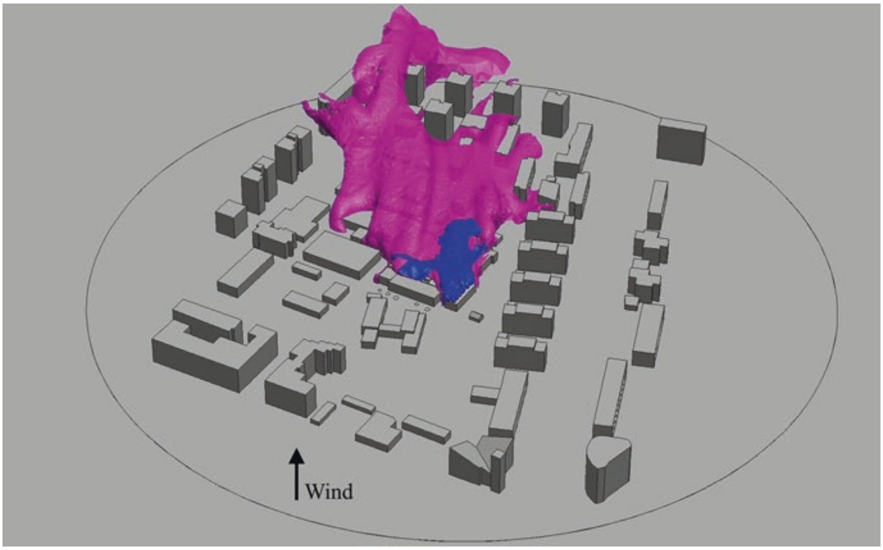


Fig. 4.1 Iso-surface of the mass density of smoke (blue colour represents 0.01 g/m^3, pink colour represents 0.001 g/m^3) illustrating the smoke dispersion from an 8 MW fire, at 5 m/s SE wind. The circular internal domain has a diameter of approx. 540 m

[7], and their use in building and fire codes, and in computer-models by [8]. If a buoyant smoke plume flows into an obstacle, such as the ceiling of a compartment, the vertical flow changes into a horizontal flow. This flow is referred to as the ceiling jet and was described by [9]. Plume and ceiling-jet models allowed estimating the smoke entrainment and transport in simple compartments. In more complex architecture, more complex smoke flow phenomena will occur – e.g. balcony spill plumes, corridor and shaft flow, some of which are illustrated on Fig. 4.2. Once the smoke fills the compartment, the exchange of heat and mass with the exterior of the compartment will take place at the openings (boundaries – doors, windows). This exchange of mass at the compartment boundaries will be one of the key factors determining further development of the fire.

The relation between the size (area, height) of openings and the flow in fire conditions was first described by [10]. We can assume that from the thermodynamics perspective the compartment can be considered as a closed system and that if the fire behaviour is unlimited by the fuel, it will be driven by the flow of fresh air into compartment. These are the basis of the simplest model of compartment fire – the single-zone model [11–13]. Ability to model the fire in a compartment opened the possibility to determine the release of smoke and pollutants to the exterior. The first instances of computer models that employed this theory were RUNF and Harvard model [13, 14].

It was quickly realized that the fires act as described in the single zone models only in their fully developed form (also referred to as post-flashover fires). Before that point, fires tend to form two layers (upper- and lower-gas layer) within the

Fig. 4.2 Smoke flow phenomena inside buildings. (**a**) door flows in a compartment fire; (**b**) complex spill plume; (**c**) homogenous smoke layer in a large open-plan compartment. All pictures were taken during "hot-smoke tests"

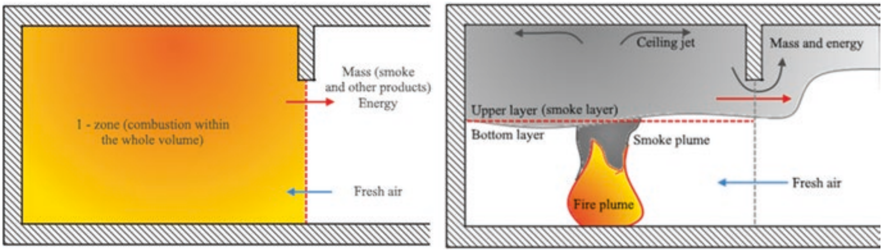


Fig. 4.3 A simple comparison between single-zone (left) and two-zone (right) models of compartment fires. One zone model represents fully developed (post flashover) fire, while the two-zone model represents the fire in the growth phase

compartment [13]. These layers are distinct gas zones, and for simplicity, the conditions in each of the zones may be considered uniform, Fig. 4.3. The upper layer is the layer of smoke and hot combustion products, driven by buoyancy. The lower layer is the area with fresh air and with a small gradient of temperature (primarily driven by the thermal radiation from the upper layer). Zone models combined the assumptions of the conservation of mass and energy at model boundaries, with fire plume models that act as a “pump” [15]. The conditions in each of the zones and the height of the smoke layer interface change with time. This allows defining the consequences of the fire (temperature, smoke and pollutant concentration etc.) as a function of time. Two-zone models were based on multiple fire experiments and thoroughly validated [16]. With the ongoing development, significant improvements were introduced to the treatment of the zones (e.g. introduction of ceiling jet and corridor flow sub-models, HVAC elements), allowing for investigation of the effects of smoke removal systems or sprinkler systems located in the upper-layer. There were more two dozens of different zone models developed, and the most important are the NIST Consolidated Model of Fire Growth and Smoke Transport CFAST [17] and the B-Risk model [18], both still maintained and developed.

The two-zone models do not provide sufficient resolution for in-depth analysis of the fire environment inside the building, as they do not account for local effects architecture has on smoke flow or smoke layers. The importance of the zone modelling has fallen, as with the increasing computational power of modern PC’s extensive use of CFD modelling of fire-related phenomena has taken its place. A simplified comparison of the representation of flows in compartment fires in models with different complexity is shown in Fig. 4.4. Comparison of the applicability of plume, zone and CFD models were presented in [19]. Despite the current trends, the two-zone models may provide quick and reliable source data for analyses of the environmental impact of compartment fires, especially ones performed with simple

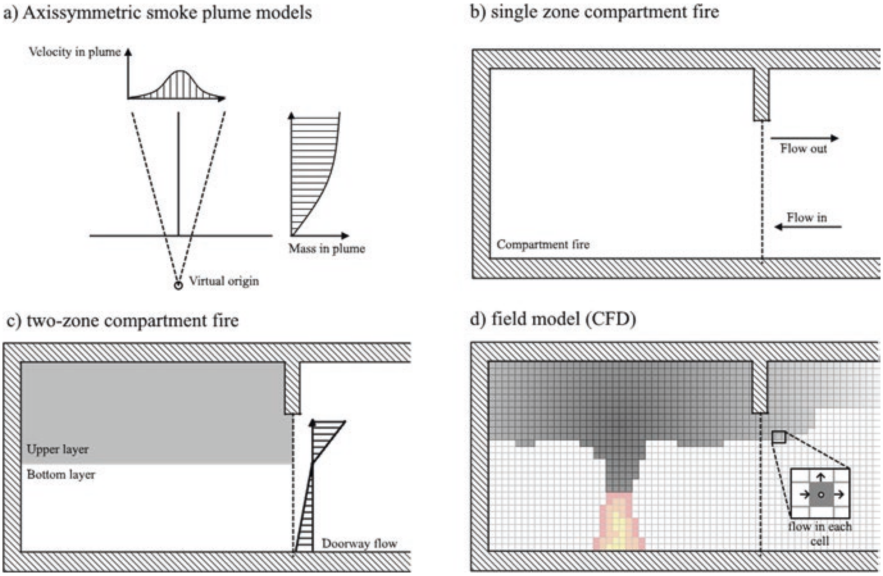


Fig. 4.4 Simplified overview of the fundamental ideas of the representation of flows in (**a**) axis-symmetric plume model, (**b**) single-zone compartment model, (**c**) two-zone compartment model, and (**d**) compartment fire modelling with CFD

pollutant dispersion models. Zone models can also be used as screening tools [13, 18]. Furthermore, zone models may also be powerful tools for parametric and probabilistic studies on the flow of smoke inside and outside of compartments and buildings [20–22].

The most advanced FSE tools are the numerical methods, including Computational Fluid Dynamics (CFD) or Finite Volume Method (FVM) and Finite Element Method (FEM) [23]. These methods allow simulating physical phenomena in fires in complex geometries accurately. Due to their complexity and numerous assumptions, they are also very prone to user's mistakes and errors. These errors were approximated in a round-robin comparison studies, carried before and after extensive fire experiments, known as the Dalmarnock fire experiment [24, 25]. Even with detailed information about the fire experiment (included procedures of measurements and recording), predictions of the CFD modelling of the experiment related to the temperature and visibility were associated with an error ranging from 20% to 200%. Furthermore, high inconsistency was observed between various engineering groups that participated in the round-robin tests.

An essential step for performance-based FSE was the introduction of a fire oriented CFD code Fire Dynamics Simulator (FDS) [26] by National Institute of Standards and Technology (NIST, USA), with the collaboration of the VTT Technical Research Centre of Finland. With its introduction, the community gained a highly optimized, fire-oriented numerical model, that helped in the further growth of the discipline in almost all conceivable areas of fire science. Along with the implementation of FDS in FSE, an enormous effort was put to validate it [27, 28]. Other popular free and commercially available CFD tools used in FSE are, e.g. OpenFoam [29], Ansys Fluent [128], Phoenics [30], Smartfire [31] or StarCCM+. Currently, CFD is the leading tool of choice for most fire safety engineering applications.

4.1.2 Brief Introduction of Computational Wind Engineering

Wind, as a complex and anisotropic flow, creates a complex flow field, Fig. 4.5. Such complex flows can significantly affect the performance of safety systems. Furthermore, the wind conditions will drive the smoke dispersion in building surroundings. To be able to quantify the impact fire has on the environment, the ability to model wind effects is essential. The Computational Wind Engineering (CWE) is the field of science devoted to numerical modelling of wind phenomena. Blocken [33] defined the CWE as the use of Computational Fluid Dynamics (CFD) for wind engineering applications. The primary areas of CWE are the prediction of wind comfort, pollution dispersion or estimation of wind loading on buildings and engineering structures, in the metrological microscale [32]. The CWE also includes other areas, e.g. simulation of spatial-time dependent wind field, simulation of feedbacks between wind force and structure response etc. Computer model validation and development is supported by in situ measurements and model experiments in wind tunnels [33].

In the review of wind and fire coupled modelling [34], the main fields in CWE along with the most researched problems are:

- Structural wind engineering in particular wind loads on various engineering structures. This field of interest remains closely linked to the bluff-body aerodynamics and investigation of the flow around generic cross-sections, like circulars and rectangles or more complicated ones representing real structures.
- Pedestrian-level wind comfort (or discomfort) and urban flows connected with air pollutant dispersion within the urban environment; the flow around a single building but also in street canyons, blocks of buildings or parts of the city is also of interest.
- The natural ventilation of buildings, cross-ventilation and the flow of the pollutants inside, and outside of buildings.
- Environmental effects connected with wind action, like wind-driven rain, snow and sand transport.

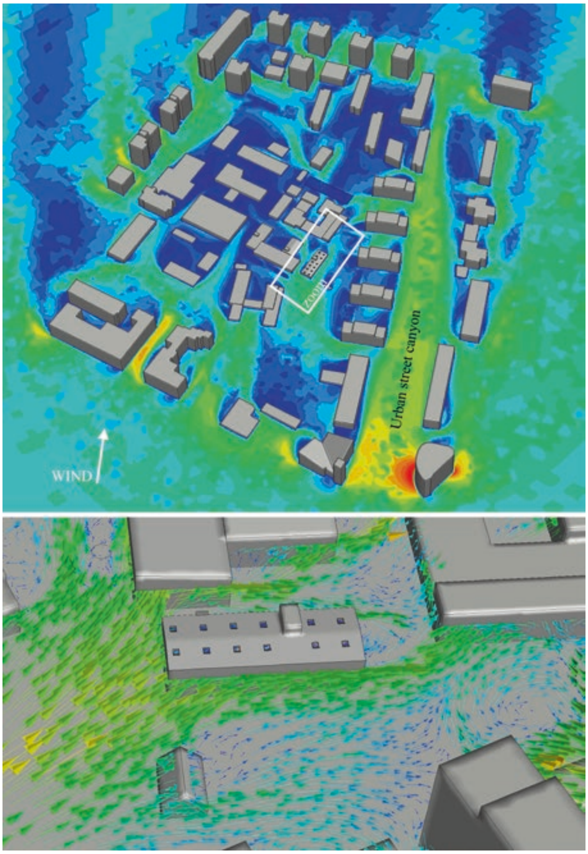


Fig. 4.5 Example of a flow field in a CWE simulation. Top: global results at 5 m above surface, simulated wind with $u_{ref} = 10$ m/s at $z_{ref} = 10$ m. Bottom: velocity vectors near the building in the central part of the domain

- Strong winds and extreme winds like tornadoes and hurricanes connected with investigations of meteorological phenomena, and simulations of the Atmospheric Boundary Layer (ABL) as well as to non-stationary winds, like frontal downbursts or thunderstorms.
- Turbulence modelling and numerical techniques connected with verification and validation of CFD models for urban physics and wind engineering.

One of the earliest considerations on the CWE is the Numerical Weather Prediction by L.F. Richardson [35]. He suggested the use of numerical solution based on finite differences of the governing differential equations to predict the change of atmospheric recirculation. His idea was brought to life with the first computers of the 1950s. Countless efforts were taken to improve the predictions of the CWE; many of them were described in the '50 years of CWE' review paper by [33]. Blocken also presented a more detailed distinction of CWE fields of interest toghether with a summary of relevant review studies. Most relevant to this chapter, the issues concerning the pollutant dispersion modelling were described by [36].

4.1.3 Wind and Fire Coupled Modelling

Coupled research on wind and fire was the focal point of the two-part review by [34, 37]. Authors identified that the difficulties with coupling FSE and CWE arise primarily in the areas of:

- Turbulence modelling and time discretization;
- Spatial discretization and the size of the domain, mesh and the details represented in the numerical model;
- Introduction of the wind as the boundary-condition for the analysis.

Furthermore, the authors identified that the difficulties in coupling the CWE with FSE are caused by the different wind velocity crucial for different problems at stake. When investigating the pollutant dispersion in the near- and far-field, different wind velocities will be associated with respective worse case scenarios for different aspects of safety. Stronger winds may cause larger wakes and downwash phenomena behind buildings, as well as more extended dispersion range in the far-field, while weak and moderate winds may promote higher plumes and more significant pollutant concentrations in the near-field.

The scale of modelled phenomena is different between CWE and FSE simulations. In the fire modelling, the phenomena relevant to the smoke plumes and entrainment are in the centimeter scale, while many phenomena relevant to wind engineering are measured in meters. Furthermore, to capture the consequences of the time evolution of the fire, the calculations and their boundary conditions must be transient. In contrary, most of the calculations in the CWE are performed as steady-state, to capture the mean flow fields.

In the practical performance-based fire engineering, the engineers have postulated the necessity for including CWE rules in the fire-related simulations. In a historical look on the coupled wind and fire modelling, some of the works have incorporated "wind" as a general term for the movement of air [4], while many others have exerted an external force (pressure) acting on the buildings in fires. In some studies, the wind was included as a boundary condition corresponding to the Atmospheric Boundary Layer (ABL) models.

In part I of the review [34] have summarized the recent achievements in both FSE and CWE, emphasizing the use of CFD wind-fire or wind-smoke coupled simulations. They have also reviewed the interaction between CWE and FSE disciplines, as well as other tools that use the wind in the prediction or explanation of the fire behavior, along with a summary of relevant historical experimental studies. The key areas of interest in wind and fire coupled modelling are illustrated in Fig. 4.6.

In part II of the review [37] they have focused on the transfer of best practice guidelines from CWE to the fire-oriented CFD simulations. This also included a framework for efficient coupling of wind and fire modelling. Most of the considerations of this framework are presented in detail in further sub-chapters.

4.1.4 Relevant Research on Numerical Modelling of Wind and Building Fires

Wind can affect the fire and smoke propagation in numerous ways, and numerical modelling is nowadays the main tool to investigate this interaction. Wind and fire coupled analyses are used, among others, for the design of more efficient smoke removal from buildings or road tunnels, prediction of smoke flow inside and outside buildings, production of smoke in large outdoor fires and critical to this chapter – smoke dispersion (in both urban and rural environments).

An overview of earlier developments on numerical modelling of fire and wind was performed in the mid-1990s by [38]. In this study, CFD modelling was used in the evaluation of the performance of natural smoke control in wind conditions. A non-Cartesian geometry 2D model of an atrium was prepared with the FLUENT code and a 3D model of an industrial building in Cartesian geometry with the JASMINE code. Both studies included three different wind velocities. It was observed that high wind velocities could lead to the blockage of fire vents, or even generate reversed flow.

The effects of non-uniform pressure distribution caused by wind were discussed by [39]. The probability of wind velocity that was sufficient to influence the smoke venting (based on Israeli and Scottish wind statistics) ranged from 1% to 25%. The influence of wind on the performance of natural smoke control systems was investigated by [40], who found that the wind can modify the flows through external doors and windows, as well as distort the thermal plume of smoke. The research on the wind effects on smoke control was also performed by [41–46]. These studies were described in more details in [34].

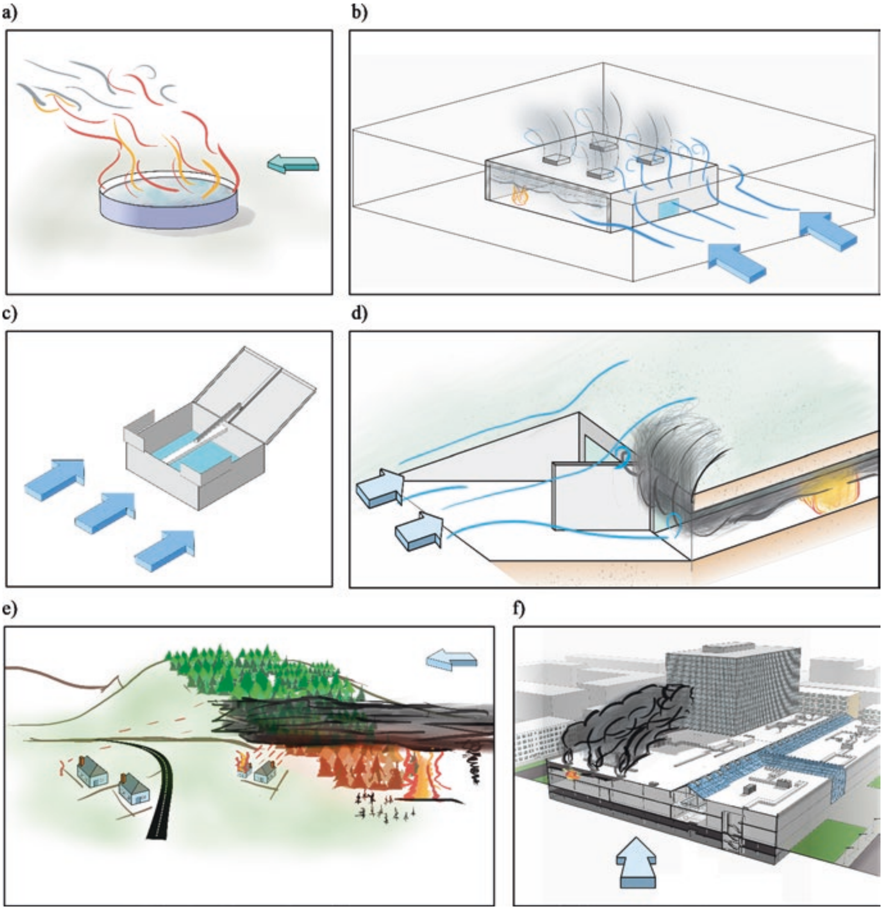


Fig. 4.6 Key areas of interest of coupled wind and fire modelling: (**a**) wind-driven pool fires; (**b**) wind influence on building fires and smoke control; (**c**) development of smoke venting technology; (**d**) wind impact on tunnel fires; (**e**) wind impact on wildfires and Wildlife-Urban Interface area safety, (**f**) smoke propagation in urban and sub-urban areas

The wind may have effects on the flame projection from a compartment, inform of externally venting window plumes of fire and smoke [47, 48]. Depending on the relative location of compartment openings and their configuration, the wind may blow into the compartment and block the flow of hot gasses, acting as an ‘opposing wind force’ [49]. Research on the fire and smoke venting with opposed openings were examined by [50]. The paper discussed the occurrence of bi- and unidirectional flows at doors, on which the wind was acting. The occurrence of unidirectional flow was only a function of wind velocity and not fuel support. The façade flame height ejected from the openings in wind conditions was recently investigated by [51], who developed a global model that incorporates the external wind velocity.

The wind may also be responsible for dangerous conditions during the firefighter operations. Tactical guidelines were developed by [52, 53]. The first study presents results of 14 full-scale tests of the wind-driven fire in a 7-storey building. The CFD method was also extensively used to understand the wind influence on fires. Barowy and Madrzykowski [54] performed CFD simulations of the wind-driven fire in a single-storey residential building. A rapid change in thermal conditions in the building was associated with a wind flow of the velocity equal to 4.5 m/s, making the firefighters' operation more difficult. The importance of wind-induced airflow in buildings was emphasised by [55]. The natural cross-flow of air caused by the wind may suddenly change the flows inside a building in a fire, which was associated with multiple firefighter line-of-duty deaths.

4.2 Modelling of Fires

4.2.1 Fire Sources and Compartment Fires

As the variations of possible fire scenarios are endless, it is not possible to estimate the results of all possible fires within a building, and in consequence, their effects on the environment. From this point of view, the fire models must be considered as explanatory, but not predictive. Fire modelling is stochastic, and we can determine the results of fires with individual probabilities. Due to high costs associated with CFD modelling of fires, multiparametric analyses are still limited to zone models [20]. To enable practical engineering, so-called "design fires" are determined. They are based on historical data, occupancy type and safety systems used within the building, and represent the worst credible fire within the compartment. An overview of design fires was presented in [56]. Difficulties associated with the choice of the worst credible fire are well illustrated by [1], who cites the OECD Committee on the Safety of Nuclear Installations (CSNI): "*not all large nuclear power plant fires are significant from a public safety point of view, nor are all safety significant fires large*".

Many physical parameters can be used to describe the fire. Among them, the most widely used is the measure of the heat released by the fire, which is referred to as the Heat Release Rate (HRR). Dependant on the model, the HRR can be presented as a value per unit area (HRRPUA) or volume (HRRPUV). The size of fire depends on the phase of the fire growth. The stage of growth of the fire is often defined as fuel- or ventilation- controlled. In fuel controlled fire the size of a fire is determined by the availability of the fuel. In the ventilation controlled fire, the HRR depends on the availability of oxygen, which is a result of the ventilation conditions in the compartment. The transition between these phases happens is referred to as the flashover phenomenon [11]. We often refer to these two phases as the *growth phase* and the *fully developed fire,* respectively, Fig. 4.7. It should be noted that this classification was developed for compartment fire dynamics framework [57], and

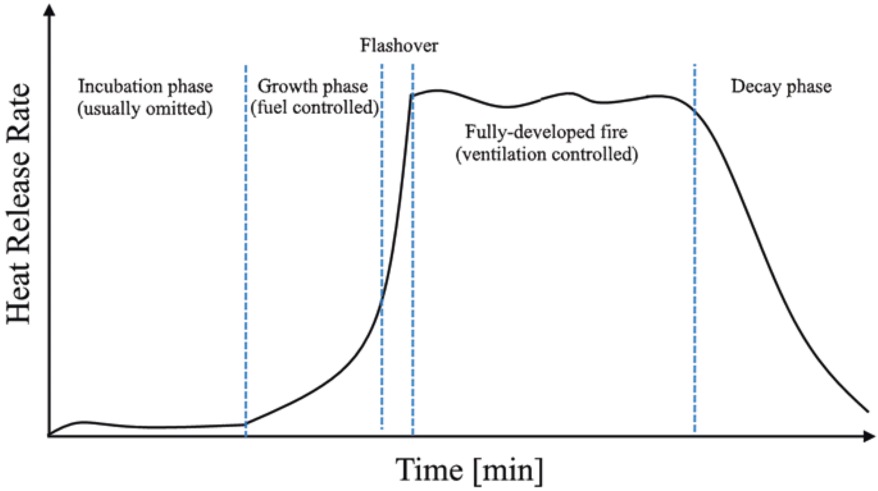


Fig. 4.7 Phases of a compartment fire

may not be accurate for the development of fires in very large, open-plan compartments. Furthermore, in some ventilation conditions, when the openings are sufficiently large, the ventilation may no longer be a dominant factor [58].

The growth of the fire is often described as a quadratic function of time, and the quadratic coefficient is the fire growth coefficient α [59]. For example, a fire that is defined as *fast* has a growth coefficient of $\alpha = 0.047$ kJ/s^3. This value is calculated following the assumption that the *fast* fire does reach 1 MJ/s of HRR within 150 s. Other common types of fires – *slow, medium* and *ultra-fast*, are defined similarly. Their time to reach 1 MJ/s is respectively 600 s, 300 s and 75 s, and their α coefficients respectively 0.0029 kJ/s^3, 0.012 kJ/s^3 and 0.188 kJ/s^3. Comparison of the evolution of HRR in time for these fires is shown in Fig. 4.8.

The production of species within the fire is defined primarily with respective yield factors, the mass loss rate of the source and the effective heat of combustion. This includes the production of soot, as well as the production of toxic constituents [60, 61].

The size and the consequences of a fire in a building in the early phase will strongly depend on the layout of air inlets [62], the shape of the building or ambient weather conditions [43, 63, 45]. The location of the fire is rarely considered as a variable [64], although the wall- and corner-location of the fire are associated with more rapid-fire development [65, 66].

Engineers can relate to probabilistic models for the choice of design fires, such as event trees [2], Monte-Carlo scenario modelling [67] or fractional factorial design approach [68, 69, 63]. With probabilistic tools and improved fire models, fire safety engineers can investigate more specific events and scenarios, which are a better representation of fire outcomes in the building. This allows creating solutions better fit to the individual building, often leading to a decrease of previous excessive safety

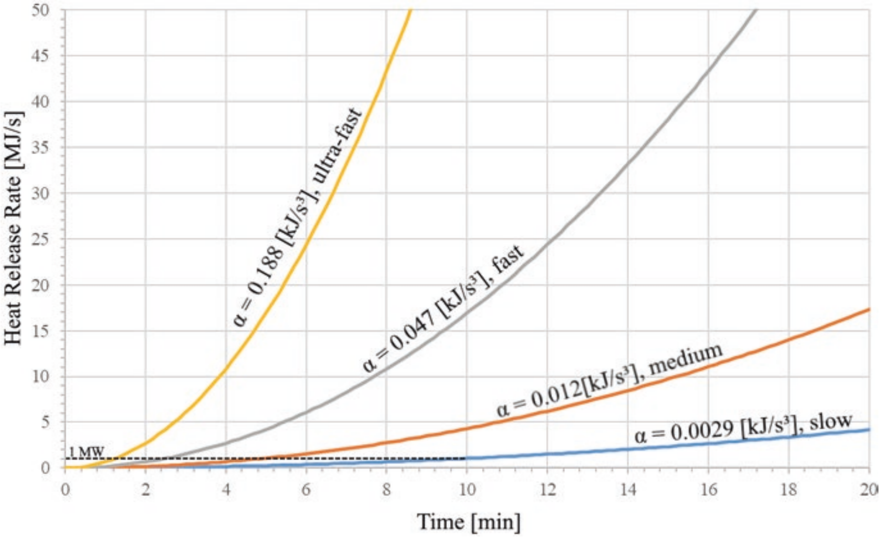


Fig. 4.8 Common curves displaying the time evolution of fires with various growth rates, as defined in NFPA 204 [59]

margins. The overview of commonly used design fires and design scenarios can be found in [70, 71].

The abovementioned models used to determine the design fire scenario for building fires are primarily related to early fire development, which is in the focus of most of the common CFD analyses of building fires. However, the fully developed fires have the larges environmental impact. If the fire is not stopped by safety systems or firefighter intervention, it will grow until it will reach a fully-developed size. The size of fire will be the limited by the availability of fuel (fuel controlled fire), availability of the oxygen (ventilation controlled fire) or will be limited by the spatiotemporal development of the fire within a sufficiently large enclosure (e.g. as in travelling fires). For the more in-depth description of fuel and ventilation controlled fires, the reader is kindly referred to the works of [72, 73, 57]. For the definition and analysis of travelling fires, the reader should consult [74–76].

As previously mentioned, single- and two-zone fire models may also be used to estimate the release of heat and mass from compartment fires to the environment. Zone models can account for phenomena in both fuel and ventilation controlled fire regimes, as well as predict the size of flaming combustion outside the building [77].

The representation of the fire in CFD framework can be done in at least three different ways, that will depend on the capabilities of the chosen solver. The first and most straightforward approach is to define a source of heat and mass (point, surface or volume) and temporal evolution profiles for the generation of heat, mass and mixture constituents from that source. The results of the combustion in terms of heat released and species produced are pre-defined by the user. The chemistry models are not used, and phenomena such as pyrolysis, self-extinguishing or under-ventilated combustion are not solved by the CFD.

The second way to represent the fire in a CFD model is to create a source of a fuel (usually in gas phase), that is ignited and further burned based on simple chemistry models (e.g. 2-eq. Arrhenius models [26], or pre-mixed burning model [128]. The heat release will be primarily dependent on the mass flow of the fuel (assuming that there is sufficient oxygen for the combustion). The species yields are dependent on the combustion model used, and the local concentration of oxygen. This approach allows considering the under-ventilated combustion and local extinction, but the user still defines the evolution of the fire size and its burnout time through the description of the fuel source.

A third way to model fires is to use a group of discrete fire sources, which combustion is triggered individually by an external stimulus (e.g. surface temperature exceeds a threshold value). Once triggered, each of the sources acts as a second type, following a pre-defined burning rate. The total HRR of the fire is the sum of the fires that are burning at a given time. This approach allows the imitation of fire growth. However, each of the individual sources is still compatible with its nature. This approach is the closest to the predicted fire development that the design fire can achieve [78]. More advanced models where the user does not govern the combustion of individual sources, but the fuel emission is dependent on the pyrolysis phenomena are still in development and should be considered as an academic tool.

4.2.2 Smoke and Particulates

Smoke, as the product of a fire, is considered as the primary threat to the building occupants and is the main element assessed in the evaluation of the environmental impact of fires. Smoke can be described as a mix of air, particulates consisting of soot, volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH) and solid inorganic compounds, and other non-particulates and gases (many of which can be considered toxic). The critical component of smoke is soot, which also acts as a very efficient adsorbent and transport mechanism for VOC and non-particulate compounds, that can pose a threat even many days after the fire [79]. In terms of acute danger and toxicity in compartment fires, toxic gases such as CO and HCN have the most substantial impact on the tenability. The damage of the smoke to humans was thoroughly reviewed by [60, 80], and the damage to the building (especially to electronic equipment) was characterised by [79]. The dangers related to general air pollution constituents were described in [81–83].

The most straightforward classification of air contaminants in relation to chemical composition and size is to separate them into particulate matter (PM) and gasses in vapour form. The particulates can be further distinguished into solid (dust, fumes, smoke), liquid (mists, fogs, smog) and bioaerosols. Dusts are solid particles with sizes smaller than 100 μm and may have different origins. Fumes are solid particles formed by condensation of vapours of solid materials (also include metallic fumes), formed by sublimation, distillation or chemical reactions. Mists are aggregations of small liquid droplets and fogs are water droplets, usually formed by condensation of water vapour. Fogs and mists are rarely an effect of fires. Besides particulates, the air contaminants also consist of vapours of organic and inorganic gases. An in-depth description of particulates in air pollution can be found in [83]. An illustration of examples of organic compounds commonly found in smoke is shown in Fig. 4.9.

Pollutant particles may also be classified according to their size (characteristic diameter) and the ability to affect humans through breathing. Particles of the diameter smaller than 100 μm are inhalable, while particles smaller than 4 μm are considered respirable. In the ACIGH criteria, particles with a diameter of less than 10 μm are considered dangerous as they can enter the thoracic duct [84]. EPA classifies the dangerous groups of pollutants into coarse (larger than 1–3 μm), fine (smaller than 1–3 μm) and ultrafine (smaller than 0.1 μm). It should be noted that smaller particles may react and combine to form larger particles and a prime example are PAH’s that can be forming larger soot particles [214]. The size of smoke particles can range from 0.01–4 μm for tobacco smoke, 0.2–3.5 μm for flaming combustion of wood, 0.03–1.0 μm for oil smoke [83]; 0.4–3.0 μm for flaming combustion of plastics [79].

In numerical modelling of fires the smoke is generated within the source of fire, usually represented as a gas-phase species introduced to the convective stream of air also produced by the source. This representation heavily relies on the main parameters relevant to the soot production – effective heat of combustion ($H_{c,eff}$), heat release rate ($\dot{Q}$) and the soot yield parameter (Y_s). The use of soot in numerical modelling of that phenomena were recently reviewed by [85]. The mass of smoke ($\dot{m}_s$) introduced into the model can be presented as:

$$\dot{m}_s = Y_s \frac{\dot{Q}}{\Delta H_{c,eff}} \tag{4.1}$$

Other constituents of the smoke can be introduced through their individual yield values. For tracking the trajectories of soot particles, they can be introduced to the model as Lagrangian particles, that further are tracked independently.

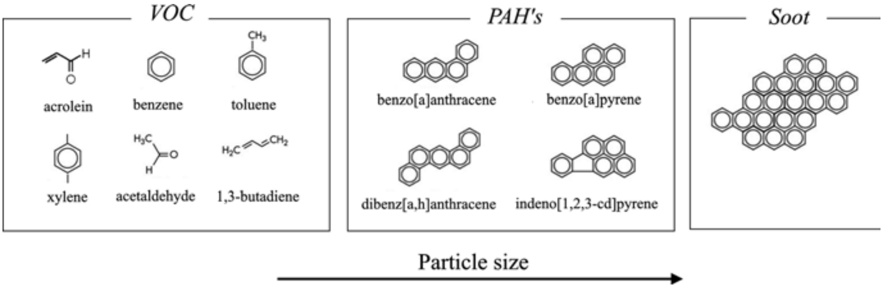


Fig. 4.9 Examples of organic compounds found in smoke, with increasing complexity and particle size

The value of soot yield depends on the characteristic of the fuel and the available oxygen during the combustion. Values may range from 0.001 g/g (methyl alcohol) to 0.178 g/g (toluene) [86]. The production of smoke will depend on the conditions in which the combustion takes place – that means that the smoke produced from the fuel in small scale laboratory apparatus may be different from the smoke produced in the large fire of the same fuel. This was highlighted in [87]. Rashash and Drysdale [57, 88] reviewed the process of soot formation in fires and provided some reference values of the smoke potential of different materials. Reference values of the soot yield, and other coefficients for production of flaming combustion products in fires, can be found in [89]. Smoke and pollutant production in peat fires was thoroughly reviewed by [90]. In FSE practice for building fires, the soot yield value for the complex materials is usually unknown. In this case, a safe assumption is to use the soot yield of 0.1 g/g. It was shown by [86] that this value is conservative. Due to the exponential characteristic of the Bougheer-Lambert-Beer law, a change of soot yield above the value of 0.1 g/g has only a minor effect on the tenability within a compartment or the definition of the Available Safe Evacuation Time. Even if the user underestimated the value of the soot yield, the effect of an introduced error on qualitative assessment is minimised. In modelling of outdoor fires, this estimate may not be representative. In such case, experimental data exist, e.g. [90] or more advanced models may be used to predict the smoke composition and individual yields [91].

An evident effect the soot has on the fire environment is the reduction of the visibility in smoke [86]. Following the Bougheer-Lambert-Beer law, the light transmittance T (I/I_0) may be calculated to determine the obscuration effect of the smoke layer on the light. This allows calculation of a contrast ratio between target and background, which may be an indication if the target will be visible through the smoke. The obscuration is dependant on the mass concentration of smoke (m), optical path length (l) and the specific mass extinction coefficient (σ):

$$I = I_0 e^{-\sigma m l} \tag{4.2}$$

The values of mass extinction coefficients for various flammable materials range from 600 to 9800 m^2/g, with the standard value of 8700 m^2/g determined by [92] and implemented, e.g. in FDS v.6. A comprehensive discussion on the values of mass extinction coefficient can be found in [92, 89].

The smoke obscuration effect of smoke on the visibility of evacuation signs can be simply calculated from the known mass concentration of smoke (m_s), according to the empirical theory of Jin.

$$V = \frac{K}{\sigma m_s} \tag{4.3}$$

The widely used values of the K-factor defining the target (and the ambient lighting) are 3 for light reflecting evacuation signs and 8 for light-emitting signs [93–95]. The

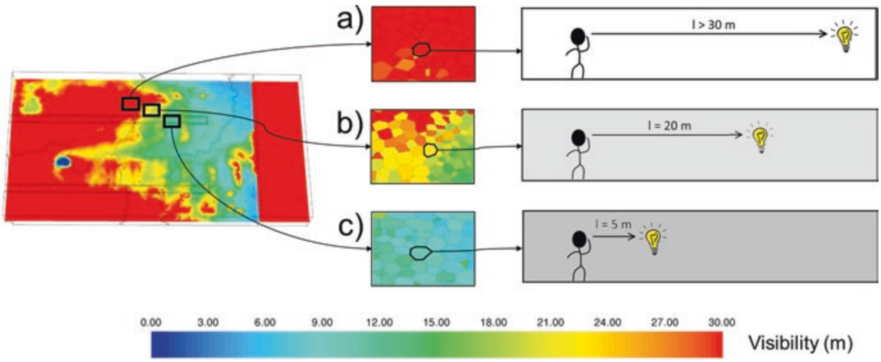


Fig. 4.10 The local visibility plot (most left, range from 0 to 30 m and more, for K = 3) is created as an array of visibility values from individual cells (middle clips). Value within each of the cells represents the distance, from which a certain object (eg. sign, light) would be seen, in a room (right side drawings) with uniform smoke corresponding to the mass concentration of the smoke within that cell [86] (©Elsevier, reproduced with permission). (Source: Wegrzynski. Right obtained through RightsLink. License number 5051871486037)

values proposed by Jin may be considered too conservative [96], and different values can be found in literature for different types of signs [97]. The illustration of the physical meaning of the value of visibility in smoke in CFD analysis calculated in multiple cells of a numerical model with the use of Jin's relation is shown in Fig. 4.10.

If the smoke disperses in the environment, the mass density of smoke is reduced by air entraining into the plume. However, in this process, the size of the plume quickly increases, meaning that even significantly diluted plume may still obscure the visibility, which is illustrated in Fig. 4.11. Furthermore, the distances to points of interest outdoors (other buildings, cars, obstacles) are considerably larger than within buildings. This means that large smoke cloud with a very low smoke density (compared to smoke density in smoke layers inside buildings) may significantly obscure vision. The visibility of outdoor objects should be determined through the light transmittance integrated over a path, rather than with simplified Jin's relation. If the average mass density over a path is known, the distance (l) at which a certain transmittance (I/I0) is reached can be calculated as follows:

$$l = \frac{\log\left(\frac{I}{I_0}\right)}{-\sigma m_s} \tag{4.4}$$

Results of calculation of the path lengths, at which a pre-defined value of transmittance is obtained, given various values of an average mass density of smoke on the path length are given in Table 4.1.

The most dangerous consequences of smoke inhalation are related to its acute and long term toxicity. This was reviewed in depth by [60, 80]. The most dangerous products are the asphyxiant gasses (produced in larger quantities in an

Fig. 4.11 Smoke plume over a large compartment fire – different visibility through different parts of the plume. (Courtesy of prof. Rein, Imperial Hazelab, 2018)

Table 4.1 Distance at which a certain value of transmittance T (I/I0) will be obtained for a given value of average mass density of smoke along the path length. Calculations performed for specific mass extinction coefficient of smoke 8700 m^2/g

Mass density of smoke [g/m^3]	T = 1%	T = 2%	T = 5%	T = 10%	T = 25%	T = 50%
0,00010	2326	1976	1513	1163	700	350
0,00050	465	395	303	233	140	70
0,0010	233	198	151	116	70,0	35,0
0,0025	93,0	79,0	60,5	46,5	28,0	14,0
0,0050	46,5	39,5	30,3	23,3	14,0	7,0
0,0075	31,0	26,3	20,2	15,5	9,3	4,7
0,010	23,3	19,8	15,1	11,6	7,0	3,5
0,025	9,3	7,9	6,1	4,7	2,8	1,4
0,050	4,7	4,0	3,0	2,3	1,4	0,7
0,075	3,1	2,6	2,0	1,6	0,9	0,5
0,10	2,3	2,0	1,5	1,2	0,7	0,4
0,20	1,2	1,0	0,8	0,6	0,4	0,2

underventilated conditions) – carbon monoxide (CO) and hydrogen cyanide (HCN). Other common toxic products of fires are irritant gases (HCl, HBr), nitrogen dioxide (NO_2), ammonia (NH_3) and acrolein (CH_2CHCHO).

The toxicity of the mixture of gas products can be assessed through the concept of Fractional Effective Dose (FED) [80]. The value of FED equal to 1 represents the sum of the concentration of various toxic constituents, that combined represent the lethal concentration for 50% of the population in a 30-min exposure (LC_{50}). Other approaches are related to the comparison of the measured concentration of contaminants with threshold values, such as LC_{50} or Immediately Dangerous to Life or

Health (IDLH) [98] or fractional effective dose for incapacitation (FEC). There is no general agreement on what value should be used for the design of emergency response, and different Authorities may declare different values as the target values. In case of absence of recommendations, NOAEL (No Observed Adverse Effects Level) concentration can be used. However, for some substances (e.g. cancirogenic substances) no-exposure may be preferred. An in depth review of smoke toxicity and various exposure levels is given in [80].

4.3 Smoke Dispersion Modelling

4.3.1 Introduction

Concepts of modelling the environmental effects of fires are not new, and various approaches were developed over the decades. Many of these efforts were connected to warfare research in order to understand and prevent the damage caused by fires started with military operations. Furthermore, the epoch of early development of urban fire and dispersion models overlapped with the epoch of imminent nuclear-weapon threat, which out of all weapons had the highest ability to start urban fires due to enormous thermal radiation released in the explosion [99]. A valuable source of knowledge on modelling the environmental effects of fires is the NATO monograph on the wind climate in cities [100].

In a review paper [101] defined four components that constitute a smoke dispersion model in the context of wildfires. The first is the description of the fire source, which means the emission of heat and pollutants. The second and third elements describe the vertical and horizontal movement of the smoke in the plume caused by the atmosphere stability and wind-profile. The fourth, albeit mentioned as non-mandatory, is the consideration of chemical transformations that occur as smoke constituents react with each other and with the atmosphere. All four components are substantial parts of the CFD-based framework. However, to maintain the historical context of the smoke dispersion modelling, earlier concepts are briefly introduced. These are (in the order of increasing complexity): Box, Gaussian Plume, Puff, Particle and Eulerian models. CFD models used for modelling pollutant dispersion and relevant experiments on the pollutant dispersion are also described in this chapter. Even though the CFD is the method of choice for the research on the near-field fire emissions, some of the mentioned models are useful as complementary tools, especially for preliminary assessment or long-term and far-field investigations of region-scale consequences of the largest fires.

4.3.2 Box Models

The simplest dispersion of smoke models are the Box models. It is assumed that a fragment of the atmosphere may be represented by a "box", which height is defined by the top of the mixed layer, and which has finite horizontal dimensions. The size of the typical box is comparable with the size of an aircraft hangar. The box acts in a similar way as the upper zone in the two-zone model of compartment fires. It means that the emissions in the box are assumed instantaneously well-mixed throughout its entire volume. Essentially, the smoke plume is not modelled in this approach and the entire box is treated as one emission source. If more than one box is used then the transport of pollutants from box to box can be modelled at their boundaries, taking into account the wind effects on the pollutant dispersion. The illustration of a box model is given in Fig. 4.12.

A well-known box model used in smoke management of wildfires was the VALBOX (Ventilated Valley Box Model). Its main purpose was to predict ground-level concentrations of pollutants under stagnation conditions in mountain valleys. The valley (box) is closed on the sides by its walls, and from the top by the atmospheric inversion. The model allows the assessment of the total pollutant concentrations within the valley. The accuracy of the results increased with the increasing sampling time. As a consequence, the box model is not able to predict concentrations from fires in the short time-frame [101].

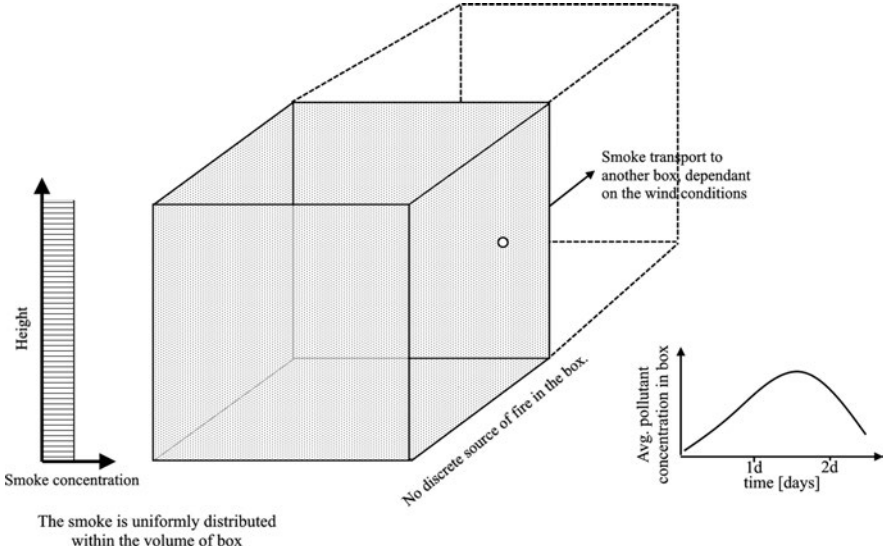


Fig. 4.12 The idea of the operation of a box model. The smoke concentration is uniform within the whole box, and no discrete source of the emissions may be distinguished. One box may transport the pollutants to another box on its boundaries

The most significant restriction of box models is the assumption that emissions are immediately well-mixed within the entire box volume. Due to the large size of the box, the time required for uniform mixing of the pollutants within its volume (1 day or more) is significantly longer than the lifetime of most of the smoke particles. A solution would be using smaller boxes and shorter time-scales for the analysis, but that was against the principle of the development of these models – to allow for quick calculations on the limited computational resources available in the 1970s and the 1980s.

Interesting use of box models in urban dispersion modelling was discussed by [102]. It was implemented for a dense urban street network, with boxes forming fragments of crossing urban canyons. The boxes were interconnected, and the mass exchange was modelled with parametric laws, driven by the external wind. The pollutant concentration within each discrete fragment of the urban canyon (each box) was uniformly mixed. Carpentieri et al. [103] have used SIRANE model to investigate pollutant concentrations in the dense urban network, previously assessed in 1:200 wind tunnel research. The numerical model performance was described as "good", with a tendency to overestimate pollutant concentration at the far-field, and underestimate close to the emission sources. Sabatino, Buccelieri and Salizzoni [102] further added that these approaches may be reliable for high-density canopy, and will decrease when the spacing between buildings increases (e.g. in suburban districts).

4.3.3 Gaussian Plume Models

The second prevalent early approach for modelling pollutant dispersion were Gaussian plume models. Instead of dividing the space into uniform fragments, plume models treat the source of emission as a point in space (or line, or area) and provide a solution for the effects of continuous emission from it according to the given atmospheric processes. The plume size and shape depends on atmospheric conditions (stability class, temperature gradient), wind direction and velocity. The crosswind dispersion of the pollutants is represented with a Gaussian distribution (hence the name for this category of models). The derivation and the detailed mathematical description of the Gaussian plume equations, also for multiple source plumes, is given in [104]. The Gaussian plume distribution:

$$\overline{c}\left(x,y,z\right)=\frac{Q}{2\pi\sigma_y\sigma_z\overline{u}}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{\left(z-h\right)^2}{2\sigma_z^2}\right)+\left(-\frac{\left(z+h\right)^2}{2\sigma_z^2}\right)\right) \tag{4.5}$$

where $\overline{c}$ is the time-averaged concentration, Q is the source term and $\overline{u}$ is the time-averaged wind velocity at the height of release h. The σ_y and σ_z describe the crosswind and vertical mixing of the pollutant [108]. Example results of Gaussian plume calculations are shown in Fig. 4.13.

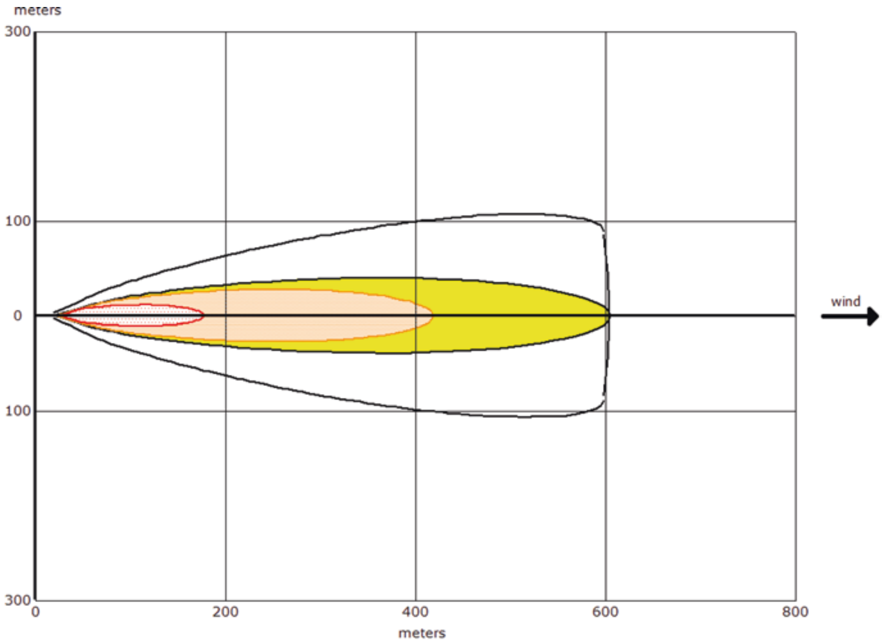


Fig. 4.13 Example results of Gaussian plume calculations, showing the range at which the smoke released in a fire will be diluted by a factor of 10^3 (red), 10^5 (orange) and 10^6 (yellow). The black outliers show the wind uncertainty range

Examples of commonly used Gaussian plumes models are ALOHA by NOAA [105] for industrial releases and disasters, VSMOKE [106] and SASEM [107] in wildfire research. In some models, such as VSMOKE the plume rise is not incorporated but could be defined by the user (in terms of fractions of release at ground and top of mixing layer levels). In ALOHA the concentration in the function of x, y, z coordinates and in the function of time t, is determined with the Gaussian dispersion model of Palazzi. The effects of the atmospheric inversion are simplified, and the boundary between stable and unstable air is impermeable to the transport of the pollutants.

The Gaussian model predicts the concentration of a steady-state release, that will appproach the Gaussian distribution with the increasing down-wind distance. The assumption is that the pollutant gas is neturally buoyant. More complex Gaussian models were reviewed by [107]. They can represent the impact of complex terrain and use parametrisation for the convective boundary layer turbulence to improve the predictions. The performance of these models may be significantly improved with semi-empirical relations, especially concerning the micro-scale retention of the pollutant within recirculation areas (e.g. building wakes and street canyons), and enhanced lateral spreading due to increased plume meandering [102].

The main strength of Gaussian plume models is their fast response time. As they solve a single formula for each target, the calculation is almost instant at any modern calculation device [108]. A significant limitation of basic Gaussian plume models is the assumption that pollutants are distributed in a straight line under steady-state, homogenous conditions. Effects of changes in weather conditions or terrain effects are excluded. Also, the pollutants in the plume may have a different trajectory than the thermal plume itself, as shown in [87]. Some considerations about the validity of Gaussian plume models in wildfire scenarios are given in [101]. Despite their limitations, [102] has mentioned that the models may be useful as a quick screening tool for short-range urban dispersion (<5 km), as far as pollutants mainly disperse above the buildings or the cloud of pollutants is significantly larger than the obstacles. Otherwise, the downwash and effects in the wake areas will make the Gaussian plume models inaccurate.

4.3.4 Puff Models

Puff models, also known as Gaussian Puff models, are another group of pollutant dispersion models. In these models, the pollutant is released continuously in time, in discrete "puffs", which are independent releases of the pollutant tracked individually in the simulation. The horizontal size (and pollutant concentration), as well as the height and the flow direction and velocity of each puff, change independently, allowing to include the effects of changing wind and terrain on the plume shape (which will be formed by a collection of individual puffs). The commonly known Puff models are HYSPLIT [109] and CALPUFF [110]. The previously mentioned Gaussian plume model ALOHA in time-dependent mode uses five steady-state releases with a finite duration, that are tracked independently, and which can be considered as the simplest form of a Puff model [105]. An idea of the Puff model is given in Fig. 4.14.

The CALPUFF model integrates a diagnostic meteorological model CALMET that produces hourly data of relevant meteorological parameters (wind velocity and direction, temperature, mixing height) in a three-dimensional discrete domain. The CALPUFF model itself is described as a non-steady-state Lagrangian Gaussian puff model containing modules for complex terrain effects, overwater transport, coastal interaction effects as well as pollutant removal sub-models (building downwash, wet and dry removal and simple chemical transformation). A unique feature of the Puff model, such as CALPUFF, is to simulate the effects of time and space varying meteorological conditions on the pollutant transport, transformation and removal. All features of the model are summarised in [110]. CALMET and CALPUFF were used in an interesting case study on the numerical modelling of smoke dispersion from fires in the urban environment [111].

The HYSPLIT model [109] is a complete system for computing trajectories of complex dispersion and deposition simulations. It uses Puff or particle approaches, which is considered in the review by [101] as a hybrid approach. The meteorological data fields may be obtained from existing archives or standardised forecast model outputs (e.g. NOAA, NCAR or ECMWF formats). The model uses discrete

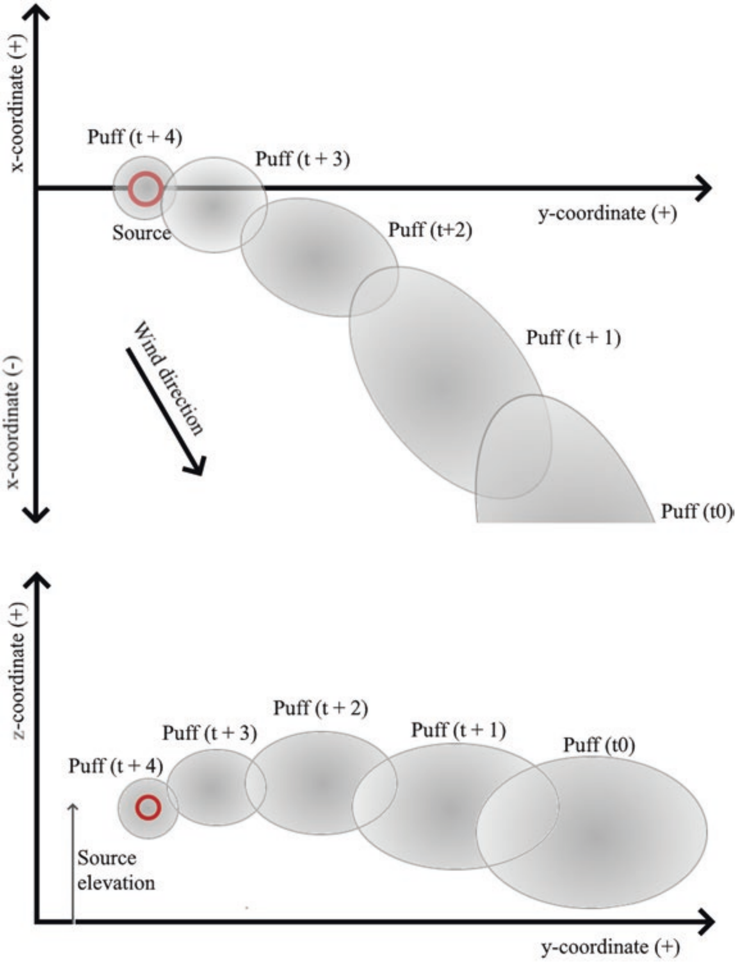


Fig. 4.14 The idea of the puff models – state of discrete puffs released for a time step length (t) at a time step (t + 4)

cells for the determination of meteorological conditions. If the given puff exceeds the size of the cell, it is split into several new puffs which are tracked independently. In the default configuration, the puff distribution model is used for the horizontal direction, and the particle dispersion model in the vertical direction, which is associated with higher accuracy of modelling.

The ability to deal with time-varying and terrain sensitive flows by Puff models was a significant development compared to the Gaussian plume models. However, some challenges remain, among them the definition of the fire source, consideration of the plume rise and distribution of the pollutants in the plume, the diffusion in downwash and wake areas that are typical for dispersion in urban habitats. An overview of Puff models used in wildfire modelling is given in [101].

4.3.5 Lagrangian Particle Models

The limitation introduced by "Puff expansion" concept limits Puff models capabilities in regions, where strong turbulence or high levels of wind shear are expected. Particle models provide the solution for such cases, where each simulated particle represents a fixed mass of the pollutant. Knowing the source characteristics and the results of modelling for a fixed number of particles, the output concentrations of pollutants may be predicted, Fig. 4.15. Thomson [112] defined the criteria for models of particle trajectories in turbulent flows, and [113] made a review of such models.

Particle dispersion models are used to numerically simulate the dispersion of a passive tracer in the lower layer of the troposphere, by calculating the Lagrangian trajectories of thousands of individual particles. The pollutant concentration is

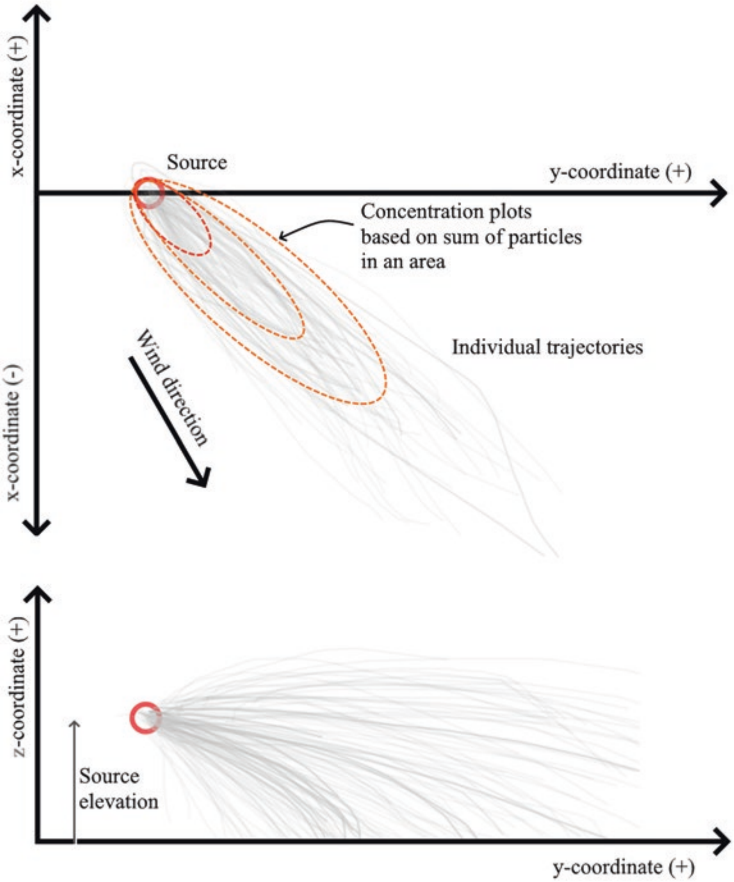


Fig. 4.15 The idea of the particle dispersion models – each solid line represents a trajectory of a single particle emitted in the source. Dashed lines represent concentration plots obtained with the statistics of particle distribution

calculated at discrete grid cells for puffs as cell-averaged concentrations of particles. Each pollutant species is summed independently in each grid [109].

An example of the Particle model is the Flexible Particle Dispersion Model FLEXPART [114]. This model is a Lagrangian particle dispersion type for long-range and mesoscale transport, diffusion, deposition and the radioactive decay of tracers released from sources of various shapes (point, line, surface or volume). The model solves Langevin equations for three independent wind velocity components, neglecting the cross-correlations that are reported to have minor effects on the results of the large-scale dispersion. Turbulence defined by the Gaussian distribution is assumed under all meteorological conditions, and the turbulent statistics are obtained using the scheme of Hanna with some modifications for convective conditions. The model implements a density correction for atmospheric Lagrangian particle dispersion, which improves the accuracy of the description of turbulent diffusion in the ABL [114]. A fire plume rise may be included in FLEXPART by an elevated source, with uniform distribution of emissions along with height [101].

Lagrangian particle models may be used to simulate the pollutant dispersion in a flow field based on previously resolved CFD simulations. This approach was briefly described by [102] as the technique ensuring spatial accuracy of a CFD but with a reduced computational cost. In such an approach, the pollutant concentrations are obtained with solving Lagrangian dispersion in the velocity field, that are previously obtained with more advanced numerical techniques (such as CFD). The models may be further modified with analytical corrections for simulation of recirculation zones, that develop in wakes areas behind buildings. This approach may be useful for accidental releases of pollutants with time-varying source strength, such as fires, even over large domains. However, in order to use this approach successfully, the flow in the plume as a result of the fire must not significantly change the flow field in the domain, which limits the applicability of the model to rather small fires and other “cold” releases.

Particle trajectories can also be used to simulate transport of pollutants directly within more complex models based on CFD. This was the approach used to simulate crude oil fire plumes in A Large Outdoor Fire plume Trajectory – ALOFT [115] and in the revised analyses presented in [116]. In this model, a number of particles representing a fire plume are released. The rising plume is simulated with the LES model; however, it does not consider the turbulence in the ABL. The simulation begins several fire diameters downwind of the fire, where the prevailing wind dominates the velocity field and trajectory of the plume. The uniform wind assumption is used to simplify the calculations. ALOFT was extensively used to determine the safe distance between fires and populated areas in Alaska and Texas, USA, before planned burning of crude oil spills.

As mentioned by [108], the computational task in Lagrangian models is the time-integration of Stochastic Differential Equations (SDEs) or Ordinary Differential Equations (ODEs) describing the motion of particles. This means that parallelisation of this task can be based on exploiting the independence of the particle trajectories, leading to virtually unlimited parallelisation on any computing architecture such as grids, clusters or Graphical Processing Unit (GPU) based computers. The limitations may be reached with the increase of the range of prediction. Long-range simulations may require the introduction of a significant number of individual trajectories, leading to a considerable increase in computational costs.

4.3.6 Eulerian Models

Eulerian models use a fixed reference frame to calculate the pollutant dispersion between the cells (or boxes) of the discrete mesh. The models solve numerically the atmospheric transport described by the second-order partial differential equations (PDEs) and require the user to define the initial and boundary conditions. The solution of the equations in subsequent time steps allows for the determination of space and time evolution of the concentration of the pollutant. An in-depth discussion of the mathematical principles of Eulerian grid models is given in [108]. An example illustration of the results highlighting the capabilities of the Eulerian grid model simulation is shown in Fig. 4.16 [117]. The figure presents the annual mean concentration of $PM_{2.5}$ in California associated with wildfire emissions.

Some of the limitations of the Eulerian grid models are shared with the Box models. The pollutant concentrations are known for each cell separately, but not in a continuous form within that cell. This makes the investigation of the near-field

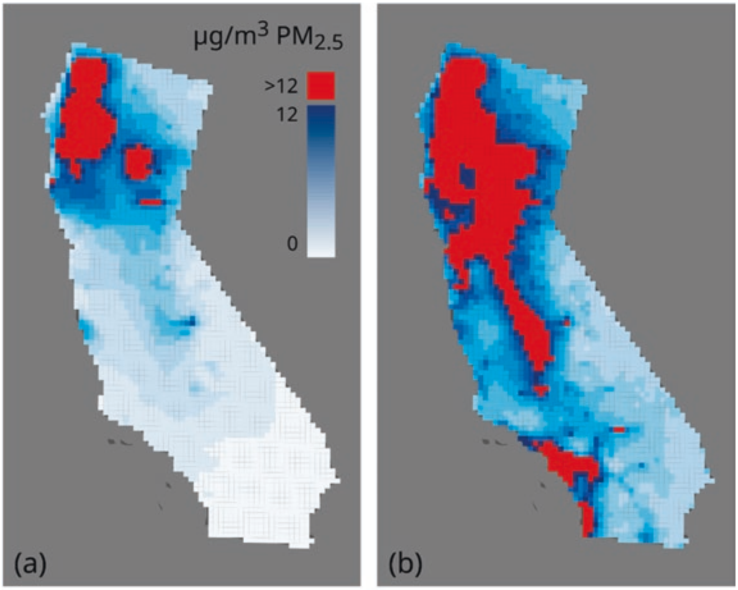


Fig. 4.16 Results of Eulerian grid model (CMAQ) for determination of mean annual $PM_{2.5}$ in California (USA) from (**a**) fire only emissions in 2008, (**b**) all emission sources in 2008. Mesh size 12 × 12 km. Figure from [117]. (Source: Under the creative commons attributed licence CCBY4, https://doi.org/10.3390/atmos10060308)

problematic but allows for quick evaluation of cumulative effects in vast areas. The Eulerian grid models are often modified with additional sub-models, that can consider smoke sedimentation or downwash, or chemical transformations as pollutants interact with themselves and with the environment. Goodrick et al. [101] stated that these models are especially useful for evaluating the effects of smoke on regional haze and ozone episodes.

A popular Eulerian grid model that is still in continuous development is the USA EPA Community Multiscale Air Quality (CMAQ) modelling system [118]. The system can account for multiple pollutants and different spatial scales, for which the scalable atmospheric dynamics and generalised coordinates will depend on the desired model resolution. The three main components are: (1) a meteorological modelling system for the description of atmospheric states and motions, (2) emission models for human-made and natural emissions and (3) a chemistry-transport modelling system for simulation of the chemical transformation. The emission must be supplied to the model, as the CMAQ depends on preprocessed emission data to prescribe primary air pollutant inputs correctly. Preparation of the emission data may be performed with Sparse Matrix Operator Kernel Emissions (SMOKE) submodel, which can provide gridded, temporal and speciated emission data. A specialised wildfire modelling framework that employs CMAQ is called BlueSky. The CMAQ model was used in the investigation of the smoke dispersion from numerous fires, as mentioned in [101], and in a recent example [119]. The features of the model make it especially useful in assessing long-term consequences of the fires in the form of emission and dispersion of $PM_{2.5}$, toxic atmospheric constituents (e.g. formaldehyde), NO_2 and O_3.

The greatest strength of the Eulerian grid models is their ability to model the pollutant dispersion in an enormous range of scales (even thousands of kilometres) and to consider chemical reactions that occur between the pollutants and the atmosphere in the long term. Eulerian grid models can include dry and wet deposition, sedimentation as well as coagulation and decay of various substances. In the CFD analyses of smoke dispersion from fires, incorporation of such phenomena would require implementing sub-models, which are not often readily available and potentially computationally expensive. Due to the coarse size of the grid necessary to solve the dispersion over large areas, the Eulerian grid models may not give accurate results in the near-field analyses.

4.4 Computational Fluid Dynamics Framework

Models described in the previous section share the same limitation – they cannot represent near-field neighbourhood of fires with sufficient resolution or accuracy, especially in proximity of buildings in urban configurations. The complexity of flows around buildings, the formation of vortices and wake regions, as well as effects of urban canyons are often omitted in the modelling of pollutant concentration. At the same time, the near-field effects may be critical for the determination of the exposure of the occupants and the consequences of fires to the environment. The investigation of the fallout in the proximity of Grenfell tower [61] or New York Times press investigation on the concentration of lead in the proximity of the Notre-Dame Cathedral in Paris [120] are examples of recent research about the near-field contamination caused by large fires. Both of these cases generated significant attention of the general public and the mainstream media. Besides the investigation of the exposure to pollutant and long term consequences of fires, the knowledge on the dissipation effects in the near-field may be necessary for planning of the safety systems, civil preparedness and the organisation of the rescue operations. The in-depth investigation of the near-field effects of fires is possible with the use of Computational Fluid Dynamics (CFD) method. This chapter provides an introduction to the use of CFD and provides references to important studies on the numerical modelling of pollutant dispersion in urban environments.

4.4.1 Principles of Computational Fluid Dynamics

In the Computational Fluid Dynamics (CFD) method sets of differential equations describing the flow of mass and energy in a thermodynamic system are solved in discrete time-steps. The domain of the analysis is also discrete, which means it is sub-divided into a finite number of small volumes referred to as cells (as in Eulerian models, albeit with much higher resolution). Contrary to simple fire models, the CFD does not explicitly model the large scale fire phenomena (e.g. plumes or ceiling jets) but uses the principal laws of physics to determine the flow in the building that is a result of a fire. If done correctly, CFD analysis should accurately represent the flow of heat and smoke in the investigated system and show the large scale features of the flow, such as thermal plumes, ceiling jets etc., Fig. 4.17. The CFD analysis should allow for coupling the building interior with its exterior, Fig. 4.18.

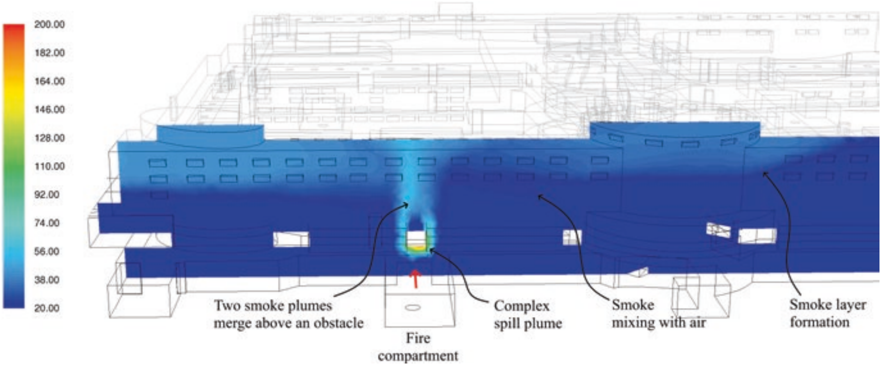


Fig. 4.17 An example of a complex CFD analysis of smoke propagation in a large shopping mall. A plot of temperature (20–200 °C) at the 10th minute of fire simulation

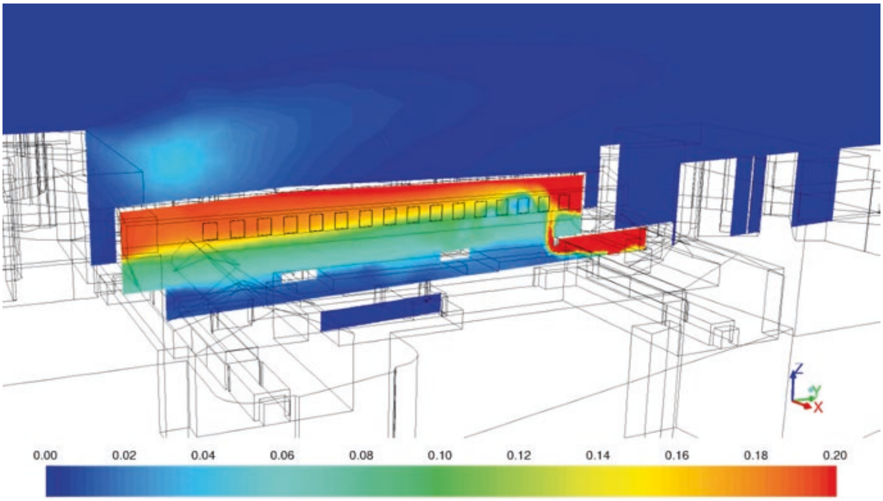


Fig. 4.18 Mass concentration of smoke (0–0.2 g/m^3) inside and outside of a historic shopping mall – an example of simulation coupling interior and exterior of a building

Compared to the simple fire models, the CFD method is significantly more complex and computationally expensive, but also can give the most detailed description of the spatial and temporal evolution of fires, and their environmental impacts. Even though the CFD models are technically advanced, their practical application in the FSE does not allow for the simultaneous solution of all the scales associated with fires: from the chemical reaction kinetics and formation of the smallest eddies to the largest vortices forming in the fire or smoke plumes outside the buildings. Some of these phenomena must be simplified into sub-grid scale models and calculated in parallel. The results of these calculations are used as boundary conditions or source terms in the ongoing numerical calculations. For the same reasons, the atmospheric phenomena that happen in a greater scale (such as mesoscale atmospheric flows) may be challenging to represent along with fires. The large difference of the scales is the most challenging aspect of wind and fire coupled numerical modelling. Even though we have the theoretical and technical solutions to solve all the phenomena together within one model, the associated costs often make such solution impossible, especially in studies of a commercial nature.

Numerous resources on the CFD method exist and are substantially more detailed than this chapter. Theoretical foundations of the CFD are described in depth in [121–124]. The description of the CFD method used in FSE was outlined by [125]. More details that are particular to the most popular Fire Dynamics Simulator (FDS) tool were considered in [126]. Merci and Beji [127] described the mathematical foundations and models used to describe the fire phenomena in the CFD. Finally, the invaluable sources of knowledge on the CFD method in fire modelling are the technical documentation of tools commonly used in the analyses, such as FDS [26], ANSYS Fluent [128], Phoenics [30] or SmartFire [31].

The core of the CFD method is formed by principles of conservation of mass and energy, together with the conservation of momentum described by the Navier-Stokes (N-S) equations for turbulent flows. Even though the N-S equations can be solved directly using computational methods, such a solution is prohibitively expensive, and examples exist only for a limited, relatively low range of Reynolds number values. This type of solution is referred to as the Direct Numerical Simulation (DNS) and is not feasible for the practical problems in fire or wind engineering. The most popular approach is to solve the N-S equations in the Reynolds-averaged form (often referred to as RANS). RANS, and in particular its most common turbulence model k-ε is based on the time averaging of the model equations. A concept to solve RANS equations in discrete, subsequent time steps to form a transient solution is referred to as Unsteady RANS (URANS). In CWE it is often considered as a tool to improve the solution convergence or capture the time features of the flow field (e.g. peak wind gusts, creation, movement and dissipation of large vortices etc.). In fire modelling, URANS is commonly used, as it allows to include the temporal evolution of the fire and investigate its consequences as a function of time. This allows comparing the results of CFD with results of evacuation modelling through estimation of the Available Safe Evacuation Time (ASET). ASET is the amount of time, after which the environmental conditions within a building exceed the tenability criteria, preventing further evacuation from the building [129]. If the building occupants have a sufficient amount of time (with a sufficient safety margin) to escape the building, it is considered as safe [23, 130]. Figure 4.19 presents an illustration of the assessment of occupant safety with CFD model.

An approach that allows investigating the evolution of large-eddy structures in fire plumes is the Large-Eddy Simulation (LES). The main idea of LES modelling is that the eddies most important for mixing (i.e. smoke and air mixing in thermal plumes, contaminant dilution in the air) are large, and can be solved directly. The effects of smaller eddies (e.g. sub-grid scale diffusion) are considered with sub-scale models. Other words, in contrary to RANS, the model equations in LES are averaged in the space domain. A view of a large compartment fire modelled with LES approach is shown in Fig. 4.20.

4.4.2 CFD Framework

In CFD modelling framework, the mass is conserved. It means that the mass in the model can be created or removed only at the domain boundaries or introduced through the source in the volume ($\dot{m}_i'''$), which is often the product of the fire sub-model. The change of mass in control volume equals to the mass flow through its boundaries and the mass introduced by sources.

$$\frac{\partial p}{\partial t} + \nabla \cdot \rho \vec{u} = \dot{m}_i''' \tag{4.6}$$

where p is pressure, t is time, ρ is density and u is velocity.

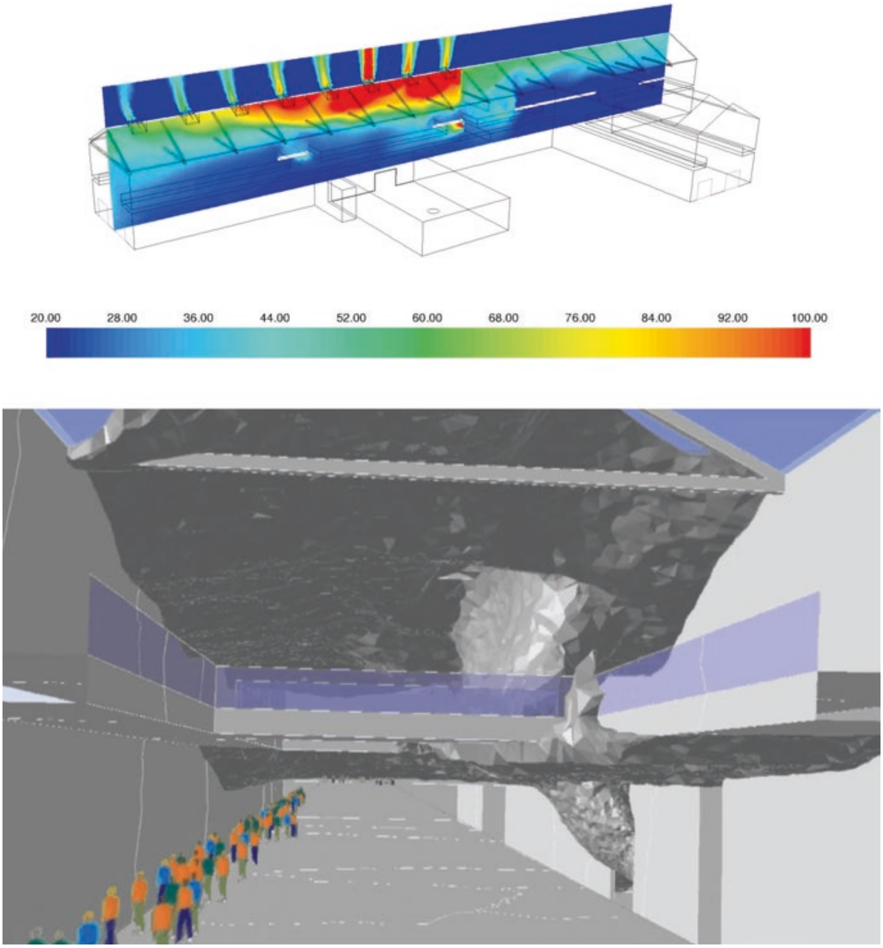
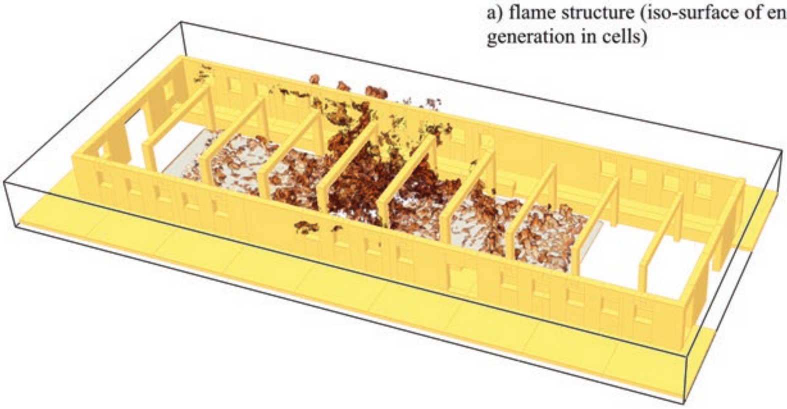


Fig. 4.19 Temperature plot (20–100 °C) in a cross-section of a mall and an iso-surface of smoke (0.05 g/m^3) from a CFD simulation (ANSYS Fluent) overlayed on evacuation process visualization (buildingExodus)

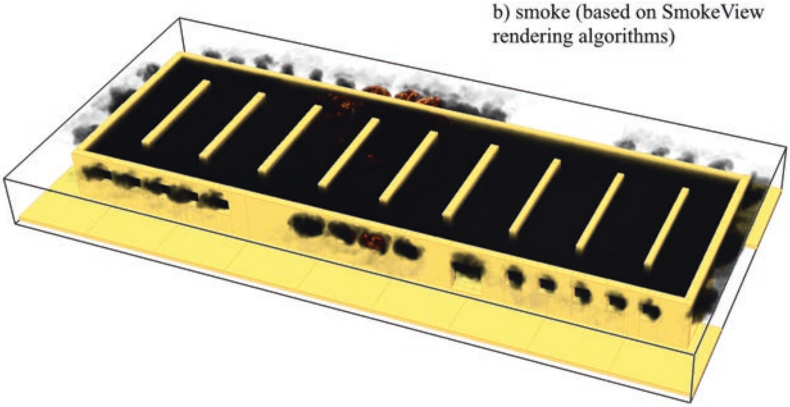
The fluid can be defined as a mixture of individual species. The concentration of each of the ingredients may be described with its volumetric concentration Y_i which conservation is also maintained. The transport of species between the cells of the model can be described as:

$$\frac{\partial\left(\rho Y_i\right)}{\partial t} + \nabla\cdot\left(\rho Y_i \vec{u}\right) = \nabla\cdot\left(\rho D_i \nabla Y_i\right) + \dot{m}_i''' \tag{4.7}$$

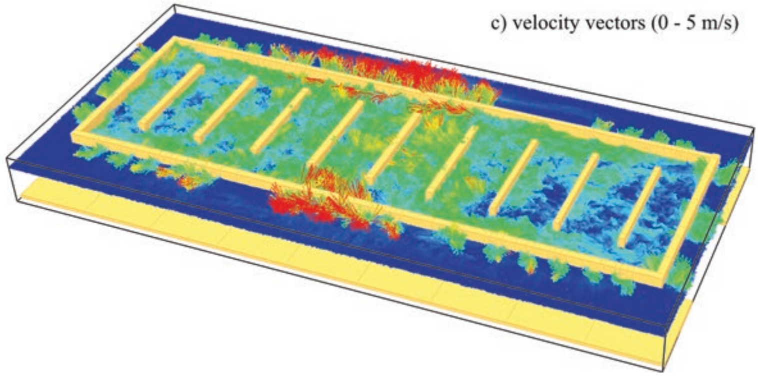
where: D_i is the dispersion coefficient of i-th species.



a) flame structure (iso-surface of energy generation in cells)



b) smoke (based on SmokeView rendering algorithms)



c) velocity vectors (0 - 5 m/s)

Fig. 4.20 CFD LES simulation of a compartment fire (modelled with FDS). (**a**) Flame shape represented by an iso-surface of heat generation (>30 kW/m^3), (**b**) smoke filling the compartment and (**c**) velocity vectors illustrating the flow field within the compartment

The momentum conservation equation is expressing the preservation of Newton's Second Law of Motion. The flow of the fluid is forced by the pressure field ∇p, tension (tensor $\bar{\bar{\tau}}$), buoyant force $\rho\vec{g}$ and external forces $\vec{F}$:

$$\frac{\partial(\rho\vec{u})}{\partial t}+\nabla\cdot(\rho\vec{u}\vec{u})=-\nabla p+\nabla\cdot\left(\bar{\bar{\tau}}\right)+\rho\vec{g}+\vec{F} \tag{4.8}$$

The fire and wind-related phenomena must account for the heat transfer within the fluid, so the conservation of energy must also be maintained. The expression describes the preservation of the First Law of Thermodynamics. The enthalpy (*h*) of the fluid is the product of its mass, specific heat (c_p) and temperature (*T*). The enthalpy in any point changes according to the stream of energy flowing into the control volume. The equation also considers the possibility of heat generation directly in the finite element ($\dot{q}'''$), which, similarly to the mass is often a product of the fire sub-model or combustion chemistry. Heat can also be delivered as a result of the fluid kinetic energy dissipation as a result of friction (ε), the impact of pressure (Dp/Dt) or radiation. In fire-safety related applications, the terms responsible for the pressure field impact and the kinematic energy dissipation are usually neglected.

$$\frac{\partial(\rho h)}{\partial t}+\nabla\cdot(\rho h\vec{u})=\frac{Dp}{Dt}+\dot{q}'''-\nabla\cdot\vec{q}+\varepsilon \tag{4.9}$$

$$h=\int_{T_0}^{T}c_p\,dT \tag{4.10}$$

The equation of state must be introduced, to couple the fluid density to the thermal field, which is needed to account for the flow buoyancy. A perfect gas assumption is justified for most of the phenomena in fire and wind engineering. The molecular mass in the perfect gas equation stands for the averaged molecular weight of the ingredients of the gas mixture, which are also used in the species transport model.

$$p=\frac{\rho\Re T}{M_{avg}} \tag{4.11}$$

$$M_{avg}=\frac{1}{\sum\frac{Y_i}{M_i}} \tag{4.12}$$

where p is pressure, R is the gas constant, T is temperature, Y_i is the volumetric concentration of i-th species and M_i is the molecular mass of the i-th species.

Physical phenomena, such as turbulence, radiation, combustion chemistry, heat transfer to and in solids etc., are solved by the CFD model using separate submodels, which are described in more details in [26, 125, 127].

4.4.3 Turbulence Modelling

The problems in fire and wind modelling are characterised by high-turbulence flow, and consequently, the description of the velocity and pressure field has a complicated form. Even though the Direct Numerical Simulation (DNS) is theoretically possible, it is not considered feasible due to associated costs. For modelling, we must apply so-called turbulence models. The mainstream turbulence models include the following:

- Reynolds-Averaged Navier-Stokes (RANS) among them:
  - *k-ε* [131], for theoretical bases see, e.g. [121, 132–134];
  - *k-ω* [135];
  - Reynolds Stress (RSM, e.g. [136]);
- Large Eddy Simulation (LES) [137–139].
- Hybrid models – Detached Eddy Simulation (DES) and Scale Adaptive Simulation (SAS) [134].

Various models were introduced throughout the years. They varied in the degree of success for use in wind engineering applications. Many of them were focused around Eddy Viscosity Model concept, that relates the Reynolds stresses proportionally to the strain rate. The most popular two-equation turbulence models based on this assumption form the *k-ε* family of models. RANS models apply a time-averaged solution of N-S equations, with the additional decomposition of velocity, pressure and field function into mean components and their fluctuations [121].

$$\left.\begin{aligned} V_i(t) &= V_i + v_i'(t) \\ p(t) &= P + p'(t) \\ \varphi(t) &= \Phi + \varphi'(t) \end{aligned}\right\}$$

The value of a parameter in a discrete time-step is equal to its mean value plus the fluctuation. The primary assumption is that the averaging time Δt is larger, than the time scale of the largest turbulent vortexes (or other relevant physical phenomena). In order to close the model (i.e. add equations), the Boussinesq hypothesis is applied, which relates the viscous friction and turbulent Reynolds stress.

The total turbulent energy consists of the following elements, which eventually lead to the formation of the kinetic energy term (k), and the dissipation rate of the kinetic turbulence energy (ε):

$$\left(\tau_\tau\right)_{ij} = -\overline{\rho v_i' v_j'} = \mu_\tau\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{4.13}$$

$$k = \frac{1}{2}\sum_{\mathrm{i}=1}^{3}\left(\overline{v_{\mathrm{i}}'^{2}}\right) \tag{4.14}$$

$$\varepsilon = \left(2\mu / \rho\right)\overline{s_{ij}' s_{ii}'} \tag{4.15}$$

In the above equation μt is the turbulent viscosity and is determined using Eq. 4.16.

$$\mu_t = C\rho v l = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4.16}$$

The constants of RANS *k-ε* model are determined experimentally, and their values for the "standard" model are $C_\mu = 0.09$; $\sigma_k = 1.00$; $\sigma_z = 1.30$; $C_{1z} = 1.44$; $C_{2z} = 1.92$. The main disadvantage of the standard *k- ε* model in wind engineering applications is over-production of turbulent kinetic energy (*k*) at the windward surfaces of approached objects. This is improved, at least to some extent, in subsequent variants of the model, such as the Realizable *k-ε* [140].

Realizable k-ε considers the turbulent viscosity in a new equation that describes the dissipation rate of the kinetic turbulence energy, ε. The Reynolds stress is calculated as incompressible strained mean by combining the Boussinesq relationship and the eddy viscosity definition [128]. This is more consistent with the physics of a real turbulent flow, as it satisfies certain mathematical constraints of the Reynolds stresses. Moreover, unlike the "standard" model, the value of normal stress cannot be negative. The conventional way to ensure the positive value of stress is to change the constant C_s into the variable, sensitive to the mean flow characteristics and turbulence. In the Realizable *k-ε* model, the C_s is a function of the mean strain and rotation rates, the angular velocity of the system rotation and the turbulence fields.

Another group of RANS models is the Reynolds Stress Models (RSM). The Eddy viscosity hypothesis is not applied here, and exact Reynolds stress transport equations describe particular components of the stress tensor. There are several RSM variants based on the different solution for the pressure-strain relation, which can be described by linear, quadratic or cubic equations. This model is often referred to as the second-moment closure model [141, 142]. It can be considered as much more developed traditional model, than the *k-ε* approach. In the RSM, the hypothesis of isotropic eddy-viscosity is abandoned. The N-S equations are solved for the Reynolds stresses, together with the equation for the dissipation rate. This means that in three-dimensional space, this model requires seven additional transport equation responsible for the streamline curvature, swirl, rotation and rapid changes in the strain rate. Due to the nature of the model and the numerous additional equations, it can be considered significantly more expensive in use, when compared with *k-ε*. The buoyancy is included in the model as an external force, and the value of the turbulent Prandtl number is 0.85 [128]. Even though the RSM can capture the near-wall phenomena and provides more detailed information on the structure of the turbulent flow, it requires significant optimisation of many numerical parameters. This makes them dependent on the computational mesh and the overall experience of the user [143].

The wide use of RANS models in wind engineering has shown their weakness in the modelling of the flow around sharp edges of the objects. A different approach to turbulence modelling is Large Eddy Simulation (LES), elaborated by [137]. He proposed a simulation of large vortices with the use of spatial averaging of the flow. Large eddies in the flow are resolved directly, while small ones are modelled artificially. The assumption is that small eddies are less dependent on the geometry and tend to be more isotropic – thus may be simulated more universally with a sub-grid scale model. The large eddies are usually problem-dependent, and cannot be modelled universally, but they are resolved directly with the filtered (averaged) N-S equations. The determination process of the eddies scale that will be resolved is called filtering, and the boundary between large and small eddies is referred to as the Smagorinsky filter. Typically, the size of the filter matches the size of the smallest mesh element or is the geometric mean of the smallest mesh element dimensions. Eddies smaller than the size of the mesh are not directly resolved, and as a consequence, the solution is more dependent on the grid quality. A rule of thumb was proposed that at least 80% of the turbulence energy is resolved directly [144].

LES approach is superior in terms of physical modelling of wind and fire phenomena compared to RANS. LES allows capturing transient evolution of eddies at the scales important to the modelled phenomena, including gusts of wind velocity or peaks of pressure as well as the puffing behavior of fire plumes and waving of smoke layers. Some of these features may also be captured with URANS approach. However, the “image” of the fire as the result of the LES simulation can be considered more realistic and easier to understand to the layman, compared to the time-averaged results of the URANS simulation [145]. Figure 4.21 presents a snapshot image (temperature plot) of a fire simulation performed with URANS and LES, where the differences in flow structure between the simulations are visible. It must be noted that the URANS presents time-averaged results – if one did integrate LES results over time, both images would look similar.

Besides the presentation of the details results the differences between models are visible in quantitative data analysis. URANS resolves the fluctuations of the large-scale flow structure, while LES (provided sufficient mesh resolution) resolves most of the scales. URANS can be considered as more applicable for flows, which unsteadiness is deterministic [143]. LES is suitable in simulations of the critical features of near-field pollutant dispersion around buildings: the 3D features of the flow, the unsteadiness of large-scale flow structures and the anisotropy of the turbulent scalar fluxes [146]. However, the use of LES is associated with significant costs compared to RANS and URANS. These costs are related to higher requirements towards the spatial (mesh, especially in the boundary layer) and temporal (shorter time step) resolution of the simulation. For this reason, in wind engineering focused on environmental issues, the 3D RANS is still the most common approach. It should

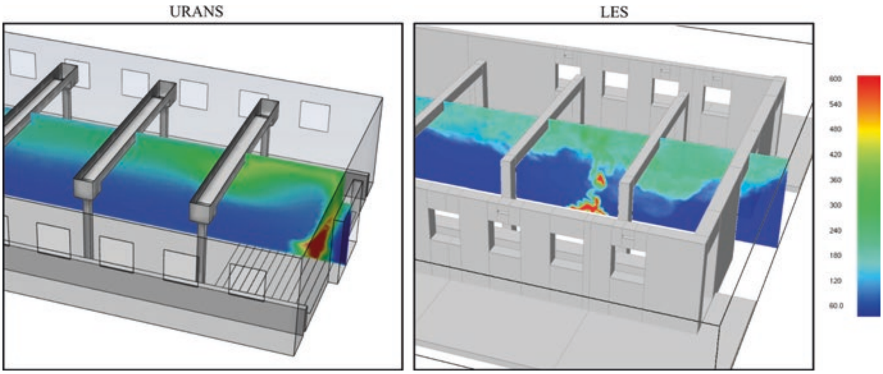


Fig. 4.21 Temperature plot (20–600 °C) in a building fire simulated with URANS and LES models. Visible differences in details of the fire plume and ceiling flow – the URANS shows time-averaged data while LES presents a “snapshot” image

also be mentioned that LES is becoming the primary tool of CFD analyses when the wind load on structures is estimated or precise behaviour of the flow is needed, e.g. in the closest proximity of the building surface.

In fire engineering, LES approach may be considered as prevalent despite the associated costs, which is possibly related to the extensive use of the FDS model, in which LES is the only available approach. LES model used in FDS follows the low-Mach number approximation proposed by [147]. In case of low flow velocities, the spatially and temporally resolved pressure can be decomposed into so-called “background” pressure, plus a perturbation. In the equation of state, only the background pressure is retained, and it also includes the stratification of the atmosphere. The fluid motion is driven by the perturbation and has a number of practical consequences that allow the simplification of the solution [145].

4.4.4 Turbulent Diffusion

In the analysis of fire effects on the environment, an important aspect is the modelling of the diffusion of species. In some approaches, the popular and cost-efficient way is to model pollutants as a neutrally buoyant (passive) scalar fluxes introduced to thermally buoyant plumes. Their distribution in space is usually described in reference to the initial value (e.g. 1/100th of the release). If the scalar flux is used to describe the species, usually the standard gradient diffusion hypothesis (SGDH) is applied. In RANS calculations the eddy diffusivity is typically being expressed by the eddy viscosity and the turbulent Schmidt number (Sc_t). This approach was unsatisfactory for several problems, especially related to the release of pollutants in street canyons. The SGDF limitations are related to problems with the definition of the Sc_t, as described in [143]. Efforts were made to define the optimum values of Sc_t with ranges spread between 0.2 and 1.3 (compared to commonly used 0.7 to 0.9) according to various flow properties and geometries [148]. Measurements imply that the Sc_t has a functional relationship to local flow properties. This means that a single global value cannot be used to adjust and correct for error in the mean flow calculations [143]. The value of Sc_t will influence the pollutant dispersion for isolated buildings, but may not have a significant impact in the presence of adjacent buildings. Nevertheless, in many studies, the use of smaller values of Sc_t was associated with better alignment of the simulation and experiments [143].

In contrast to the Standard *k*-*ε*, and constant Smagorinsky LES models, in the dynamic Smagorinsky sub-grid scale model, the calculation of the sub-grid scale diffusion is dependent on the flow conditions. The so-called Smagorinsky constant (of the typical value $C_s = 0.23$) that is used in the determination of sub-grid scale turbulent viscosity is calculated with a dynamic procedure, based on the resolved field., The C_s value is bounded to a fixed range to avoid numerical instabilities. The consequence of this dynamic approach is the ability of the model to provide more accurate results without the introduction of any parameters to solve the dispersion equation. It was mentioned as the main advantage of the LES approach in investigations of pollutant dispersion by [149].

4.4.5 Examples of the Use of CFD in Smoke Dispersion Modelling

CFD method was widely used in the studies on the smoke and pollutant dispersion in various environments. This sub-section presents examples of the most relevant studies performed in recent years.

A study on a city scale pollutants dispersion from a 100 MW fire in a tunnel (emitted through a tunnel portal) was presented by [111]. The Author used atmospheric dispersion model CALPUFF coupled with TAPM and CALMET prognostic models to develop the three-dimensional meteorological data and consequently to determine the most onerous scenarios for CFD analyses. In the chosen scenario (2,3 m/s wind velocity, at angle 92°), CFD analysis (RANS realizable *k*-*ε*) was performed in ANSYS Fluent to determine the concentrations of CO and PM_{10}. The polyhedral mesh domain had dimensions of 2 km × 2 km × 0.5 km. The paper emphasized on the benefits of using a puff model (CALPUFF) for the screening of the worst-case scenario, and further investigation with a more detailed CFD analysis.

Atmospheric gas dispersion was studied with LES oriented code of Fire Dynamics Simulator (FDS, version 4) by [150]. The wind profile was a power-law function, dependant on the atmospheric stability class, with temperature gradient and sinusoidal velocity fluctuations. Passive dispersion conditions were investigated, that is a release of CO, ammonia and LNG. The CFD model predicted the maximum downwind concentration well, except for the case of unstable conditions. The cloud shape was mixed for neutral and unstable conditions. To assess the ability of CFD to consider the influence of obstacles, the results were compared to the MUST experiment

[151]. It is important to note that the FDS code was significantly improved since the time of the reviewed study. For validation of newer versions of the FDS solver for the dispersion modelling, please consult the FDS reference guide [28].

An interesting approach to dispersion modelling was presented by [152]. They investigated the release of NO_2 from a fire on a ship transporting Ammonium Nitrate (NH_4NO_3), that occurred near a festival area. This scenario was a part of a larger project named CascEff, performed in 2014–17 by RISE in Sweden [153]. The dispersion was modelled with FDS (version 6.1.2), Fig. 4.22. The wind profile was based on the power-law formula, which at the time of the analysis was the only available option. The innovative approach used in this study was based on the dynamic absorbed dose. The central assumption was that the occupants could move away from the danger and their exposure was a function of time and space. The results indicated significant difference in the relative frequency of injury and mortality, with the static approach providing significantly worse results. From the modeling point of view, the use of the dynamic approach requires more resources, as the behaviour and movement of people must be modeled along with the reslease and dispersion and the absorbed dose must be integrated for a moving target. However, this approach gives improed representation of the evacuation scenario and the exposure conditions.

Pollutant dispersion in a group of buildings was studied by [149] with use of RANS standard k-ε and LES models in ANSYS Fluent package. The Authors modelled experiments performed by Concordia University in downtown Montreal in a 1:200 scale in the wind tunnel [154]. The tracer gas used in the experiments and modelling was SF_6. The domain dimensions were based on the COST 732 guidelines [155] and one block in each direction of the urban canyon was explicitly modelled. For the standard k-ε model wind tunnel measurements were used to determine the inlet profiles of velocity, k and ε. For LES, a vortex generation method was used to generate a time-dependent velocity field. For the standard k-ε model, a significant

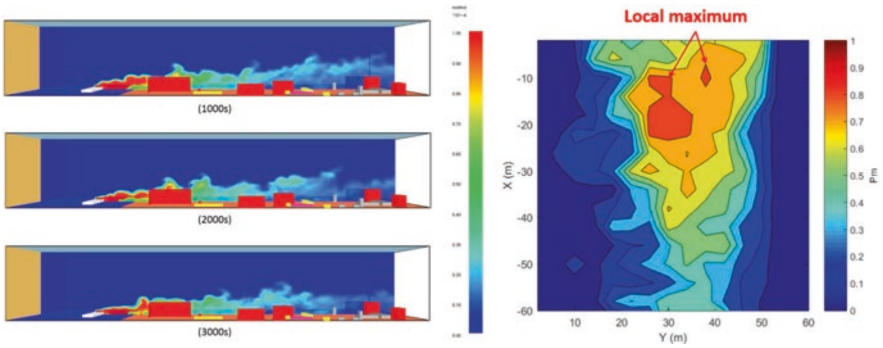


Fig. 4.22 CFD results of NO_2 concentration contours in a vertical plane through the source at different times from release (left), and identification of areas having the highest probability of mortality, P_m (right) [152]. (Rights obtained through RightsLink License Number: 4321891085923 ©Elsevier, reproduced with permission)

dependency on the turbulent Schmidt number (Sc_t) was observed. For two investigated layouts (SW and W direction of the wind velocity) the agreement between numerical simulations and wind-tunnel measurements was good, although better for the LES model. It was observed that the flow separation at the sharp edges of the buildings was crucial for the proper simulation of the concentration fields, which is essential not only for CFD but the dispersion modelling in general.

Moon et al. [156] used a modified version of FDS to model turbulent flow and dispersion characteristics over a complex urban street canyon. The study concerned two variants of LES differing in their approach to subgrid-scale (SGS) – constant Smagorinsky and Vreman models. The role of the SGS model was reported as small. However, the Vreman model was recommended for urban modelling by the authors.

Applicability of CFD modelling for city-scale pollutant dispersion was presented in a case-study for local removal of outdoor particulate matter in the Eindhoven city centre [157]. RANS Realizable k-ε modelling was performed in ANSYS Fluent (14.0). Firstly, an in-depth validation study against the results of wind tunnel experiments was performed. A passive pollutant source was modelled as the term in the advection-diffusion equation at one of the street intersections. Satisfactory agreement between CFD simulation and experiment was achieved even in a long distance from the source. In the main study, the city centre of Eindhoven was modelled (area of about 5.1 km^2). The whole domain had dimensions of 4.41 × 3.57 × 0.6 km. The area outside of the high-fidelity model was defined with respective roughness, in order to obtain the correct formation of the wind boundary layer. The pollutant source terms were located in the streets and car parks and were based on external data on the vehicle traffic. Coupling approach was used to combine the release in underground car parks with the simulation of the exterior. The primary interest of the paper was to assess the potential of local filters to reduce the traffic-induced fraction of outdoor PM concentrations. This study showed the applicability of city-scale CFD analysis in the determination of the pollutant dispersion and coupling of the interior and.

Another research illustrating city-scale numerical analyses for the urban microclimate was carried out by [158]. The CFD simulation of a dense, heterogeneous district in Nicosia, Cyprus, was performed and validated using high-resolution data obtained with in situ measurements. The pollutant dispersion was not modelled. However, the flow buoyancy was considered by the use of the Boussinesq approximation. Simulations were performed with ANSYS Fluent (16.0) and a 3D Unsteady RANS Realizable k-ε model. The resulting air temperatures were compared with thermal images of the city and were predicted by the CFD with satisfactory accuracy. The largest discrepancies were found for areas with materials not explicitly modelled (e.g. metal covered roofs) and in narrow street canyons. This study illustrates the potential of URANS approach in modelling city-scale buoyant flows. Other relevant recent studies that illustrate the use of RANS CFD to predict city-scale flows are [159] and [160].

Emissions from a fire of tanker vehicle in an urban area were investigated by [161], with the use of Lagrangian particles within a CFD model. The analysis was focused on time-averaged concentrations of pollutants along with their aerial distribution. In a similar study, the dispersion of hazardous gas emitted from a point source located on the ground in Tokyo in turbulent flow was simulated with LES and validated with wind tunnel measurements [162]. The results were additionally compared with RANS simulations using standard k-ε. Among others, they found that average concentrations in low-velocity wind areas were higher, whereas peak concentrations were higher in high-velocity wind areas.

4.5 Practical Considerations for the CFD Modelling of Fire and Smoke Dispersion

4.5.1 Best Practice Guidelines in Computational Wind Engineering

To the best of the authors' knowledge, there is no single review or guidance document, that would cover all aspects of modelling of the environmental impact of fires. Review papers [34, 37] were an effort to summarize the concepts and the best practice guidelines of the Computational Wind Engineering (CWE) for numerical modelling of various issues focused on fires under the influence of wind.

The best practice guidelines were given in a thorough review concerning the 50-years of the development of CWE [33]. In addition to reviewing the available best practice guidelines, this paper also presents the essential research to the flow around a single building and over flat roofs. The paper describes the basic problems of CWE in full-scale and model-scale measurements, as well as numerical simulations. It also illustrates difficulties which can be encountered during wind action analyses and provides an extensive database of information to employ in coupled analyses.

The second CWE guidelines essential to the modelling of the environmental impact of fires are the results of the European Cooperation in Science and Technology (COST) action 732 [155, 163, 164]. The recommendations focus on the prediction of mean velocities and turbulence intensities in urban areas and cover a quite large field of applications, including dispersion of pollutants. The guidelines are relevant mainly to steady RANS but also URANS, LES and hybrid models.

Other guidelines relevant to coupled wind and fire modelling were reviewed by [37]. These include the following works:

- [146] where spatial and temporal scales in urban physics are outlined and 'ten tips and tricks towards accurate and reliable CFD simulations' are given, primarily related to the creation of the numerical domain and the introduction of the wind into the numerical analysis.
- [165], which is focused on the modelling of natural (cross-ventilation) of buildings. This paper has an interesting discussion on the consequences of the choice of various user-defined parameters on the analysis results.

- Recommendations of the Architectural Institute of Japan (AIJ) [166–169]. These guidelines cover recommendations on the use of CFD in building design process and cover topics related to flows around isolated buildings, city blocks and complex urban environments.
- [170]; which covers the review of LES applications in the wind engineering primarily related to boundary layers, wind actions on structures, flows over complex terrains, wind climate in an urban environment and the pollutant dispersion. In this review, the LES model was found to be more accurate compared to RANS with respect to the evaluation of peak values (gusts, loads, concentrations).
- [171]; which is focused on the pedestrian wind comfort, illustrated on a case of the Eindhoven University of Technology campus.
- [172, 173] and [140]; which consider the flow in cross-ventilated buildings and pollutant dispersion in such buildings. In these papers, the LES model was found to be superior to RANS.

4.5.2 Building the Domain

The rules of CWE evolved from the best practices elaborated for wind tunnel experiments. One of the rules is that the blockage ratio in the cross-section of the numerical domain at which the flow occurs should not be larger than 3% [163]. The blockage ratio is defined as the ratio of the building cross-section to the domain cross-section, measured in a plane perpendicular to the flow. An illustration of the recommendations for the size of the domain and the concept of the blockage ratio is presented in Fig. 4.23.

The numerical domain has a lateral and top boundary which should be in the distance of at least $5H_{max}$ away from the group of explicitly modelled buildings, and H_{max} is the height of the tallest building. The reason is to limit the error caused by the modelling of the flow velocity in the building proximity. In case of a too-small domain, a strong artificial acceleration or blockage of the flow may occur. The outflow boundary distance should be at least $10H_{max}$ [169] to $15H_{max}$ [164] away from the group of explicitly modelled buildings. It allows the development of the full wake flow, which is crucial if inlets to the building are placed on the leeward side of it. A detailed discussion of the influence of the domain size on the results of numerical analysis is presented by Ramponi and Blocken [165]. In this analysis focused on the natural ventilation of buildings, the Authors observed a significant error caused by the reduction of the domain dimensions (which means the increase of the blockage ratio), and thus confirming previous recommendations, summarized in Fig. 4.23.

When considering flow and pollutant dispersion in urban terrain, it may be necessary to represent a broader region. It is assumed, based on wind tunnel tests, that a building of a height H_b influences the considered area within $6H_b$ from its location [163, 164].

In analyses for cities, it may be necessary to include a few rows of surrounding buildings, that may influence the flow around the building of interest. In some cases,

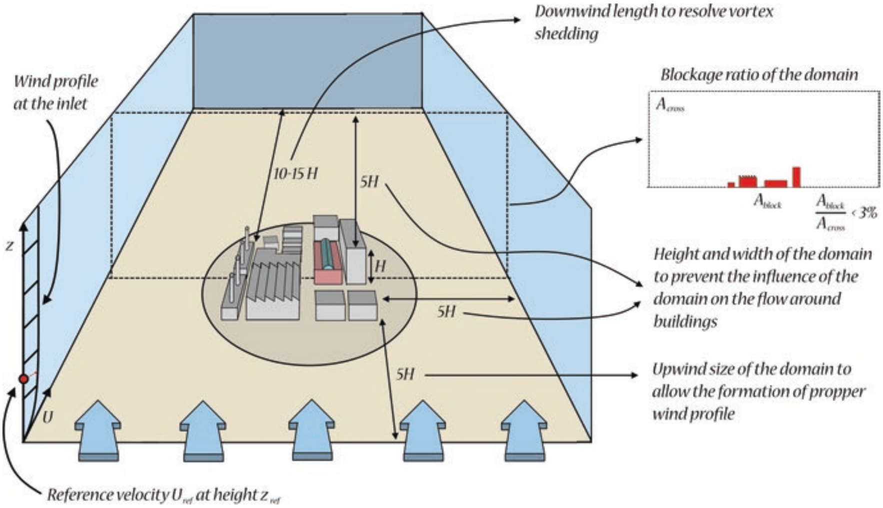


Fig. 4.23 Illustration of the numerical domain and its dimensions recommended for wind and fire coupling analysis. *H* is the height of the highest explicitly modelled building [37]. (Rights obtained through RightsLink License Number: 4744170733134)

when the terrain roughness is included in the numerical model, and proper wind boundary conditions are used at the inlet, it may be sufficient to include only the buildings in the closest proximity to the one tested. Nevertheless, a sensitivity analysis regarding the size of the domain should always be performed. An example of a model of surrounding buildings for the natural smoke control analysis is shown in Fig. 4.24.

An essential problem in the coupled wind and fire studies is the use of appropriate numerical mesh. As defined in [37], for FSE applications the typical meshes range from 0.10 m to 0.20 m, while for the CWE applications the mesh requirements are usually less restrictive. As shown in [159] the grid size in a far-field of an urban terrain model was 20 m, in the area of explicitly modelled neighborhood was gradually reduced to 8 m, and for the inner region that was analyzed, the size was 4 m to 6 m. In other studies reviewed in [37], the mesh sizes varied from 0.02 m to 120 m. The primary concern is not to meet the specific value of the grid size or some dimensionless characteristic of the mesh, but to provide a solution that is not mesh dependent. This must be measured in a mesh independency study. A notable example of such analysis is given in [174, 175] and a practical example in [176]. A discussion on other useful concepts related to mesh generation (D^*, $y+$, u^*) are given in the previously mentioned review by [37].

Another important aspect concerning the modelling of transient phenomena is the correct choice of the length of a time step. In some cases, such as in the FDS solver, the time step length is evaluated automatically by the solver, based on the CFL (Courant-Friedrichs-Lewy) value. CFL is mostly dependent on the size of the numerical mesh and the flow field characteristics [126]. In the case of other solvers,

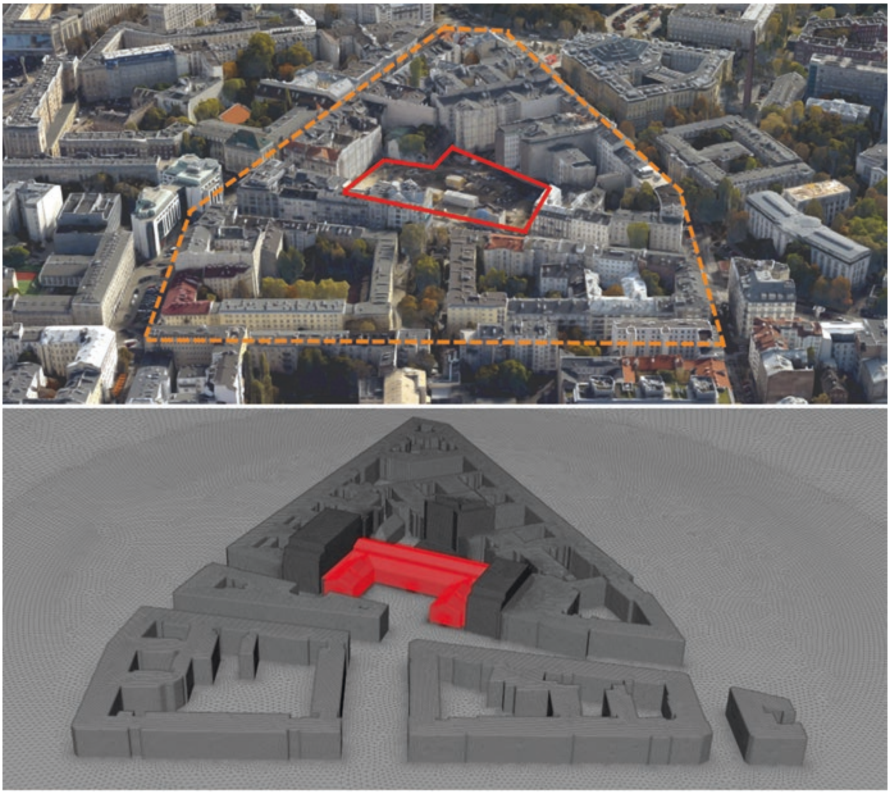


Fig. 4.24 Aerial photograph of Warsaw (upper picture, source: Google Earth) and the numerical domain in the model for the investigation of smoke control in the central building (bottom picture) [37]. (Rights obtained through RightsLink License Number: 4744170733134)

especially ones that use URANS modelling, different time steps lengths may be adequate for different phenomena investigated. As a rule of thumb, implicit upwind schemes are preferred, and the solver should provide proof of convergence. If, however, the default convergence criteria are too loose, oscillatory convergence behaviour may be observed [146].

4.5.3 Introduction of Wind into Numerical Analysis

The description of the wind boundary conditions (inlet to the model) can be considered as an implementation of the mesoscale atmospheric phenomena through an Atmospheric Boundary Layer (ABL) model into the micro-scale application in CFD. This implementation usually requires the knowledge of two parameters – the upstream aerodynamic roughness length and the vertical profiles of the mean wind velocity and turbulence [146]. Sometimes, these parameters are described as the time functions, to allow for the temporal evolution of the wind boundary condition. In general, boundary conditions introduction to CFD domain concerns two aspects – defining the wind inlet boundary conditions, and obtaining the atmospheric data through downscaling the mesoscale measurements (which is described in the next section).

Not all buildings or natural obstacles are modelled explicitly in the CFD domain. As explained previously, the recommended distance at which the buildings are modelled in details is six times the height of the tallest building. Beyond this area, it is common to include the effect obstacles have on the flow by the use of aerodynamic roughness length z_0 [146]. This parameter must be distinguished from the sand-grain roughness height k_s [144, 174]. The confusion of these parameters may lead to substantial simulation errors. The relationship between z_0 and k_s for several codes of practice was presented in [177]. The fire oriented code FDS uses sand roughness in the definition of surface roughness, which in the case of this solver may be considered to be 30 times higher than the chosen value of aerodynamic roughness length z_0 [26].

The aerodynamic roughness length can be computed using the Davenport-Wieringa model [178]. This parameter will determine profiles of wind velocity and turbulence within the domain and will essentially guide the movement of the air in the proximity of the building. Blocken [146], describes five key areas related to the modelling of flows, in which the aerodynamic roughness length should be specified, Fig. 4.25.

Area 1 lies upstream the explicitly modelled buildings and outside of the computational domain. The roughness of this area will determine the shape of the inlet profiles of velocity and turbulence. Area 2 lies within the domain and upstream of the buildings. In this area, aerodynamic roughness length based on [178] and the near-wall functions of the turbulence model can be used to shape the flow, although obstacles within this area are not being modelled explicitly. Areas 3 and 4 usually

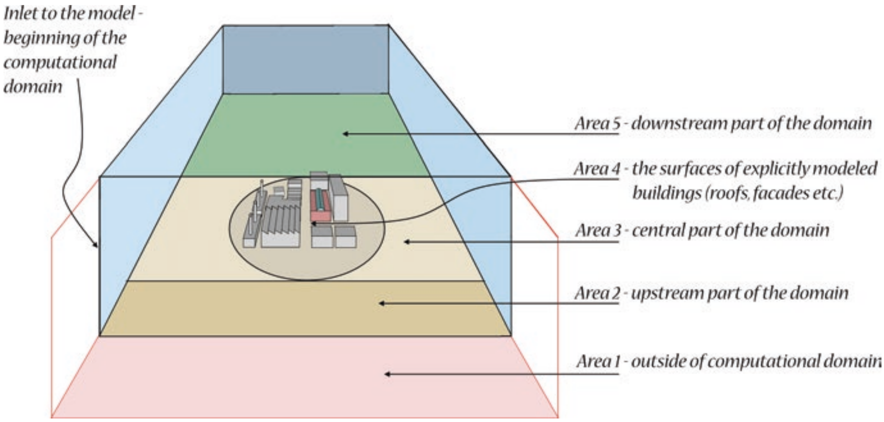


Fig. 4.25 Areas of the numerical domain for which roughness length should be specified [37], based on [146]. (Rights obtained through RightsLink License Number: 4744170733134)

consist of explicitly shaped obstacles. Area 5 lies within the computational domain, but downstream of the explicitly modelled part. For more detailed practice guidelines on shaping the domain and the choice of the appropriate terrain roughness length (or equivalent sand-grain roughness height), one should refer to the review by [146].

The wind is introduced to the computational domain at the edge of Area 2, which can be considered as the virtual boundary between Areas 1 and 2. The wind is usually introduced, in 3D analyses, as the boundary condition that describes its vertical velocity profile. Commonly used wind velocity profiles were defined by [179] and [180, 181]. Illustration of an example the wind velocity profile at a boundary of the numerical domain is shown in Fig. 4.26.

The Richards and Hoxey model assume that the turbulence intensity determines a profile of turbulent kinetic energy $k(z)$, that is constant with the height in the surface layer. This is not always the case. To mitigate this [169] proposed to obtain $k(z)$ from the wind tunnel experiments. Otherwise, a specific profile for the turbulence intensity should be provided. It is worth mentioning that despite the turbulence intensity vertical profile, turbulence length scale also influences flow, especially behind the building in the wake region. This is why the numerical domain should be built in a way that allows the formation of the boundary layer specific to the terrain that is modelled.

In the FDS solver, the sub-model for wind boundary conditions is consisted in forcing the mean flow velocities and is based on Monin-Obukhov similarity parameters. This approach allows modelling the velocity and temperature profiles in the function of the domain height, aerodynamic roughness length, scaling potential temperature and the Obukhov length. The default reference height for this model is

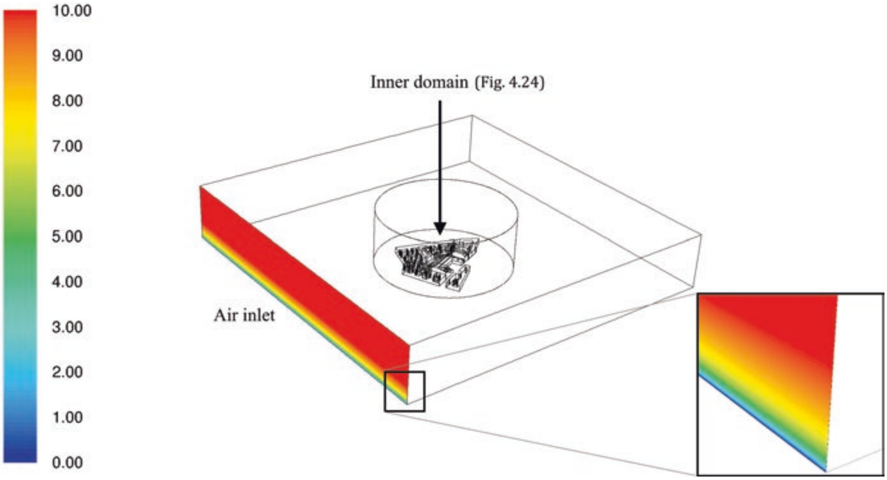


Fig. 4.26 View of the logarithmic wind profile applied at the velocity inlet boundary condition (0–10 m/s) at a boundary of the domain shown on Fig. 4.24 [182]. (Rights obtained through RightsLink License Number: 4744170733134)

2 m and can be altered by the user. The description of similarity parameters is presented in [183], while a thorough description of this approach is given in [26]. The FDS allows the mean flow velocities within the domain, reaching desired values by adding a forcing term to momentum equation, taking into account the relaxation time scale. This significantly simplifies the modelling of oblique wind angles in rectangular domains. FDS solver also allows temporal and spatial variation of the wind, through the application of time-profile functions (so-called “RAMP”) on velocity components.

The provision of a reliable ABL modelling in LES may be ambiguous, as the turbulent behavior of the wind cannot be simplified in the $k(z)$ and $\varepsilon(z)$ parameters, but has to be explicitly modelled. Some guidelines on this subject are available in [184]. Possible solutions to the problem are: synthetic turbulence generation, or modelling a sufficiently large inlet area of the domain for the formation of the correct turbulent layer, Fig. 4.27. The first approach uses inlet boundary conditions with a complex definition of the velocity field, changing in time and space. This approach is used mainly in hybrid turbulence models as a boundary condition between RANS and LES zones [185]. A similar approach could be used at the domain boundary, where the ABL model can define the flow velocity, turbulent kinetic energy and its dissipation rate. A comprehensive review of possible inlet conditions for LES modelling is presented by [186].

Alternative (or complementary) to the synthetic turbulence generation, is to allow the solver to resolve the wind. The idea is to build a sufficiently long inlet domain, in which flow characteristics are generated through modifying sand-grain roughness at boundaries or through placing blocks in the domain to get the flow with appropriate turbulence, Fig. 4.27. These obstacles allow the formation of the turbulent boundary layer, which has to be measured and compared with the assumptions. This process may require multiple iterations before the desired wind profile is obtained. This approach may be combined with previously mentioned sub-models, to create high-quality boundary layers. Although this approach may be time-consuming, it could be implemented in most of the solvers and should generally

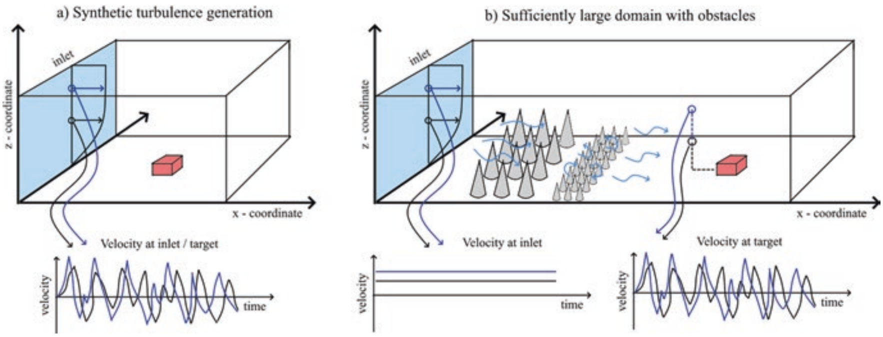


Fig. 4.27 Approaches in the definition of the wind velocity profile at a target building with LES modelling – (**a**) synthetic turbulence generation, (**b**) sufficiently large domain with obstacles

provide the best results. Regardless of whether a synthetic turbulence generator or a large inlet domain combined with block elements is used, the wind profile and the parameters of turbulence at points of interest (location of the building, fire) should be measured, and preferably validated with wind tunnel measurements.

As previously mentioned, according to [180], ABL could be modelled as the horizontally homogeneous turbulent surface layer. This means that turbulence is homogeneous in horizontal directions parallel to the ground and varying in the vertical direction, normal to the ground. The shear stress in the ABL is close to constant in the domain height and has a value as at the walls. Due to this, for calculations performed in domains much lower than the ABL upper limit, the vertical profiles of particular parameters can be simplified to the forms presented in the equations below, taking $k(z)$ profile as constant along the height.

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right) \tag{4.17}$$

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \tag{4.18}$$

$$\varepsilon(z) = \frac{u_*^3}{\kappa(z+z_0)} \tag{4.19}$$

where z is the height [m], z_0 is the aerodynamic surface roughness length [m], κ is the von Karman constant [−] (0.40–0.42), C_μ the model constant [−] (0.09) and u_* the friction velocity [m/s].

An example of the introduction of the velocity inlet boundary conditions is shown in Fig. 4.28.

4.5.4 Mesoscale-Microscale Coupling

The most common way to get information about wind action for design purposes is to refer to standards and codes of practice. Every wind code defines basic wind characteristics within the ABL: the averaging time of wind speed (usually 10 min), terrain categories (from open sea terrains to centres of large cities), the mean wind velocity profile based on a logarithmic or power-law formula and dependent from the region of the given country, turbulence intensity in the longitudinal direction, longitudinal turbulence length scale and power spectral density of the wind speed. Turbulence characteristics in directions perpendicular to the mean wind velocity generally are not provided by codes, but the empirical relations between cartesian components can be found in the literature. Most widely used wind standards are: Eurocode 1 [188], ASCE [189], AS-NZS [190], AIJ [191], ISO [192]. The very

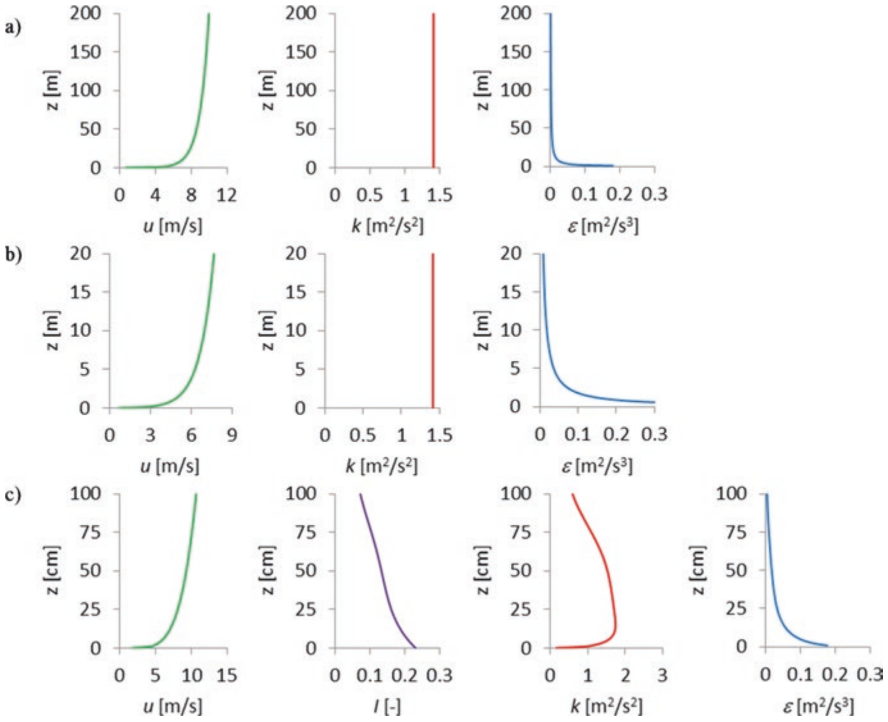


Fig. 4.28 Wind inlet boundary conditions: (**a**) and (**b**) according to Richards and Hoxey [180], (**c**) according to wind tunnel measurements by Bęc J, Lipecki T, Błazik-Borowa [187]

wide scope of experimental data and empirical formulas based on them can be found in documents published by the Engineering Sciences Data Unit (ESDU), the UK engineering organization. The basic information can also be found in fundamental books for wind engineers by [193–197].

In the field of simulations related to wind and fire, two spatial scales have essential meaning: mesoscale and micro-scale. The first one is over 2 km, the second below 2 km in length. Nowadays, the numerical combination of these two scales becomes more common and is based on the coupling of two parts – Mesoscale Meteorological Model (MMM or MEM) and Microscale Meteorological Models (MIM realized by CFD).

The aim of MIM or CFD is to describe wind speed or pressure fields around structures, while MEM considers mainly topographic and thermal effects on the flow. The main differences apply to the definition of boundary conditions. Mesoscale initial atmosphere conditions and equations considering energy and water phase changes are introduced, and they can evolve naturally under continuous calibration based on, e.g. satellite observations [198]. The complexity of the flow field in mesoscale is well visible in publicly available online services (such as *windy.com*). An example of such results at four heights (ground, 1500 m, 3000 m and 5500 m) is

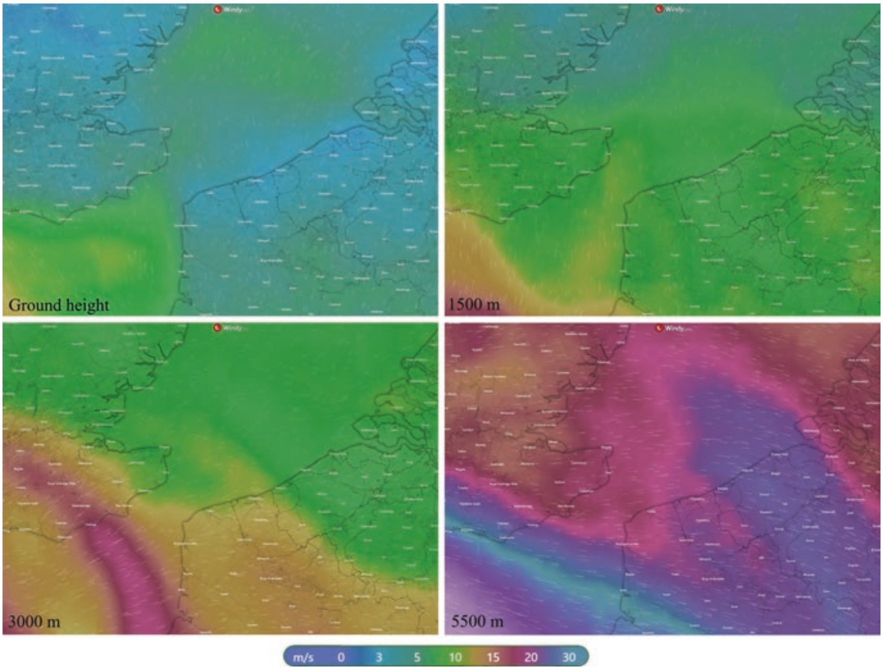


Fig. 4.29 Wind velocity above Western Europe at the ground level, 1500 m, 3000 m and 5500 m. Data for the evening of 04.03.2020. (Source: windy.com, CC BY)

shown in Fig. 4.29. What is noticeable is that not only wind velocity changes with the height, but also the wind direction.

Many variants of MEM are in use, among others: A2C (Atmosphere to CFD), ARPS (Advanced Regional Prediction Systems), COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System), Eta, FITNAH, MEMO, METRAS, NHM (Non-Hydrostatic Model), RAMS (Regional Atmospheric Modeling System), MM5, WRF (Weather Research and Forecasting), MC2 (Mesoscale Compressible Community) and others. The last two MEM models are used most often in calculations in wind engineering.

The description of methods used for parameterisation effects of obstacles in mesoscale models was provided by Schlunzen et al. [199] and more recently by Hangan et al. [198]. The authors distinguished the following approaches: (a) Main land-use approach – only the main characteristics of the land (e.g. buildings) are considered in a grid cell. (b) Parameter averaging method – effective values of parameters of, e.g. roughness and temperature are approximated by linear or higher-order averaging within a grid cell. (c) Flux aggregation method (mosaic method) – each grid cell is subdivided into a limited number of homogeneous land-use types. (d) Canopy layer (single and multi). Single-layer urban canopy model considers the geometry of building areas, street canyons, exponential wind profile at the canopy level and heat transfer from infrastructure. In multi-layer urban canopy models momentum, heat, moisture are calculated at several levels. Masson [200] discussed various aspects of canopy models giving some examples of their use in urban surface modelling. A detailed review of the development of urban canopy models for mesoscale climate models is presented in [201]. Tree representation in the single-layer canopy model was considered by [202] and in the multi-layer canopy model by [203].

In fire-related analyses, MEM-MIM coupling is used for research related to wildland fires. For the behaviour of wildland fires, the most import factors are the wind velocity and its direction affected by the terrain topography. There are a few models which allow estimation of fire propagation (eg.: FARSITE, FireStation, Wildfireanalyst, CARDIN, BEHAVE, Prometheus, etc.). The application of these models requires a more exact definition of wind parameters than it is performed in mesoscale.

A review of approaches used to simulate fine-scale surface winds for the wild rye fire management was presented by [204, 205]. Three approaches have been identified: (1) uniform wind field, (2) mass-conserving model and (3) mass and momentum conserving model. Two latter approaches are new developments and are implemented in the model WindNinja, while the first one was widely used in the past. The Authors discuss the validity of the approaches, along with their computational efficiency, that is a determinant factor for use in operational modelling. The WindNinja is the wind simulation model which supports wildland fires operation. It takes into account the influence of terrain on the flow and dynamically downscales data from the mesoscale simultaneously provides a good resolution. The bases of the model, comparisons of various approaches to simulate wind in wildland fires and model applications are described in above-mentioned papers by [204, 205], and also by [206]. WindNinja was recently upgraded with a coarse grid RANS model, that improves the predictions in the complex terrain [207], Fig. 4.30. Coupling between the FARSITE model of the fire propagation and WindNinja and several proposals of coupling improvements was discussed in papers by Sanjuan et al. [208–210], Brun et al. [211].

A new tool called QUIC-Fire was recently proposed in [212] and it is mainly designated not for operational fire actions but for the planning of design burn plans. This tool uses two-way fire and atmosphere feedback by coupling a wind solver (QUIC-URB) with a cellular automata model for fire behavior.

4.6 Challenges in CFD Modelling of the Environmental Impact of Fires

4.6.1 *Time-Scale of the Analysis and the Particle Lifetime*

As mentioned by [36] if we focus on the dispersion in the near field, we do not need to consider mixing induced by very large scales associated with plume meandering, weather or diurnal cycle. A similar case can be applied to the particulate lifetimes.

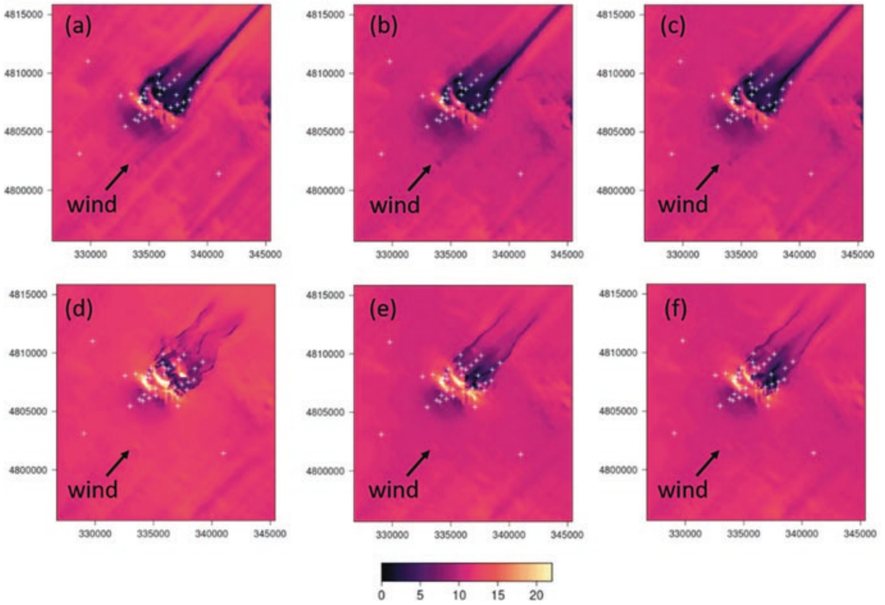


Fig. 4.30 CFD predictions of WindNinja model – the wind velocity at 3 m above ground over a complex terrain (Big Southern Butte), with algorithms: (**a**) myKELU, (**b**) KELU, (**c**) RNGKELU, (**d**) KEQUICK, (**e**) KEQUICK, (**f**) RNGKEQUICK. Axes labels are in meters, wind speed in [m/s] [207]. (Creative commons Attribution License https://doi.org/10.3390/atmos10110672 CC BY)

Very large particles with sizes greater than 10 μm have settling times up to a few minutes (from a height of 1 m). Moreover, the greater size of the particle means the shorter settling time. These particles include hair, skin flakes, common pollens or visible dust in the air, and usually are not within the interest of the fire modelling. Coarse particles (1–10 μm) have quick settling times (scale of minutes to hours) and usually are found close to the emission source. Fine particles (0.1–1 μm) have a measurable settling time, but in case of the lower end of the size distribution, it may be so long, that it is irrelevant compared to other phenomena. Ultrafine particles with diameters smaller than 0.1 μm behave like gases and do not have a measurable settling time.

The sizes of soot particles mean that for the near-field and the simulation scale of the order 30–60 min, the settling phenomena for most of the particles will not be relevant. However, the soot deposition on walls, ground and canopy as the effect of turbulent flow of the smoke near the walls and obstacles may be significant. An overview of models of soot deposition and gravitational settling modelling in Fire Dynamics Simulator was presented by [85] and [213].

If the focus is on the consequences of fires in a long term exposure (hours), soot agglomeration and coagulation must be considered, as well as soot formation from smaller PAH particles [214]. A plume of large soot particles may decouple from the thermal plume. This was observed in simulations presented in [215]. It is essential to highlight, that soot and PAH in smoke can transport many different substances, including VOCs, that are known for their cancerogenic effects [60]. Furthermore, in a long time-scale, additional physics and chemistry models should be employed to include in analyses the coagulation of particles, and their chemical reactions with each other or with the atmosphere, as well as the changes in the particulates being the effect of UV radiation. These phenomena may be costly to model with CFD, and Eulerian modelling approach is recommended.

4.6.2 Transport of Firebrands

Vegetation fires produce small, solid particles that can burn for a long time period, and can be carried away by the fire for enormous distances. Such burning embers are known in the literature as firebrands. The phenomenon connected to the spread of wildfire by the firebrand ignition of subsequent fires is referred to as "spotting". The maximum spotting distance is considered as the distance that firebrands are transported and deposited with sufficient heat to cause the ignition [216]. This maximum distance may range from a few hundred meters to kilometres [217]. In the extreme reported cases, the spotting was observed up to 30 km away from the fire front. The problem was summarised in a review studies by [218] and [34].

The travelling distances of firebrands caused by the wind were computed with the use of CFD in [219]. The authors examined two shapes of wood firebrands (cylinders and disks) of different diameters and with the flow velocity equal to 0 and 9 m/s and obtained quite good agreement with the experiment. The travelling distance of firebrands changed almost linearly with the wind speed and weakly depended on the fire intensity and the diameters of the firebrands. The numerical modelling of firebrand showers through the coupling of the fine resolution time-varying LES model with the fully deterministic 3D 6-DOF firebrand transport model was performed by [220], Fig. 4.31. CFD was used to resolve the velocity field of jets/plumes, and the approach was validated against wind tunnel experiments by the same authors [221]. A coupled physics fire model HIGRAD/FIRETEC for firebrand transport was introduced by [216]. Its goal was to estimate the transport trajectories of the disk and cylindrical firebrands.

For more information about the creation of firebrands and the phenomena related to the ignition of subsequent fires, the reader is referred to the review papers by [218, 222] and further to work by [216].

4.6.3 De-coupling of the Wind and Fire Analyses and the Temporal Discretisation

The typical CWE analyses for urban-scale phenomena are performed as steady-state solutions with RANS k-ε as the most commonly used turbulence model. From the wind engineering point of view, the use of steady or unsteady simulations

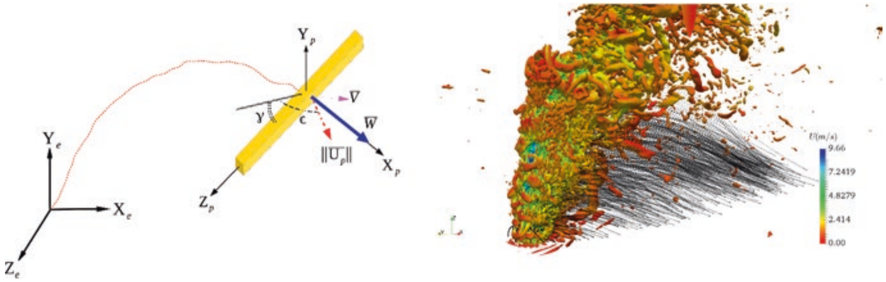


Fig. 4.31 A general schematic of firebrand trajectory and influential parameters (left) and a simulated trajectory of model firebrands (non-compact with aspect ratio 6) within the envelope of a plume bent-over in cross-flow boundary layer which is obtained with Large Eddy Simulations. (Courtesy of dr Ali Tohidi)

depends on whether the area of interest is mean or peak values. In case of flows behind buildings, both steady and unsteady RANS simulations could be burdened with significant inaccuracies. Conversely, the use of LES to capture the time-dependent flow behaviour increases the accuracy of results but simultaneously the computational resources required for the analysis, and in consequence, the overall costs also increase. The user must find the balance between accuracy and costs.

In fire safety engineering, most of the analyses are performed as unsteady (transient), as the fire itself is a transient phenomenon. Thermal effects, which are usually neglected in wind-related analyses, have a strong influence on the solution in fire-related analyses (plume flows, ceiling jets, pressure differences etc.). Furthermore, the results of the analysis are also assessed as a function of time to determine the Available Safe Evacuation Time (ASET).

Taking into account the large combination of wind angles and wind velocities, performing all coupled wind and fire simulations as transient would require immense computational power. In order to reduce the computational cost, the analysis may be divided into two steps, Fig. 4.32. (steps 3 and 4). In step 3, a preliminary steady-state analysis is performed for the wind flow in the domain, which allows determination of the most unfavourable wind action angles. This simulation may be carried out according to two approaches – coupled and decoupled [165]. In the coupled approach, the numerical domain contains the exterior and interior of the model, which are connected through inlets. As a consequence, the solver will resolve the indoor flows. This simulation is performed in ambient temperatures, and the flows may differ from the results obtained in the fire simulation, due to the lack of buoyant forces generated by the fire. This approach requires the high-quality mesh and a specific domain, but because fire does not have to be resolved, it is significantly cheaper than the transient, fire-oriented CFD. In the decoupled approach, the domain contains only the exterior, whereas the interior may be resolved in a separate model (or just discarded). In this case, the user assumes that openings are sealed, so no wind penetration to the building interior appears. As the general recommendation, the coupled approach is prevalent in wind engineering [33] and, thus, also recommended.

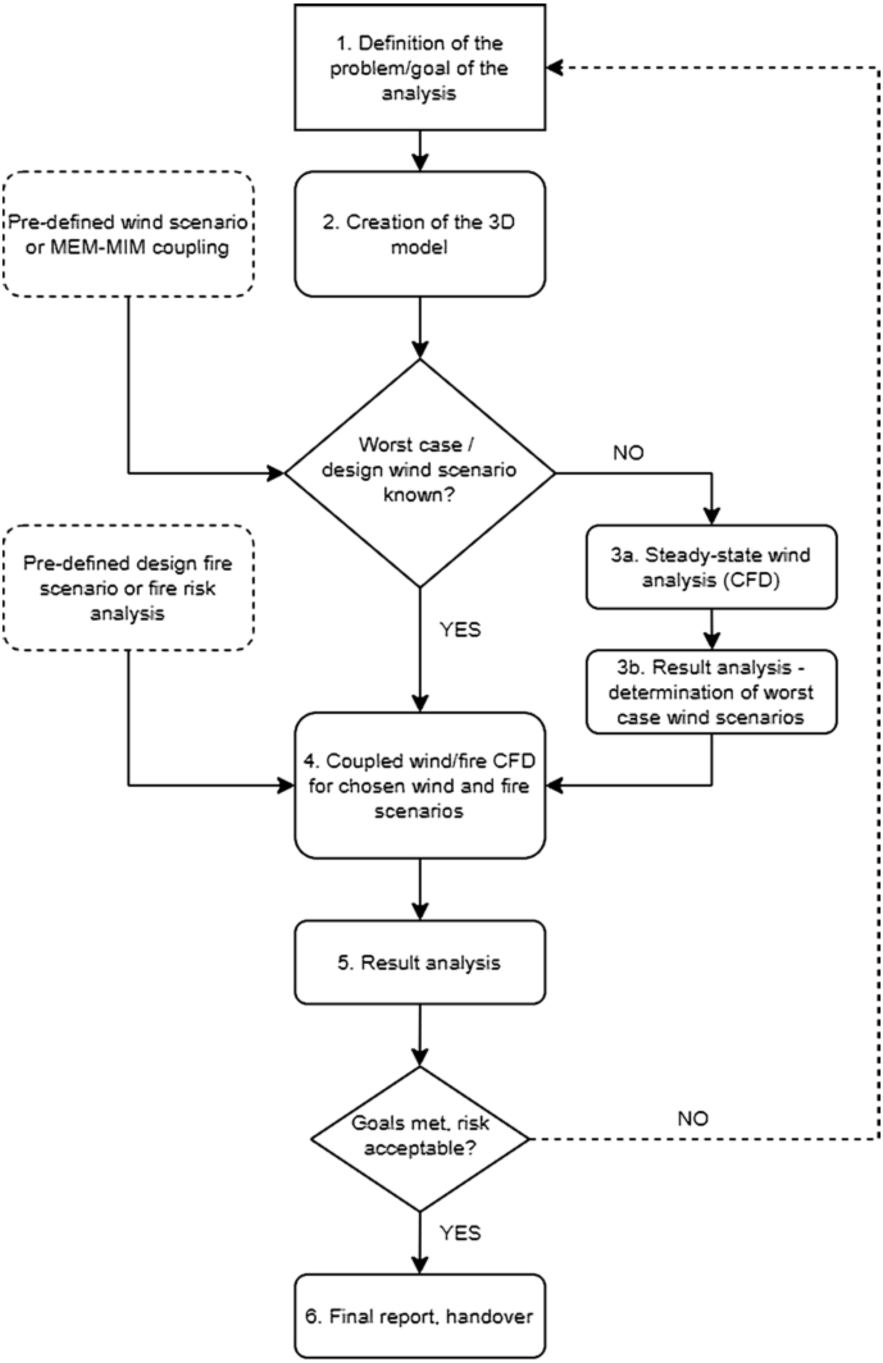


Fig. 4.32 The workflow of wind and fire coupled CFD analysis with possible de-coupling of steady-state wind CFD simulations

The results of preliminary wind analyses should provide information regarding pressure on the building inlets and outlets, as well as about the indoor flows induced by the wind. The analysis itself is steady-state, and the averaged conditions and flow features are estimated. The results of such study are investigated with respect to wind pressure coefficient values in areas where elements of the natural smoke exhaust system are located. The worst scenario is usually one with the highest pressure on ventilators, the highest suction near inlet air openings or with the highest air velocity inside the building. Wind analysis may provide multiple scenarios for further evaluation with wind-fire coupled CFD simulations. Once the worst scenario (or scenarios) is determined, the transient simulation with the fire inside the building can be performed. This is the second step of the wind-fire analysis carried out with the representation of the fire, for the most unfavourable angles of wind, as described in [37].

In some cases, such as simulations during emergency response or to recreate the course of historical fires, the wind is known, and no angle sensitivity study is needed. In this case, step 3 (Fig. 4.32) is not required. However, for the design and preparedness planning, the wind angle sensitivity study may be critical fo the determination of the worst-case scenarios.

4.7 Example of a Near-Field Smoke Dispersion Analysis

4.7.1 Assumptions for the Modelling

To illustrate the CFD framework presented here, a series of CFD simulations with commercial code ANSYS® Fluent® was performed. The analysis aimed to investigate the smoke dispersion in a near-field of a fire in a warehouse building. The building was located in an urban area, near an urban street canyon. The height of the warehouse building was 8 m, and the height of the tallest building in the neighbourhood was 60 m. An overview of the modelled neighbourhood and the numerical model are shown in Fig. 4.33. The domain was subdivided into three areas of interest, as shown in Fig. 4.34. The middle of the domain was an area within 30 m from the warehouse building. This area was modelled with a dense mesh, and the buildings in this area were represented with fine details. The second part of the domain stretched in the distance 250 m from the internal high-definition region. In this area, the building models were simplified, although their shape and height were preserved. This area was placed within a cylinder-shaped volume, with a diameter of 750 m. The rotation of the cylinder (before numerical calculation) was used to represent different wind directions (12 wind angles for each wind velocity). Finally, the cylinder domain was located in a larger box-shaped domain with dimensions of 1000 m × 1000 m × 360 m. In this area, the buildings were not modelled explicitly, and terrain roughness of $z_0 = 0.4$ was used to represent the effects urban environment has on the wind profile. The level of details in the domain was based on the work of [159].

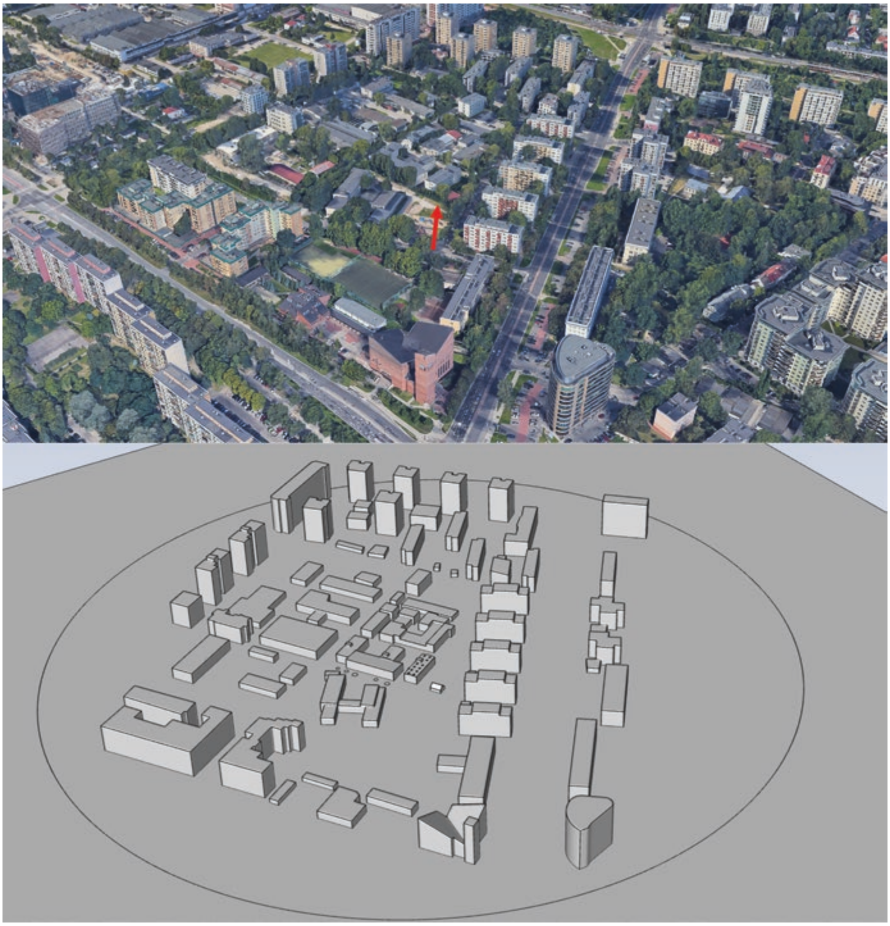


Fig. 4.33 Bird-eye view of the modelled neighbourhood and the corresponding view of the numerical model used in the analyses. (Source: Google® Earth, own work)

Differentiating of the large domain into three subdomains (Fig. 4.34) also did allow to use different meshing strategies in each part. The mesh was based on the previous experience described by [160]. The unstructured tetrahedral mesh was used for this case study, primarily due to the ease of meshing interior of the building. It should be noted that more sophisticated structured meshes are often associated with the improvements in computational efficiency of simulations and decrease of numerical diffusion that adds to the model uncertainty. For the generation of high-quality meshes, please refer to [140]. The mesh inside and on the external walls of the warehouse building (red building in the middle of high-resolution domain, Fig. 4.34) had maximum element length of 40 cm, which was narrowed to 12 cm on vents, inlets and in the proximity of the fire, Fig. 4.35. The mesh growth rate factor was 1.15 in this area. The mesh on buildings in the high-resolution part

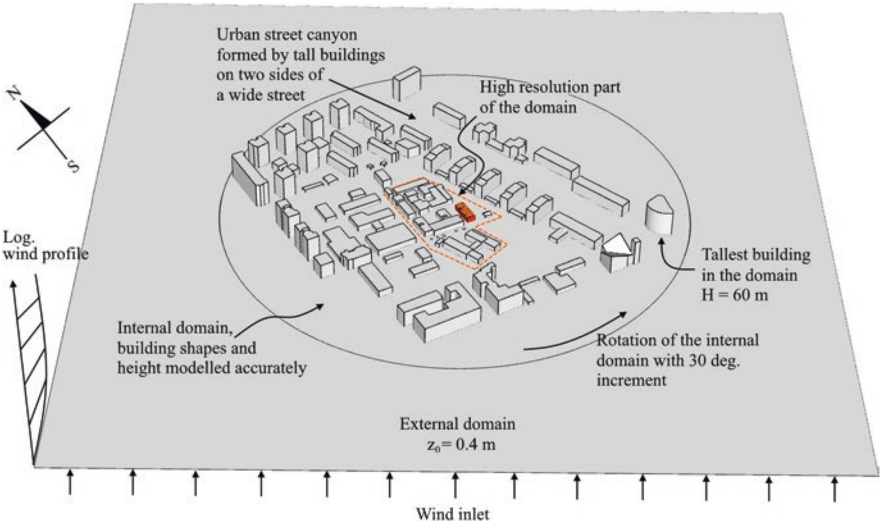


Fig. 4.34 Overview of the three main regions of the domain with different level of details

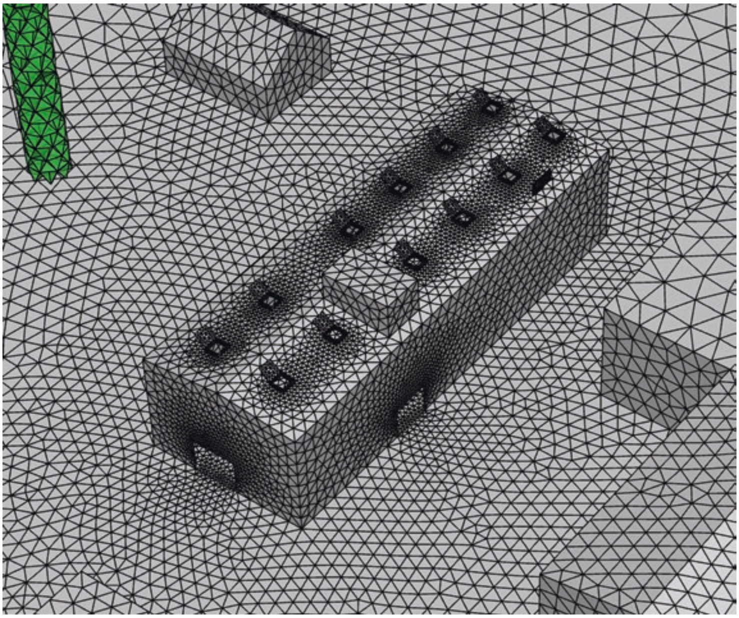


Fig. 4.35 Overview of the numerical mesh in the high-resolution part of the internal domain – the modelled warehouse building and its near surroundings

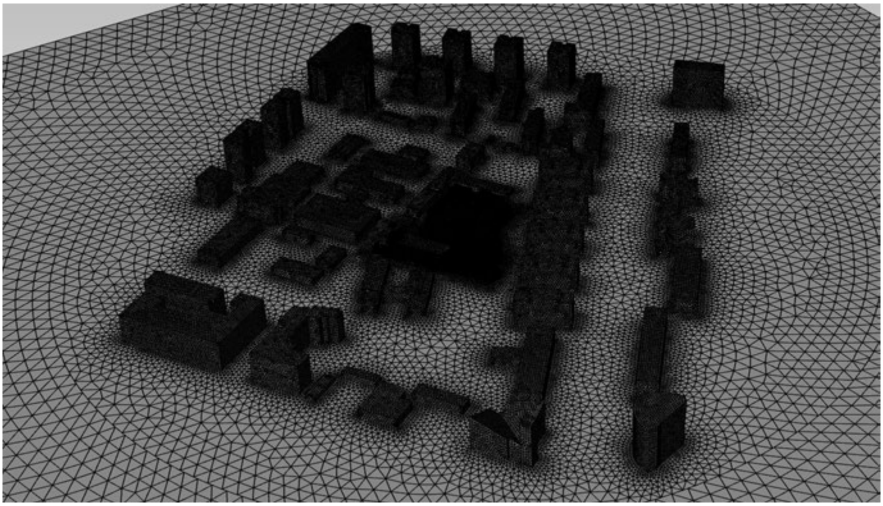


Fig. 4.36 Overview of the numerical mesh in the internal domain

of the domain was up to 1 m, and in other parts of the detailed internal domain up to 2 m, Fig. 4.36. The mesh in the external domain ranged from 2 m to 15 m, and was growing in size with the distance from the internal domain, reaching the maximum size at the domain boundaries. The total number of elements used in this model was approx. 4,000,000.

The warehouse building had external dimensions of 32.00 m × 12.00 m × 8.00 m. The fire was defined as a volumetric source of heat and mass without explicit combustion modelling. The evolution of the Heat Release Rate was defined with an "αt^2" relation, with the value of $\alpha = 46.70$ W/s^2, commonly known as the *fast* fire [59]. The Heat Release Rate was limited to 8,00 MW, which was reached by the fire in the 400th second of the analysis. Conservative soot yield value of $Y_{soot} = 0.1$ g/g was assumed [86]. The dimensioning of the smoke control system was based on the principals described in [59]. A total of 12 natural ventilators (1.00 m × 1.00 m) was evenly distributed on the roof of the building. The approximate total aerodynamic free area of the system was 7.44 m^2. The make-up air was supplied through two large doors, one in the north-facing façade (2.50 m × 3.20 m, A = 8.00 m^2) and the other in the west-facing façade (2.20 m × 2.72 m, A = 6 m^2).

The wind was introduced at the boundary of the external domain as a logarithmic wind profile. The wind velocity u_{ref} was 5 m/s and 10 m/s measured at the reference height $z_{ref} = 10$ m. These wind scenarios are further referred to as the moderate and strong wind, respectively, The terrain roughness in the external domain was $z_0 = 0.40$ m.

The simulations were performed with a double-precision 3D solver in the segregate numerical scheme (second-order). The simulation was transient, and the turbulence was resolved with k-ω SST model (in this case unsteady-RANS or URANS), modified for enhanced wall functions (shear stress in the near-wall region) and modified to account for buoyant forces. The radiative heat transfer was modelled with Discrete Ordinates model (162 discrete angles), and the heat transfer to the walls was modelled as a combination of convection and radiation (referred to as the third type boundary condition). The heat transfer within walls was modelled with the implementation of the Fourier law. The building walls were simplified and modelled as concrete, with a density of 2200 kg/m^3, the specific heat of 820 J/kg*K and thermal conductivity of 1,20 J/m^2*K. The roughness constant of walls was 0.05 and the mean roughness height of 0.01 m. A summary of the essential solver settings is given in Table 4.2.

Table 4.2 Summary of relevant solver settings for the CFD calculations

Solver	Pressure-based
Mathematical models	
Turbulent flow sub-model	k-ω SST
Time discretisation	Unsteady analysis, variable time step = 0.1–0.5 s
Total length of simulation	1200 s
Radiation heat-transfer sub-model	Discrete ordinates-
Convective heat-transfer sub-model	Based on the Fourier law
Computational scheme	PISO
Scheme of the analysis	All sub-models as second-order
Under-relaxation coefficients	ANSYS Fluent defaults
Initial and boundary conditions	
External and supplied air temperature	20 °C
Wall temperature (initial)	20 °C
Wall roughness height (buildings)	0.001 m
Fluid material	Air (incompressible ideal gas)
Operating pressure	101,350 pa
Fluid density	1.205 kg/m^3 at 20 °C
Fire representation	Volumetric source of heat and mass
Heat release rate (peak)	8.00 MW (from the 400th second of the analysis)
Soot yield	0.1 kg/kg
Convergence criteria	
Mass	10^{-4}
Energy	10^{-4}
Radiation model	10^{-6}
k	10^{-4}
ω	10^{-6}

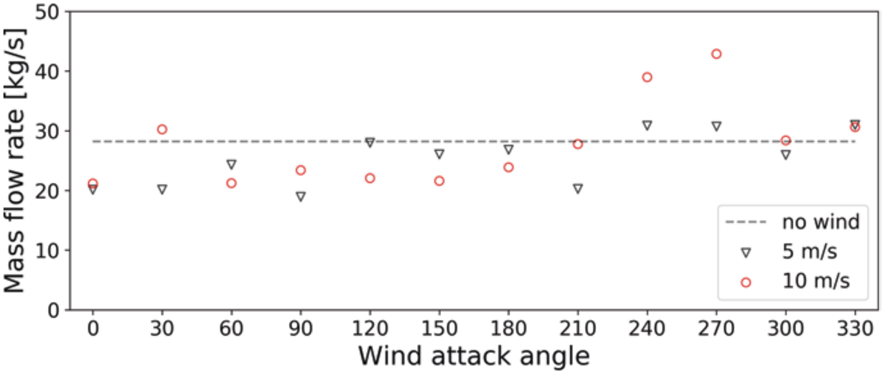


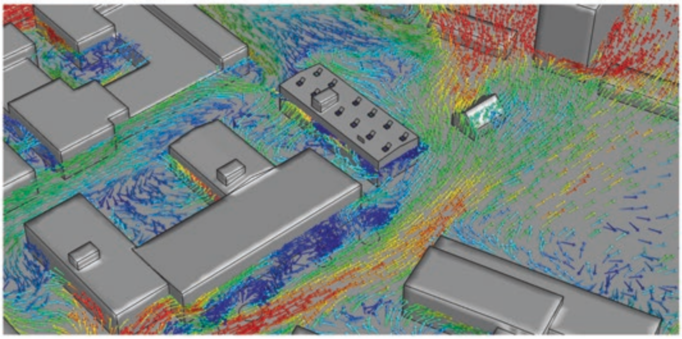
Fig. 4.37 Average mass flow rate at the natural ventilators for different wind angles and velocities. The dashed line represents the value measured in no-wind conditions

4.7.2 Results

The wind has a considerable impact on the performance of smoke venting system, which can be measured with the total mass flow rate through the natural ventilators, as summarized in Fig. 4.37. The mass flow rate of the system changes with the different wind attack angles and wind velocities. In the no-wind conditions, the mass flow rate through ventilators averaged at 28.12 kg/s. In case of moderate wind ($u_{ref} = 5$ m/s) the average mass flow rate of the system varies from 18.91 kg/s (at 90°) to 30.95 kg/s (at 330°). In case of strong wind ($u_{ref} = 10$ m/s) the minimum average mass flow rate was 21.16 kg/s (for 0°), and the maximum was 42.86 kg/s (for 270°). For most of the wind attack angles between 0°–210° and 300°–330°, the average mass flow rate with the wind was lower, than mass flow rate without wind. It is worth noting that for angles 60° and 120°–180° the mass flow rate at strong wind was lower than for the moderate wind.

The differences in mass flow rate between different wind attack angles can be attributed to the different flow and pressure field in the near-field of the building in each of the cases, which was illustrated for wind angles 90° and 240° and strong wind ($u_{ref} = 10$ m/s). For cases with wind attack angle 240°, the wind was blowing directly into the opening to the building (large doors in the northern façade of the building). For the cases with the lowest mass flow rate at the ventilators (0°–90°) the inlet opening was in an area of low pressure. This qualitative finding is in line with previously described case studies. Comparison of velocity vectors at 5 m above ground, and the pressure values at building boundaries are shown in Figs. 4.38 and 4.39 respectively.

Wind angle 90° and strong wind ($u_{ref} = 10$ m/s)



Wind angle 240° and strong wind ($u_{ref} = 10$ m/s)

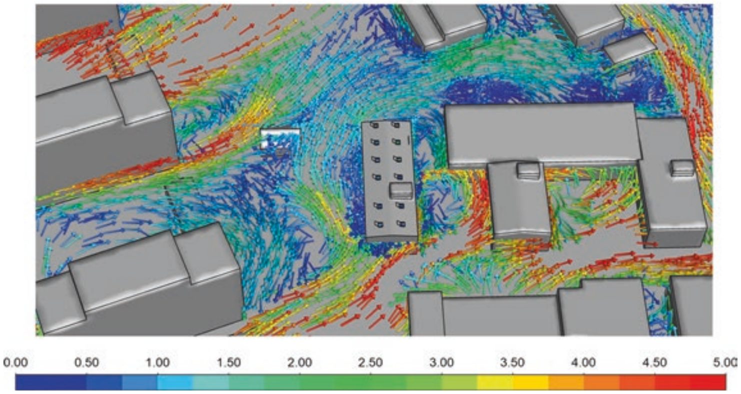


Fig. 4.38 Differences in flow field for cases with wind attack angles 90° and 240°. Velocity vectors (0.00–5.00 m/s) at the height of 5.00 m above the ground

The dispersion of pollutants in the near-field of the warehouse is also sensitive to the wind direction. The differences in the near-field smoke dispersion in the case of strong wind are illustrated in Fig. 4.40. Illustrations show the mass density of smoke at the surface of building walls and ground, with a logarithmic scale of 0.0001–0.1 g/m^3. The mass density of smoke of 0.1 g/m^3 is a value, for which the corresponding visibility of smoke for light-emitting signs is approx. 10 m (4 m for light reflecting signs). The illustrations were normalized for the wind direction, meaning that the flow direction in each of the illustrations is the same, but the domain is slightly rotated (by 30°) in each subsequent case.

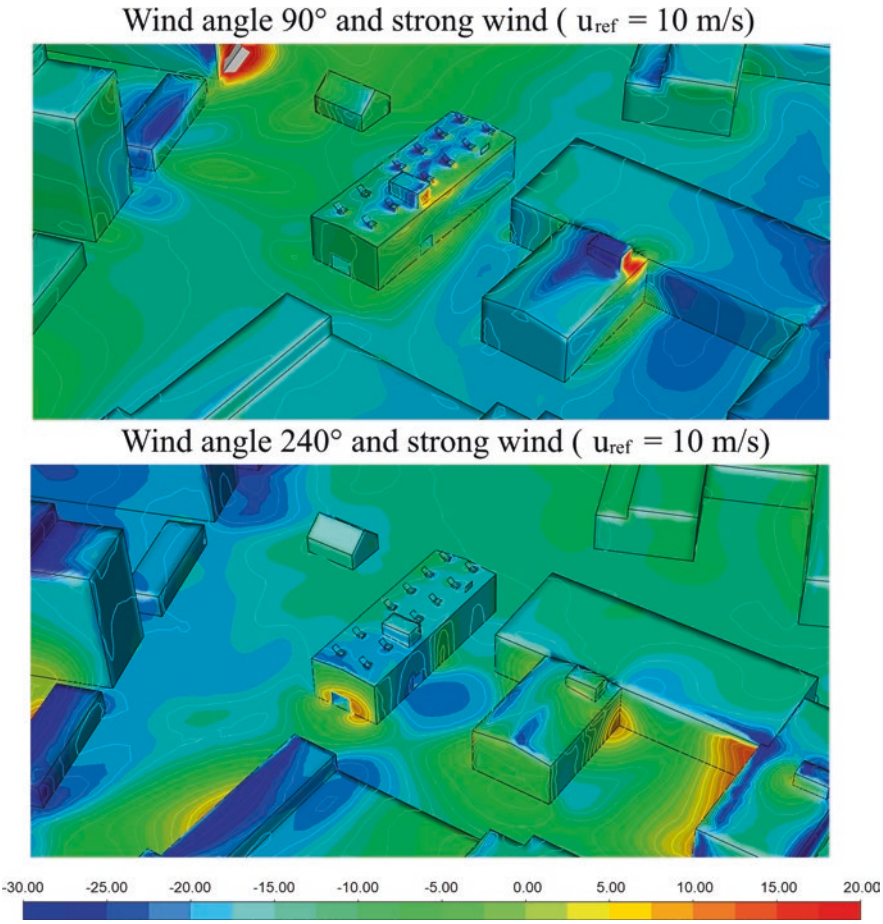


Fig. 4.39 Differences in pressure field for cases with wind attack angles 90° and 240°. Pressure values (−30… + 20 Pa) at the model walls

In some of the analysed scenarios (0°, 60°, 150°, 180°, 240°, 300°) the smoke plume is narrow and high above the surface (Fig. 4.41). In other cases (90°, 210°) the plume is wide (Fig. 4.42), and in the case of wind angle 330° very wide, Fig. 4.43. In the case of the wide plume, the area with a high concentration of pollutants spans over multiple neighbouring buildings, Fig. 4.44. In terms of environmental pollution, the 330° case would result in the most significant near-field contamination. The local concentration of smoke in the close neighbourhood of the warehouse building is substantially more polluted than in other analysed cases.

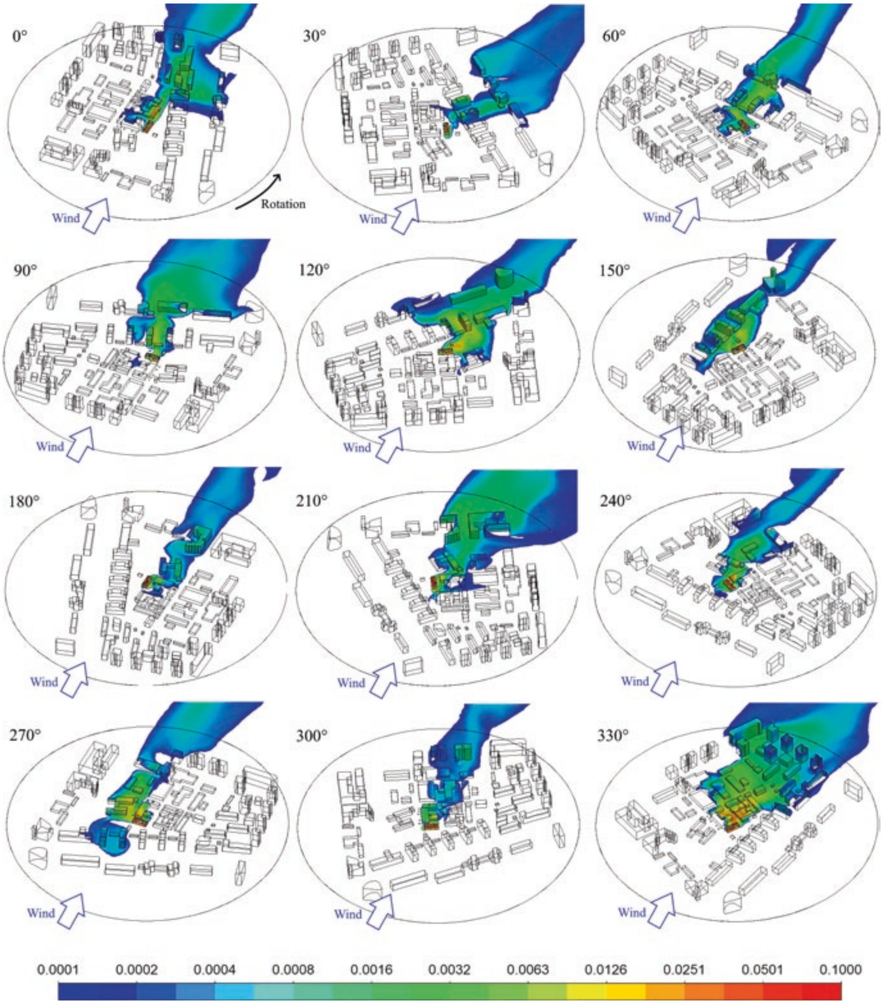


Fig. 4.40 Mass density of smoke at the surface of buildings and ground (0.0001–0.1 g/m^3, log scale). Wind angles 0°- 330°, $u_{ref} = 10$ m/s

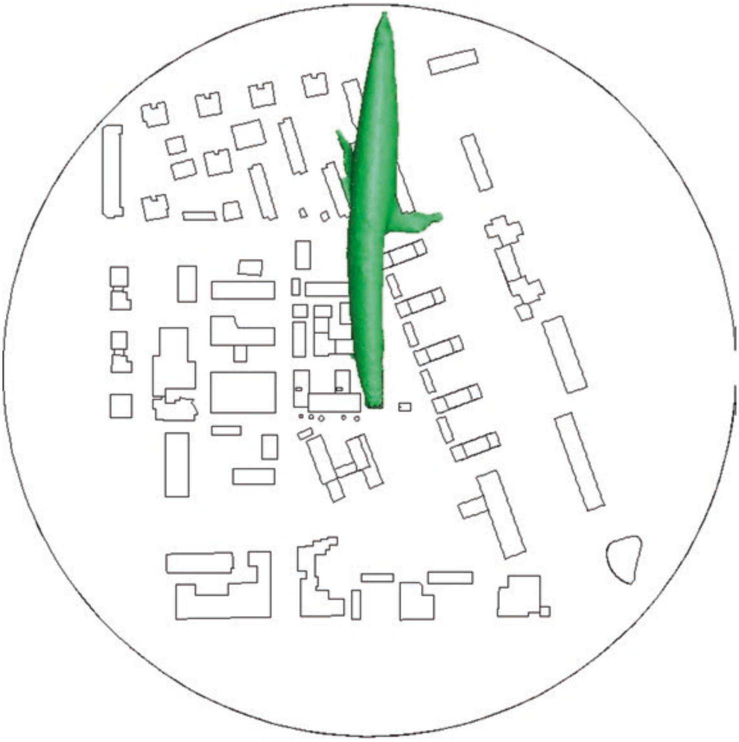


Fig. 4.41 Iso-surface of the mass density of smoke (0.001 g/m^3). Narrow plume observed for wind angle 0°, $u_{ref} = 10$ m/s

Comparison of the near-field smoke concentrations for 60°, 210° and 330° cases is shown in Fig. 4.44.

The differences in the contamination in the near-field at wind velocities of 5 m/s and 10 m/s (at different wind angles) are shown in Figs. 4.45 and 4.46, respectively. The differences in the size and shape of contaminated areas are visible. Cases of wind attack angle from 30°–90° provide a great illustration of the downwash effect on smoke behind a group of tall buildings, that form the eastern boundary of the urban street canyon. The vortices behind these buildings lead to the formation of areas with a high density of smoke, at a considerable distance from the fire (over 200 m). The effect of the urban street canyon is well visible in the case of 120° wind angle. The smoke is trapped in the area between two rows of high buildings, and the flow direction is not completely aligned with the wind direction. Also, some

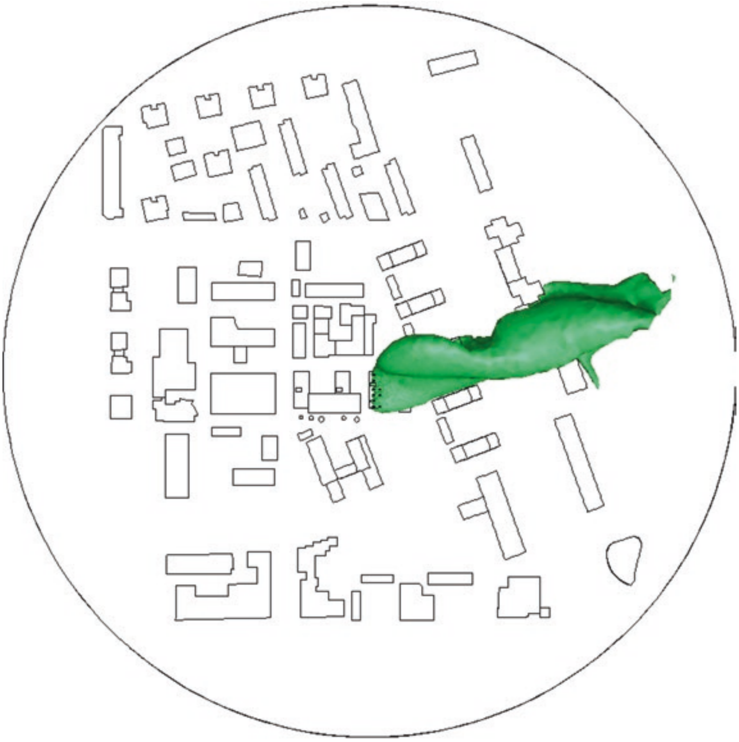


Fig. 4.42 Iso-surface of the mass density of smoke (0.001 g/m^3). Wide plume observed for wind angle 90°, u_{ref} = 10 m/s

up-wind smoke movement is observed. In cases of 300°–0°, the smoke is pushed on a group of buildings with height similar to the height of the warehouse. In these cases, the smoke gathers in court areas of buildings and in the narrow passages between buildings. At the strong wind, significant smoke contamination above 0.015 g/m^3 (approx. 30 m of visibility range) was observed at 130 m distance, and smoke density of 0.005 g/m^3 (approx. 100 m of visibility range) was observed at 250 m from the fire. These local effects are larger for stronger wind. This may be attributed to more significant building wake and downwash effects at high wind velocities.

As observed in the qualitative result assessment, the wind has a significant impact on pollutant transport in the urban environment. Even though the fire was limited to a moderate size of 8.00 MW (400 s of "*fast*" growth), the observed pollutant emissions were considerable. In some scenarios, smoke was able to accumulate behind tall buildings or was transported for a long distance through an urban street canyon.

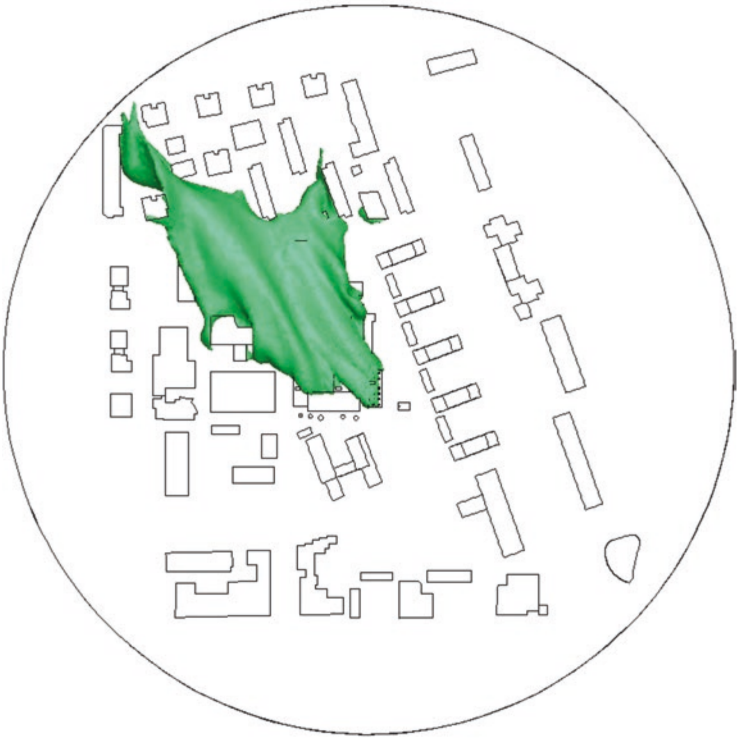


Fig. 4.43 Iso-surface of the mass density of smoke (0.001 g/m^3). Very wide plume observed for wind angle 0°, $u_{ref} = 10$ m/s

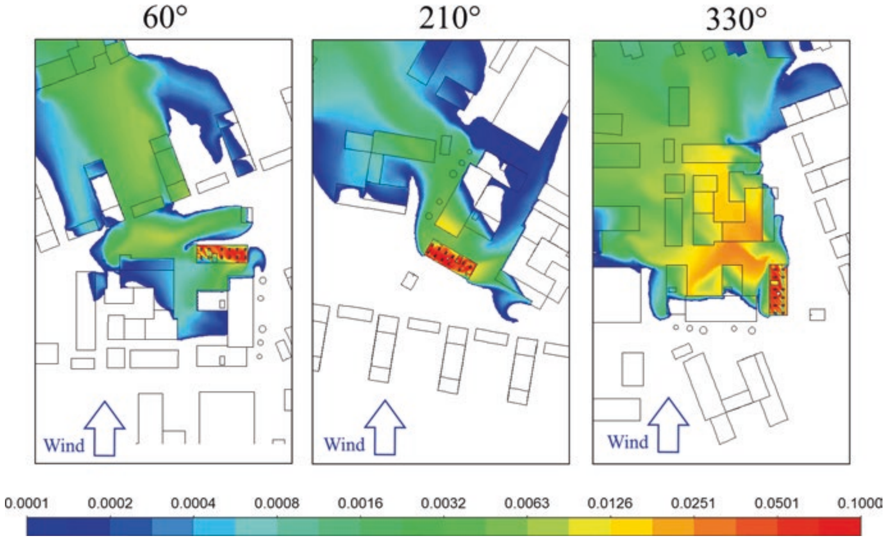


Fig. 4.44 The mass density of smoke in the near-field, at the surface of buildings and ground (0.0001–0.1 g/m^3, log scale). Wind angles 60°, 210° and 330°, $u_{ref} = 10$ m/s

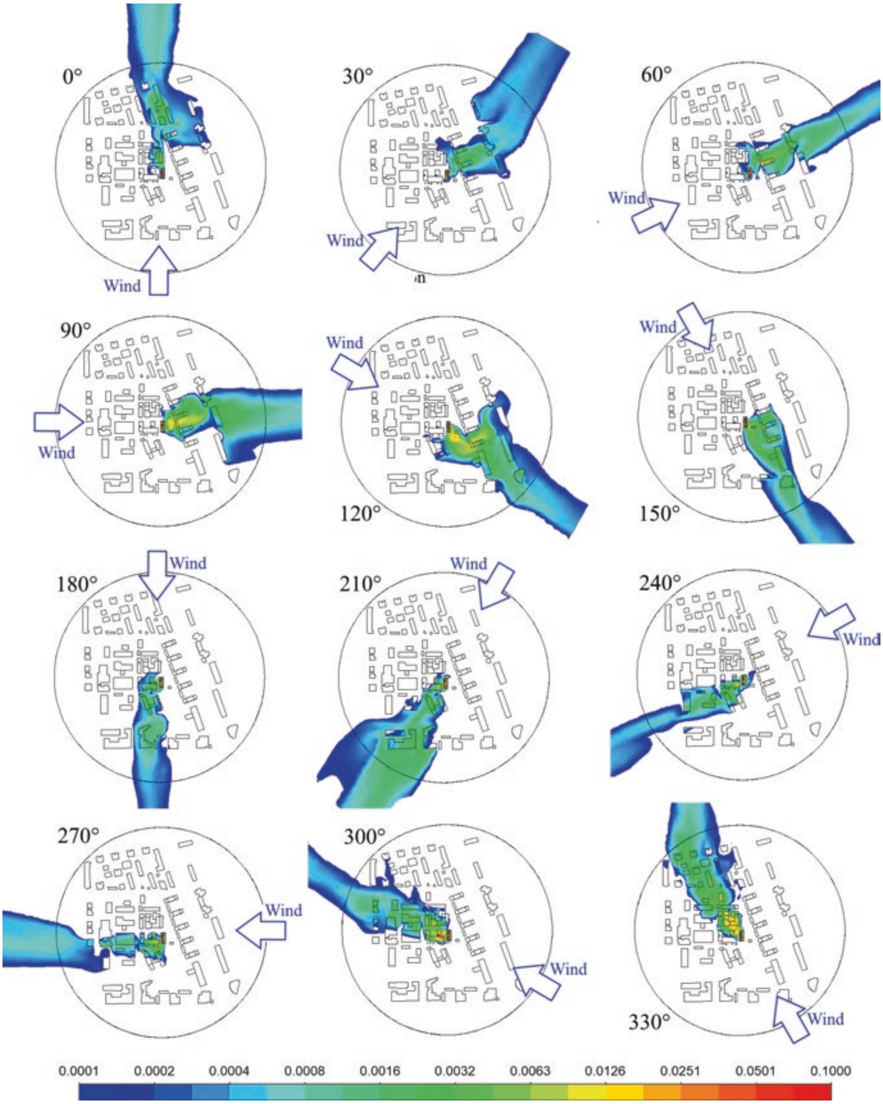


Fig. 4.45 Top view of the mass density of smoke at the surface of buildings and ground (0.0001–0.1 g/m^3, log scale). Wind angles 0°–330°, $u_{ref} = 5$ m/s

Comparison of the CFD predictions with results of Gaussian plume modelling (Fig. 4.13) highlights the strengths of modelling near-field effects with CFD. Fires of large buildings may have HRR measured in hundreds of MW, which means their contamination distance and smoke concentrations can be considerably higher than in presented case study.

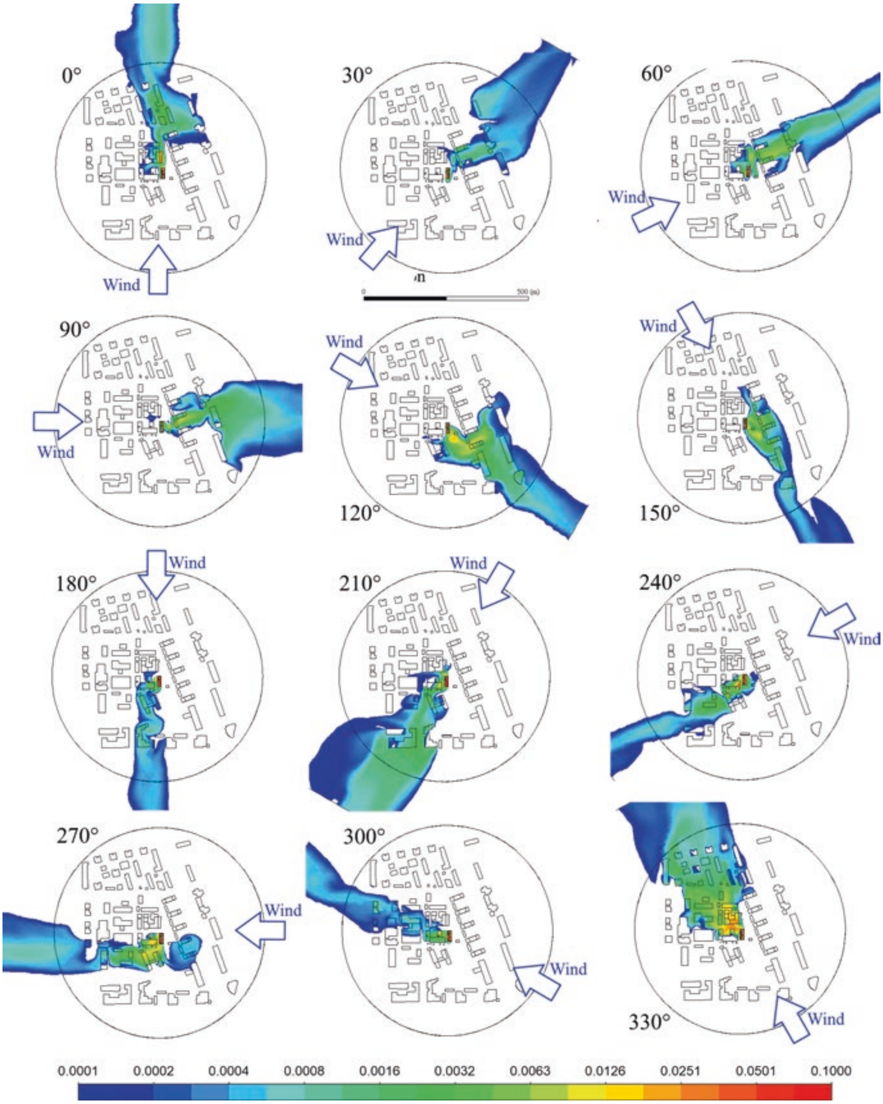


Fig. 4.46 Top view of the mass density of smoke at the surface of buildings and ground (0.0001–0.1 g/m^3, log scale). Wind angles 0°–330°, $u_{ref} = 10$ m/s

4.8 Summary

This chapter served as an introduction to computer modelling of smoke dispersion and assessment of the environmental impact of fires. Different models were described, and among them:

- computer models of compartment fires, including 1-zone, two-zone and CFD models;
- smoke dispersion models, including the box, Gaussian plume, puff, Lagrangian particle and Eulerian models;
- CFD coupled modelling of wind and fires.

The ability to model the near-field region of fires in an urban environment was highlighted, and the use of CFD for this purpose was presented in-depth. The challenges with CFD modelling were identified, and practical recommendations are given. Finally, the described methodology was used in a case study of a warehouse fire in an urban environment, highlighting the strengths of CFD modelling of the near-field effects of fires on the environment.

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Chapter 5
Emission Measurements

Eric Guillaume

5.1 Introduction

Large fires impact their environment by different pathways and at different contamination levels. These pathways, levels and fuels influence species to be analyzed and matrixes for the analytes. As generic environmental impact of fires is an increasing topic nowadays, ISO is developing a series of documents [1, 2]. There are many variables to be considered when evaluating the environmental impact of fires. Some of these variables have an impact on combustion efficiency and environmental impact [2]. Depending on the particular fire conditions there can be other variables that need to be considered [3]:

- Fire size influences the quantities of airborne pollutants that are produced.
- Fire duration influences the quantities of airborne pollutants that are produced and has an impact on soils.
- Fuel nature influences the nature of pollutants generated
- At environmental scale, topography matters, e.g. for wildland fires: upslope conditions result in a fire that produces different emissions from those produced by a fire occurring under no slope or downslope conditions: the former case results in combustion that is more efficient. Slopes are also more prone to erosion following a fire [4]. Post-fire turbidity levels in watercourses are affected by the steepness of the burned slopes [5].
- Weather conditions:
  - Weather preceding a fire includes rainfall, air temperature and humidity. High temperature, no rainfall and low humidity conditions allow producing emissions that are different from those produced by a fire occurring after a period

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  of low temperatures, rainfall and high humidity: the former case results in more efficient combustion [6].
  - Weather during a fire includes wind speed (See Fig. 5.1), air temperature and humidity. High winds, high temperatures and low humidity results in a fire that produces different emissions from those produced by a fire occurring when there is little or no wind, low temperatures and high humidity: the former case results in combustion that is more efficient.
  - Weather following a fire includes rainfall and humidity. Rainfall immediately after a fire can lead to soil loss and contamination of water supplies. Also rain can help extinguish a fire or at least the smouldering particles after the passage of a flame front. Humidity has an influence on the nature and persistence of aerosols and particulates in smoke plumes.

- Location of sampling: depending on this location, concentration of effluents may vary from several orders of magnitude.

Soil moisture content also plays an important factor in smouldering fires, which are non-negligible in term of emission. In fact, smouldering of forest fuels is responsible for a significant fraction of the pollutants emitted into the atmosphere during a wildfire. Smouldering (peat, duff, hummus.) fires play a major role in the global emission to the atmosphere, the destruction of carbon storage in the soil and the damage to natural environment. It has been reported that peat fires can consume around 50% or more of the total burned biomass in temperate and boreal fires [7].

Fig. 5.1 Wildland fire and smoke dispersion over urban area, due to local wind conditions. (Open picture from NASA Earth Observatory [10])

Typical example on its impact close to urban areas are the fires around Moscow in June 2010. The 2007 Anaktuvuk River Fire was an unusually large fire that occurred in the tundra of the Alaskan Arctic [8]. This fire burned 1039 km^2 of the tundra on Alaskas North slope, which had not been disturbed by fire for more than 3000 years [8]. The fire burned deeply into organic peat soils releasing enough carbon into the atmosphere to offset all of the carbon taken up by the entire arctic tundra biome over the past quarter-century [9]. This shows that the effects of wildfires are not limited to threats to ecosystems but can offer positive feedback into climate change processes as CO_2 released from ancient carbon stocks will result in further warming.

5.2 Contamination Overview and Selection of Analytes

5.2.1 Background

The initial decomposition is generally done by pyrolysis: under the effect of heat, the materials decompose to give a set of by-products that provide the volatile fuel for combustion. The basic composition of materials provides recommendations for the prediction of combustion or decomposition products that can be created during a fire. The composition or molecular structure of the materials can affect the combustion efficiency and the mixture of organic and inorganic combustion products generated by the fire. Research on fire emissions from real fires shows that if gases such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), nitrogen oxides (NO_x) and other irritants are particularly important in terms of acute toxicity, high molecular weight organic species and aerosols, such as particulate matter, polycyclic aromatic hydrocarbons (PAHs) and dioxins, have a considerable impact from the environmental point of view [11, 12]. These references provide recommendations for the environmental impact of major fires involving plastics. Specifically for wildland fires, reader is invited to read the following references [13–18].

The measurement of fire effluents (including soil, water, gases and aerosols) from fires remain a great challenge to the analyst [19, 20]. For example, the mobile atmosphere close to the fire may typically be at temperatures of over 1000 °C, highly turbulent, contain a very wide range of compounds (possibly several hundred of direct interest to the toxicologist and environmentalist) and with concentrations varying over several orders of magnitude. The atmosphere will typically contain acidic or corrosive species, labile or unstable species, condensable vapours (including water) and a range of liquid and solid aerosols covering a very wide range of particle size fractions and physical properties. In addition, such aerosols may also contain a wide range of adsorbed and/or absorbed chemical species that can contribute to the overall toxicity and environmental effects.

Close to the fire, temperatures are likely to be high enough to promote a range of chemical reactions resulting in a very time-variable content in the effluent. Chemical content of the emission here is likely to be mainly governed by thermodynamic equilibrium considerations. As the distance from the fire increases, the chemical nature of the atmosphere will change due to an increase of kinetically "frozen" chemical reactions as the gases cool. Agglomeration of aerosol particles can occur and any changes in concentrations of species will mainly be the result of dilution rather than further chemical reaction, although some components (e.g. nitrogen oxides, aldehydes) will continue to be modified at cooler temperatures and under other influencers such ultraviolet (UVs). Chemical species may also be partially absorbed and/or condensed onto surroundings. At positions relatively distant from the fire source, other phenomenon such as sedimentation of particulates may occur and affect measurements.

The choice of analytes and analytical techniques depends in a large proportion on the phase of the analysis (air, soil, water), the matrix effects (interactions between analytes and their phase), and the level of concentration. As a consequence, choice of the species to be analysed and related techniques first starts with study of the contamination pathways as detailed in this section. The effect of these various emissions depends on the transfer mechanism and on the specific species, and these species could present chemical changes after emission. Common examples are the evolution of nitrogen oxides (NO_x) in the atmosphere due to ultraviolet (UV) or the generation of tropospheric ozone. A wide variety of toxic effluents is emitted in fires. These effluents can follow a number of pathways to impact on human, animal or plants targets.

Initial decomposition is generally through pyrolysis, by which combustibles are broken down by heat to yield a range of organic by-products that provide the volatile fuel for combustion. The elemental composition of combustibles provides guidance when predicting the combustion or decomposition products that can be generated during a fire. However, fires consist of a complex mixture of fuels and conditions of ventilation/combustion, which can affect combustion efficiency and the mix of combustion products generated in such fires. The relative yields of the various combustion and pyrolysis compounds depend mainly upon the combustion conditions.

Recent investigations of emissions from large fires indicate that, whereas gases such as CO, CO_2, HCN, NO_x and other irritants are most important from an acute toxicological point of view [21], organic species of high molecular weight and aerosols, polycyclic aromatic hydrocarbons (PAHs) and dioxins, are most significant from an environmental point of view [2, 12]. Carbon dioxide is the highest airborne combustion product by mass, followed by carbon monoxide [22]. Particulate matter (PM_{10}) is probably the third highest airborne combustion product by mass. Fine particulate matter ($PM_{2.5}$) are produced in particularly large portions [12, 23]. Species of interest also include dioxins [24–26], hydrocarbons in substantial quantities [22]and aldehydes, mainly formaldehyde [27].

Examples of effluents quantified for their environmental impact from real fire incidents are available in appendix A of ISO 26367-1 [2].

5.2.2 Contamination Pathways

Emission to the Air

Airborne emissions from fires comprise particulates, aerosols and gases. Effects could be local and acute near the fire [28], or have an action at long distances, for example on climate [3] and/or regional visibility [29]. The production of aerosols plays an important role in the regional radiative balance, and can produce regional cooling [30]. Forest fires, when compared to all fires, are a significant source of PAHs (polyaromatic hydrocarbons) and VOCs (volatile organic compounds) [12, 31]. Agricultural fires can cause long-term air quality issues [32], as highlighted for CO [14]. Gases, especially the lighter ones, are often characterized by their acute effect near the fire. As well as the primary combustion products, secondary combustion products can result from photochemical reactions in the smoke plume [33].

An estimate of the total quantities of pollutants produced in a fire can be modelled by the USDA (US department of Agriculture) First Order Fire Effects Model (FOFEM) [34]. However, this approach is often oversimplified: Fuel consumption is used to determine the emissions of effluents by multiplying by pre-tabulated emissions factor. Land-based measuring stations have been be used to record both gases and particulates [23] in prescribed burns. Aircrafts have been be used to carry out comprehensive analyses of smoke plumes [35] and more recently drones. In areas remote from the fire, the impact on air quality should be measured by a three-hour Pollutant Standards Index (PSI) developed by the U.S. Environmental Protection Agency [36]. While real-scale fire tests provide important information concerning airborne emissions, some measurements, such as emission factors for CO and CO_2, can be conducted at laboratory scale with several limitations: in one hand, laboratory experiments allow to collect all effluents and provide global values more readily. In the other hand, there are some difficulties understanding if the behaviour at laboratory scale represents to a sufficient degree what would occur at larger scales, and phenomenon such smouldering/flaming transition would be different. In that way, laboratory data can overestimate the quantity of emissions of some species [37].

The dispersion of the fire plume within the atmosphere causes elevated concentrations of airborne pollutants, increased risk from exposure to airborne pollutants, and reduced visibility. Particulate atmospheric emission results from reducing visibility and obstructing fire-fighting operations, as well as pervasive reduction in the environmental quality and in potential long-term toxicity. PM_{10} airborne particles present an important potential environmental problem due to their direct effect on the respiratory system and to their transport of carcinogenic organic species such as PAHs, dioxins and furans. Both local topography and meteorological conditions, such as wind speed and air stability characteristics, have an influence on the characteristics of dispersion and the extent of the fire plume zone. Furthermore, the fire-fighting strategy also impacts the levels of pollutants in the plume. Short-term environmental impacts are most significant in this zone. Valleys, hills, basins, and canyons, adjacent to or surrounding the fire, constrain dispersion of the plume. Low wind speed, temperature inversions and other conditions that promote rapid plume deposition also hinder plume dispersion. The combined effects of local topographical features and local meteorological conditions that lead to restricted dispersion are generally additive and result in higher air pollutant concentrations within the fire plume. Visual impairment occurs during fires as a result of atmospheric particles, reducing visibility by scattering and absorbing light. This issue tends to receive lower priority than other environmental aspects because there is no associated biological toxicity or clearly definable cost; nevertheless, it results in a pervasive reduction in environmental quality.

The plume deposition zone encompasses the area under the fire plume zone. Topographical features and meteorological conditions influence the plume deposition zone. Air temperature normally decreases with increasing altitude. Reversal of this gradation in which a layer of warmer air lies above a cooler layer is known as temperature inversion. As the cooler layer of air is denser than the warmer layer, it cannot rise, and this result in any pollutants emitted below the "warm" inversion layer becoming trapped and disperse horizontally (Figs. 5.2 and 5.3). Heaviest particulate deposition occurs close to the fire source, where the lighter ones may be entrained far from their origin. Atmospheric releases also affect terrestrial and aquatic environments through deposition of pollutants. Many thermal degradation products can be adsorbed by the soot particles and be transported with the smoke.

Health and ecological damage can arise from exposure to deposited pollutants though a variety of pathways, such as aerial deposition to water and land, and accumulation in the food chain and subsequent consumption, either directly or indirectly by contaminated food. Important species in this zone include high-molecular-weight organic compounds, such as PAHs and dioxins. In order to obtain an accurate measure of the environmental impact of a particular fire, full knowledge of weather conditions is essential for the determination of deposition patterns.

Fig. 5.2 Examples of smoke plumes from building fires (grey smoke) and from petroleum fire (black soot), and the regional impact of fire plume over London, Buncefield oil depot fire, December 11th, 2005. (Pictures from wikimedia, license CCBY-SA 3.0)

Fig. 5.3 Inversion layer and horizontal dispersion of fire plume, Buncefield oil depot fire, December 11th, 2005. (Picture from wikimedia, license CCBY-SA 3.0)

Emission to Water Environment

Water fluxes potentially affected include streams, rivers, lakes, water storages, aquifers and coastal waters [38–40]. Pollutants can come from water run-off from fire-fighting activities or rain following fires. Combustion products of vegetation, combustion products of manufactured items or structures also involved during fires, soils loosened by vegetation loss and firefighting activities, can cause contamination. Pollutants can be solid or liquid both being soluble or not in water. Soluble materials can be toxic to riverine wildlife. Insoluble materials can cause trouble, which can interfere with the ecology of a water flux [41]. Vegetation removal can lead to erosion and soil loss by wind and by rain for an extended period after the fire. These sediments run-off into nearby watercourse could be a source of pollution. Water temperatures can also increase due to both radiation and run-off [5] and biotopes may be very sensitive to rapid changes in water temperature. Run-off from fires in coastal areas can have a negative impact on the ecology and biota of coastal regions and coral reefs, especially massive release of sediments and water temperature.

The major threat to the water environment posed by fires arises from the direct run-off of contaminated fire-fighting water, foam and chemical agents into rivers, streams, lakes, coastal water, groundwater or sewage treatment works, although some threat to water fluxes is caused by the deposition of airborne pollutants into the water environment (Fig. 5.4). Existing water monitoring stations shall are used to provide data on the impact of fires on water quality [42]. The impact that any discharge of fire run-off has on the water environment is dependent on a wide variety of factors, including:

Fig. 5.4 Fire at the Bistoon Petrochemical Powerhouse, Iran. Firefighting foam dispersed, July 13th, 2016. (Picture from wikimedia, license CC BY 4.0)

- The possible presence of water basins to catch firefighting water run-off and its sizing, see ISO/TR 26368 [43];
- The volume of run-off produced, the time of travel from the site of the fire to the target, the dilution afforded in the receiving water body, the temperature, chemistry and type of the receiving water;
- The chemical composition of the run-off, influenced to a great extent by the chemistry of the fire, which involves a complex mix that includes soot, ash and other suspended solids, the decomposition products of combustion washed off by the run-off, and the fire-fighting agent;
- The sensitivity and the distance time of travel from the fire to the receiving targets, such as public drinking-water abstraction points, fisheries or valuable aquatic ecosystems.

The effects of a water run-off from fires or fire suppression activities to surface water are mainly short term and can include the contamination of public drinking-water supplies during or immediately following the fire. The effects are usually greatest within the immediate vicinity of the fire, where the levels of pollutants are at their highest. As well as short-term impacts, one can observe long-term impacts arising from direct ingestion of some organic compounds in watercourses contaminated by fire-water run-off and/or plume deposition, as well as chronic effects on ecosystems. It is important that run-off water does not reach water treatment plants as these can be rendered non-functional by the inclusion of large volumes of pollutants or surfactants such fire-fighting foams. In the case of the pollution of groundwater, the effects can sometimes last for decades as renewal times may be very long, and lead to long-term or permanent closure of some water supplies. The pollution of groundwater can also involve the pollution of groundwater-dependent surface water.

The polluting effects of fire-water run-off, related to both surface water and groundwater, are due to direct toxicity of firefighting agent, oxygen depletion or physical aspects such suspended solids covering the river bed or effecting the gills of fish. Both land and aerial application of fire-fighting media shall be considered.

Emission to the Terrestrial Environment

Contamination of the terrestrial environment occurs both from direct emissions from the fire and emissions prompted either by fire-fighting activities, or through interaction with weather, especially wind and rain. Atmospheric releases also affect the terrestrial environment through deposition of pollutants, which can be exacerbated through the effect of weather. Pollutants can be solid or liquid, both being soluble or not in water. Adverse impacts include breakdown of surface structure, deposition of ash and impact on soil microbiota [6]. Nutrient losses can be enhanced by soil leaching and erosion [44]. Vegetation removal can lead to erosion and soil loss by wind and by rain. A major short-term impact is an increase in pH as ashes are generally basic [45] After a forest fire, an increase in soil carbon is observed. New carbon species, mainly in the form of charcoal and other charred materials, enters the soil organic pool, and the organic matter already present in the soil experiments molecular modifications that affects structural and colloidal (condensation, aromaticity and solubility) properties [45]. There are also non-adverse effects such as recycling of nutrients [46] All these points can also favour the development or even invasion of some species that are more or less fire prone, over other ones. The application of fire-fighting chemicals can also have an impact on soil microbiota [6]. Fire can also suspend contaminants sequestered in the soil. An example is the case of wildland fires around Chernobyl in April 2020, which resuspended radionuclides deposited during the 1986 incident.

5.2.3 Contamination Targets

Fire retardant chemicals can be toxic to aquatic wildlife and mammals [47]. Only fire-fighting chemicals that have been tested and met specific requirements with regard to mammalian toxicity shall be used [48, 49].

Short-term fire-fighting chemicals can have an impact on the health of plants [41]. They can increase the effects of fire on cations in the soil [44]. Long-term firefighting chemicals can act as nutrients, having both positive and negative impacts on vegetation [41]. The presence of fire-fighting chemicals can produce greater increases in soil pH than that produced by the fire itself [50].

The predominant impact on exposed human populations is from airborne combustion products. The main pollutants are persistent gases and fine particulate matter. As well as the short-term effects of smoke and gas exposure, prolonged exposure can lead to long-term effects, especially when personal protective equipment are misused by exposed populations such firefighters [33]. Smoke haze from fires can have deleterious effects on the health of distant human populations [51]. It can significantly increase the mortality burden for effected human populations, and has large effects for vulnerable groups, such as seniors [51]. Hazardous household materials can remain present after the fire [52]. The respiratory health impacts identified include chronic respiratory illness people that can experience a worsening in their respiratory symptoms, increase of incidence of mild respiratory symptoms amongst previously healthy individuals and increased doses of anti-inflammatory and bronchodilator medication. Whilst airborne combustion products provide the major impact on health, exposures to contaminated soil and water are also health threats [53].

5.2.4 Contamination Duration

Short-Term Impacts

Short-term environmental impacts from exposure to fires pertain mostly to the local environment, within the fire plume zone and water run-off zone. Short-term environmental impacts from exposure arising from atmospheric releases are principally associated with asphyxiant gases and irritant gases/aerosols as detailed in ISO 13571 [54]. Species of interest are listed in Table 5.1. Most toxic releases are unlikely to be generated in sufficiently high concentrations apart in the local environment to result in immediate incapacitation. High concentrations of substances of acute toxicity in run-off water, draining within a local catchment area, represent worst-case impacts on natural watercourses and associated aquatic habitats and species. Impacts on land, through deposition, from large fires are unlikely to result in short-term impacts. Environmental impact to surface water is typically short-term in case of rapid renewal.

Long-Term Impacts

Long-term environmental impacts are those occurring after the fire over a period of years. They are experienced largely within the local environment, within the fire deposition zone and along impacted surface and groundwater. Long-term

Table 5.1 Pollutants associated with short-term effects in fires

Species	Analytical environmental phase
Halogenated acids (HCl, HBr, HF) Nitrogen oxides (NO, NO_2, N_2O) Sulphur dioxide (SO_2) Volatile Organic compounds (VOCs)	Air
Metals	Air, water, soil
Particulates	Air, water, soil

Table 5.2 Pollutants associated with long-term effects in fires

Species	Analytical environmental phase
Metals	Air, water, soil, sediment
Particulates	Air, water, soil
Perfluorinated compounds (PFCs) Polychlorinated biphenyls (PCBs)	Water, sediment, soil
Polychlorinated dibenzodioxins and furans (PCDD/PCDF)	(Air), water, sediment, soil
Polycyclic aromatic hydrocarbons (PAHs)	Air, water, soil
Volatile organic compounds (VOCs)	Air, water, sediment, soil
Endocrine disruptors	Water, sediment, soil

environmental impacts from emissions within the local environment and within the fire deposition zone are principally associated with persistent organic pollutants and other long-lived toxicants. Pollutants associated with long-term adverse effects of the fire on the environment are listed in Table 5.2. Long-term environmental impacts on surface waters are rare if sediments are not impacted, as there is a rapid exchange of water. Long-term environmental impacts on groundwater can be due to persistent organic pollutants and metals that are able to percolate into the groundwater system. Effects of endocrine disruptors have also to be considered as they could massively impact reproduction of animal species.

5.3 Sampling

5.3.1 Sampling Requirements

The size of the fire and the distribution or spread of fire effluents into the environment determine the need for, and location of, sampling and analysis in the post-fire assessment of the environmental impact. The flow chart shown in Fig. 5.5 facilitates the determination of which samples should be made and which analysis of the samples is to be preferred. Determination of points of deposition and areas impacted from major fires can be defined according to satellite survey of fire plume, as seen on Fig. 5.6. Sampling of the atmosphere may be performed according to ISO 11771 [55]. Samples from water (surface and groundwater) as well as firefighting water run-off can be collected according to ISO 5667-1 [56] and ISO 5667-20 [57]. Sampling of soils can be performed downwind of the fire according to ISO 10381-1 [58]. Emission to air, water and soils from residues can be significant after the fire has been extinguished, i.e. by lixiviation of fire debris by rainfall.

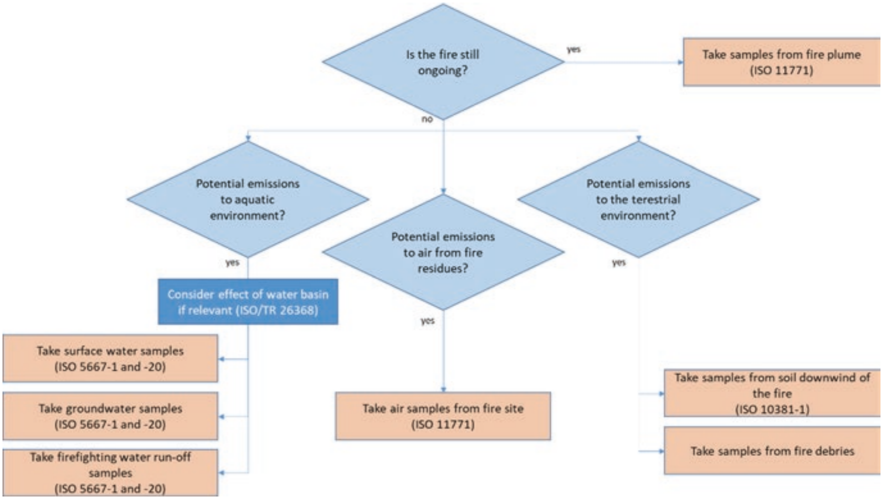

Fig. 5.5 Sampling choices. (Adapted from ISO 26367-1 and ISO 26367-2)

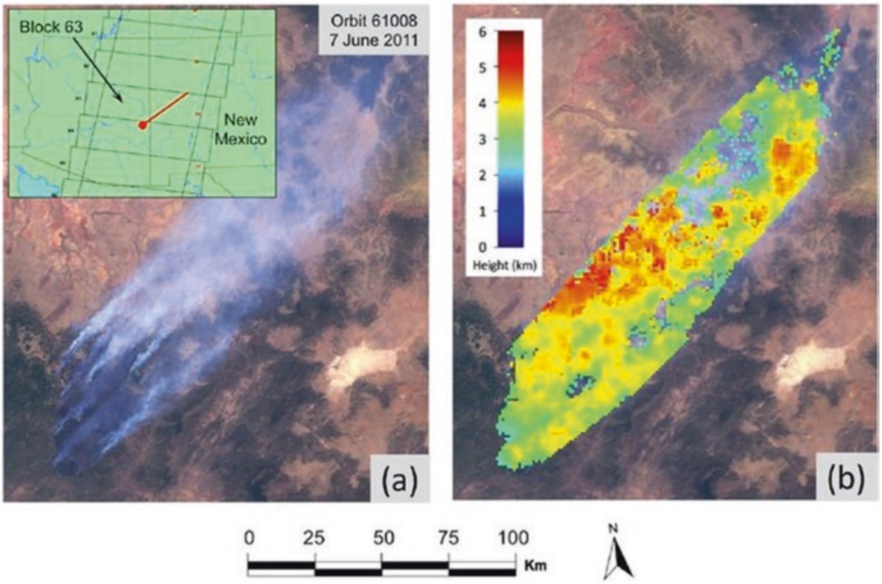

Fig. 5.6 Example of satellite monitoring of plume height from a wildland fire, the Wallow fire in Arizona, June 7th, 2011 [59]

5.3.2 *Apparatus and Techniques*

The equipment and techniques needed to analyse contaminant samples are dependent on the environmental phase (air, surface water, groundwater, sediment, or soil) and on whether the analysis takes place in situ or in a laboratory. They are also dependent on the nature of the chemical compound or specie of interest. Many compounds and species are emitted into multiple phases as fire effluent or are transported across phase boundaries over time.

5.3.3 Emissions to the Air

Sampling of emissions to the air can mainly be made when the fire is on-going. Sampling from the fire plume is extremely difficult. While attempted at times through airborne sampling from a variety of aircraft or drones, it is unclear how such point samples can be related to deposition. Ground-based sampling below the plume can provide more direct input concerning potential deposition. Grab sampling and post-analysis in the laboratory could also provide data on the emissions of toxic and ecotoxic species, including inorganic gases, PAHs and dioxins. This data would not, however, be time-resolved and some losses or concentration changes may occur during transportation.

In general, chemical analysis techniques for gases and vapours require a relatively "clean", stable, cool, sample, free from solid contaminants-conditions rarely arising in fire gases. In presenting such a sample to the analyser from its source in the fire atmosphere, various losses and physical and chemical changes can be anticipated due to the need to cool and filter the sampled gases and to remove condensable species (e.g. water). It is therefore necessary to consider all these factors when sampling and analysing a fire atmosphere. However for some species it must be accepted that accurate analysis will be very difficult - e.g. where sampling times may not be long enough for a representative sample, or where the species may be highly volatile and subject to change over a short period (e.g. Dioxins). The requirement for any fire atmosphere sampling system is to obtain a realistic and representative sample for presentation to the analysis equipment. How far this ideal is achieved depends on a number of factors including the chemical and physical nature of the species for analysis, the temperature, length and material used for the sampling probe and extract tubing (sampling line), sample flow rate, the type and position of particulate filters and type and position of condensate (e.g. water) traps. Fardell and Guillaume [20] give many recommendations on sampling and analysis of fire effluents (Fig. 5.7).

Sampling can be either "extractive" where the samples are removed from the fire for analysis either immediately or at a later stage, or "in-situ" where the measurements of chemical species are made directly at their point of generation, e.g. the space within or immediately surrounding the fire. The choice is often limited by the methodology available for analysis or the risk associated with the sampling. The more commonly used extractive methods usually utilize a sampling probe positioned at the required sampling point, connected to an inert (often heated) tube connected to a pump to conduct samples continuously to the collection or analysis point. Particulate filters and condensate traps are also commonly used in such a

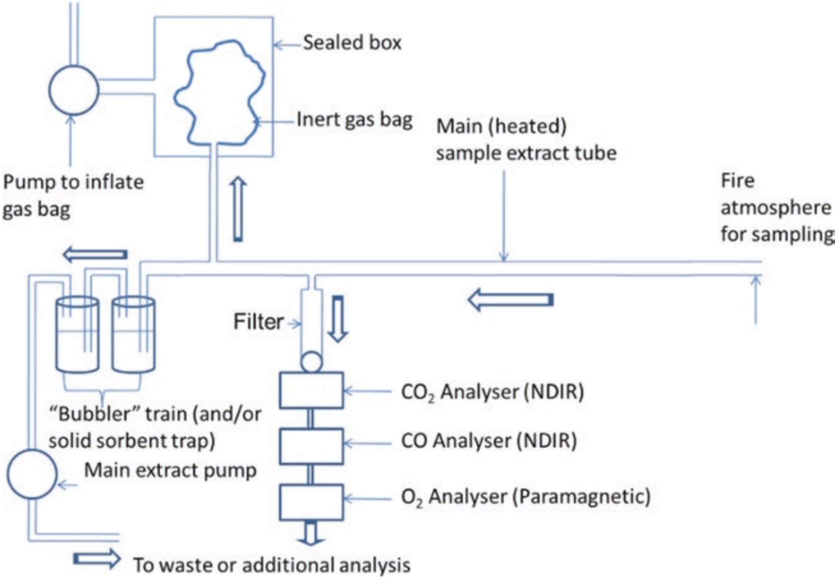

Fig. 5.7 Example of sampling lines for fire atmosphere analysis. (Adapted from Fardell and Guillaume [20])

sampling line. The samples may be analysed immediately or stored for analysis at a later stage. Typical extractive methods include:

- Direct continuous analysis from the sampling line using non-dispersive infrared spectroscopy (NDIR) for CO, CO_2, paramagnetism for O_2, quasi-continuous analysis by Fourier transforms infra-red spectroscopy (FTIR) for a variety of inorganic and organic species.
- Indirect analysis from the sampling line (Gas valve, gas syringe or auto-sampler followed by gas chromatography (GC) or GC/mass spectrometry (GC/MS) for many inorganic and organic species.
- Trapping with a solid adsorbent/absorbent, with chemical reaction e.g. silica with a 2,4-dinitro phenyl hydrazine (DNPH) coating for aldehydes and ketones.
- Trapping by solid, inert, adsorbent e.g. "zeolites" or activated charcoal for polycyclic aromatic compounds (PAH), benzene and other volatile organic compounds (VOC) followed by GC/MS or GC/flame ionisation detector (FID).
- Trapping by solution in the liquid phase e.g. sodium hydroxide (NaOH) solution for HCN, HF, water for HCl, HBr, hydrogen peroxide (H_2O_2) for SO_2, and HCl + DNPH for aldehydes).
- Collection in an inert bag e.g. chemiluminescence for analysis of oxides of nitrogen.

As a general rule the sampling probe and sampling line should both be inert to the species of interest and other compounds present in the effluent, be heated to a temperature sufficient to avoid condensation of any component of the sample, be as short as possible to minimize losses and have a high extract velocity to limit the time delay between sampling point and analysing or trapping system. Fire plume sampling or sample collection procedures shall be as possible conducted in accordance with standardized methods as included in ISO 19701 for sampling for in-situ and laboratory analysis for general fire gases [60], ISO 19702 for sampling for in-situ FTIR analysis [61], ISO 29904 for aerosols [62], ISO 12884 [63] and ISO 16362 [64] for PAH.

Consideration shall be given to the storage of samples not analysed in real time directly from the sampling line. This will arise where samples such as those from a bubbler train, solid sorbent sampling tube, or inert gas bag are to be analysed at some period after collection. Clearly, to reduce losses it is important to store such samples for the minimum possible time and under refrigerated conditions where possible. In some cases, the adsorbing and/or absorbing medium where used, can react with the required species over time and produce a lowering of the measured concentration.

Recently, qualitative and semi-quantitative methods have been used to obtain gas-phase data from external fires, without sampling. These are detailed in second section of paragraph 5.4.2.

5.3.4 Emissions to the Water Environment

Emissions to the aquatic environment can affect both surface and ground water. Transport of fire effluents to the aquatic environment can occur through deposition of airborne contaminants onto soil or water surfaces or from fire water run-off that carries extinguishing media and/or residue from the fire ground. The location and nature of sampling should be based on the knowledge of the pathway by which fire water run-off spreads into the environment. A detailed post incident analysis of pathways should be conducted to reveal all potential or actual routes to receptors.

The exact analysis of the samples should be determined based on the fuel involvement from the fire and their likely breakdown products, as well as on the fire-fighting agent used. Examples of the determinants that can be analysed include PAHs, volatile organic compounds (VOCs), hydrocarbons, ammonia (NH_3), pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD) and suspended solids (SSs). In some cases, toxicity tests and biological monitoring can also be useful.

Liquid samples should be collected in accordance with standardized methods; such methods are detailed in Table 5.3 and include ISO 5667-1 [56] for waster waters, sludge, effluents and bottom deposits. ISO 5667-6 [65] for rivers and streams, ISO 5667-10 [66] for waste water, and ISO 5667-11 [67] for groundwater. ISO 5667-15 [68] provides guidance on procedures for the preservation, handling and storage of samples of sewage and waterworks sludge, suspended matter, saltwater sediments and freshwater sediments, until chemical, physical radiochemical and/or biological examination can take place. It only applies to wet samples. Liquid

Table 5.3 Guidance available for water environment sampling

Reference	Details
ISO 5667-1 [56]	Provides guidance on the design of sampling programmes and sampling techniques for all aspects of sampling of water (including waste waters, sludge, effluents and bottom deposits)
ISO 5667-6 [65]	Provides guidance on the design of sampling programs, sampling techniques and the handling of water samples from rivers and streams for physical and chemical assessment. Not applicable to estuaries, coastal waters, sediment, suspended solids or biota and has limited applicability to microbiological sampling.
ISO 5667-10 [66]	Contains details on the sampling of domestic and industrial waste water, including the design of sampling programs and techniques for collection of samples. Covers all kinds of waste water, but not accidental spillage
ISO 5667-11 [67]	Guidance on necessary considerations when planning groundwater sampling for assessing quality. Includes saturated and unsaturated zones. Not applicable for potability measurements.
ISO 5667-12 [70]	Provides guidance on the sampling of sediments from rivers, streams, lakes and similar standing waters and estuaries. Sampling of industrial and sewage plant sludge and ocean sediments are excluded.

phase samples should be stored and handled in accordance with standardized methods; such methods include the USEPA Method 1669 for metals [69].

Consideration must be given to the storage of samples not analysed in situ but at some period after collection. Clearly, to reduce losses it is important to store such samples for the minimum possible time and under refrigerated conditions where possible. In some cases the adsorbing and/or absorbing medium where used, can react with the required species over time and produce a lowering of the measured concentration.

5.3.5 Emissions to the Terrestrial Environment

Samples of soil in the downwind direction from the fire and in the path of the fire plume should be taken, downwind being used as reference. Design experiment and tools such satellites or plume modelling may help to determine the most appropriate sampling points (example in Fig. 5.8). The exact analysis of the samples should be determined based on the fuel involved as well as based on the fire-fighting agent used. Examples of the determinants that can be analysed for include PAHs, and pH. In some cases, toxicity tests, dioxins and metals analysis can also be useful.

Emissions may occur to the terrestrial environment. Samples of soil and sediment should be taken of soil at least in the downwind direction from the fire in the path of the fire plume. Solid phase sample collection procedures should be conducted in accordance with standardized methods; such methods include ISO 5667-12 [70] for sediments, ISO 10381-1 [58] and ISO 10381-5 [71] for soils, ISO 5667-1 [56] for sludge and effluents and bottom deposits. ISO 10381-1 [58] describes general principles for designing sampling programs for characterizing

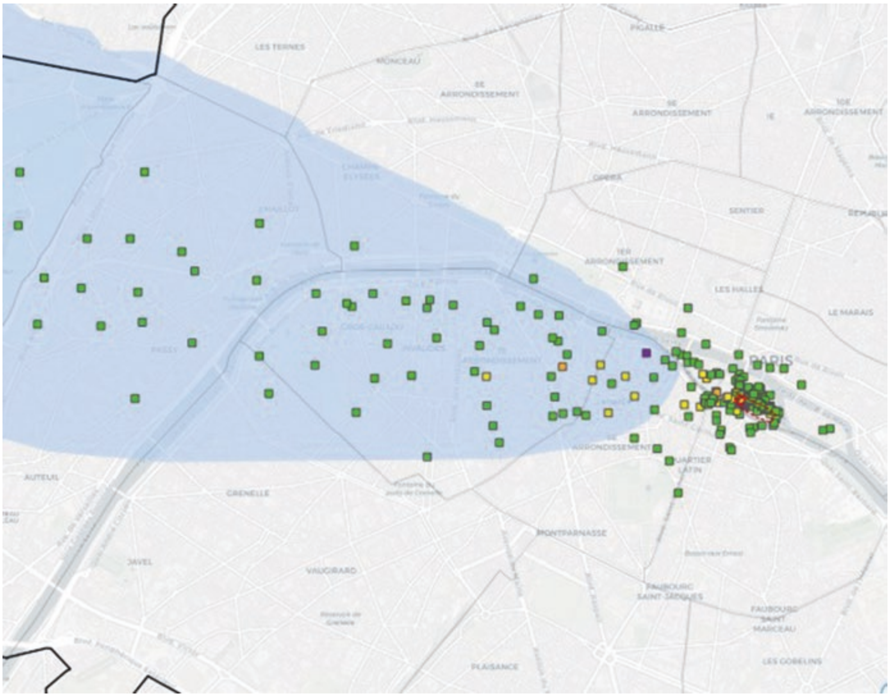

Fig. 5.8 Examples of sampling of lead contamination of soils after Paris Notre-Dame cathedral fire, April 15th, 2019. Green squares mean lead concentration below 5000 µg/m^2. Yellow means between 5000 and 20,000 µg/m^2. Orange means between 20,000 and 50,000 µg/m^2 and purple over 50,000 µg/m^2. The fire perimeter is in red [73]

and controlling soil quality and identifying sources and effects of contamination. It emphasizes sampling locations, instrumentation, sample size, combination of samples, collection methods, and containment, storing, and transport of samples. ISO 10381-5 [71] provides guidance on the procedure for investigating urban and industrial sites where soil contamination is suspected. This is useful when there is a need to establish the environmental quality of a site. It includes guidance on the collection of information for risk assessments and remediation action plans.

Without pre-fire collection, the method and depth of sampling are of primary importance and shall be selected according to the needs. For example, sampling using sample wipes is possible on certain surfaces and immediately after the event. On the contrary, soil coring is necessary for older events. Both sampling techniques, as well as the core depth, significantly affect the results.

Solid samples should be stored and handled using standardized procedures to preserve the sample quality; such methods include ISO 5667-15 [68] and ISO 10381-2 [72].This last standard gives guidance on techniques for taking and storing soil samples. It includes information on equipment and references to groundwater and soil gas sampling. It is not applicable to hard strata. As for air and water samples, consideration must be given to the storage of samples should at some period after collection. Losses of volatile compounds is one of these issues. Soil samples shall be preserve in inert and tight containers such glass flacons and kept in relatively fresh conditions where possible. In all cases, samples may evolve from sampling to analysis and corrections may occur.

5.4 Analysis

5.4.1 Pollution Indicators

Every major change in physical or chemical compositions of water or soils (and in a lesser extend air) should be considered as an indicator of pollution. Pollutants indicators that either typically occur as a result of a large outdoor fire are listed ISO 26367-2 [74] and are also given here. The properties listed in Table 5.4 represent general indicators of environmental pollution, the relevant environmental phase and examples of available techniques in each case. Specific pollutants can be associated with short-term adverse effects and/or long term adverse effects on the environment.

Fire effluents could affect global parameters of waters and soils such biological oxygen demand (BOD) or chemical oxygen demand (COD). These two parameters are essential characteristics of media, and used for potability measurements. Other global parameters of interest include alkalinity, acidity and conductivity of water, all possible indicators of modifications to the phase. Alkalinity is covered by ISO

Table 5.4 Guidance available for pollution indicators analysis

Indicator	Phase	References of the method
Biological oxygen demand (BOD)	Water (surface and groundwater), sediment	ISO 10707 [83] ISO 10708 [84]
Chemical oxygen demand (COD)	Water (surface and groundwater), sediment	ISO 15705 [85]
Alkalinity	Water (surface and groundwater), sediment, soil	ISO 9963-1 [75] ISO 22719 [76]
Acidity – pH	Water (surface and groundwater), sediment, soil	ISO 10523 [77] ISO 10390 [78]
Electrical conductivity	Water (surface and groundwater), sediment, soil	ISO 7888 [79]
	Soil	ISO 11265 [86]
Turbidity	Water (surface and groundwater)	ASTM D 4189 [80]
Hydrocarbon and oil	Water (surface and groundwater), sediment, soil	ASTM D 5412 [81]
Toxicity assessment (direct)	Water (surface and groundwater)	ISO 6341 (Daphnia test) [87]
	Soil	ISO 15952 (Snail test) [88] ISO 17155 [82]

9963-1 [75], which specifies a method for the determination of alkalinity of water, applicable for the analysis of natural and treated water, and waste water. For sea water, ISO 22719 [76] is recommended. Acidity of water is covered in ISO 10523 [77], describing a method for determining the pH value in rain, drinking and mineral waters, bathing waters, surface and ground waters, as well as municipal and industrial waste waters, and liquid sludge, within the range pH 2 to pH 12. Soils are covered in ISO 10390 [78]. Conductivity is covered in ISO 7888 [79].

Turbidity is also a parameter of first importance to describe how fire plume deposition and fire water run off could affect the surface water. ASTM D 4189 [80] may be used for the determination of the silt density index (SDI) of water. This test method can be used to indicate the quantity of particulate matter in water and is applicable to relatively low turbidity waters (1.0 NTU) such as well water, filtered water, or clarified effluent samples. Since the size, shape, and nature of particulate matter in water may vary, this test method is not an absolute measurement of the quantity of particulate matter.

PAH and oil residues in water are covered by methods such as ASTM D 5412 [81]. This test method covers a mean for quantifying or characterizing total polycyclic aromatic hydrocarbons (PAHs) by fluorescence spectroscopy (Fl) for waterborne samples. The characterization step is for finding an appropriate calibration standard with similar emission and synchronous fluorescence spectra.

There are also toxicity test methods (direct methods), which evaluate the global impact on target species, whatever the pollutant is. These methods are powerful, as they do not request identification of the origins of contamination. However, it is sometimes difficult to relate the observed effect to the suspected cause. For example, significant mortality in the target species may be related to factors other than those thought to be due to fire effluents, making interpretation difficult. Some analysis techniques address eco-toxicity in a general sense, such as ISO 17155 [82] for soils. These techniques measure the effects of the contamination on the environment rather than concentrations of specific chemicals. Daphnia tests are used for water; trout and Salmonidae are also good indicators of water pollution, supposing a preexisting sufficient population. Juvenile snails or earthworms are commonly used to characterize soil pollution.

5.4.2 Analytical Techniques Suitable for Air

Ground and Laboratory Analysis

Analysis of air contamination should be made using standardized in-situ measurement methods or by laboratory analysis of collected air samples. Table 5.5 gives an overview of main test methods. Fardell and Guillaume [20, 60, 61] and ISO 19702 [61] provide more details on several analytical techniques.

General atmospheric pollutants of interest include CO, CO_2, hydrogen halides, sulphur dioxide, nitric oxides. Ozone could be interesting too at large distances, as

Table 5.5 Guidance available for atmospheric analyses of pollutants from fires

Species	Reference method
General atmospheric pollutants	ISO 19701 [60] ISO 19702 [61]
Volatile organic compounds (VOC)	ISO 19701 [60] ISO 19702 [61]
Polycyclic aromatic hydrocarbons (PAH)	ISO 12884 [63] ISO 16362 [64]
Polychlorinated dibenzodioxins and furans (PCDD/PCDF)	EN 1948-3 [90] ISO 16000-14 [93]
Metals	ISO 19701 [60]

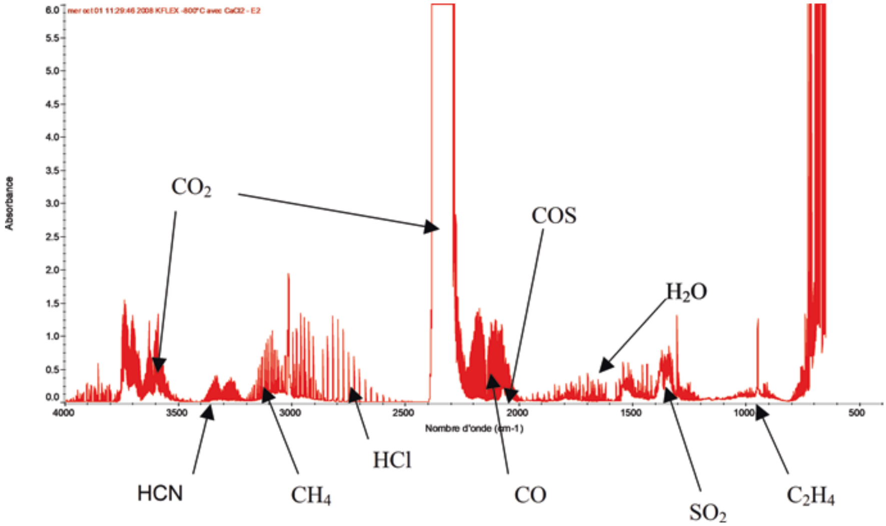

Fig. 5.9 Example of FTIR spectra according to ISO 19702, for a complex fire effluent from fuel containing nitrogen, chloride and sulphur

a secondary generated pollutant following atmospheric reactions. These species can be all measured with a large number of techniques, including the appropriate methods given in ISO 19701 [60], ISO 19702 [61] (Fig. 5.9), and ASTM E 800 [89]. ASTM E 800 is a tool for the selection of a suitable technique from alternatives to quantify gaseous fire effluent, but it does not provide enough information for the setup and use of a specific procedure. Several other methods are available from airborne analysis standards from ISO TC 146, but they have not necessary being evaluated on matrixes such fire effluents.

ISO 12884 [63] specifies sampling, clean-up and analysis procedures for the determination of polycyclic aromatic hydrocarbons (PAH) in ambient air. It is designed to collect both gas-phase and particulate-phase PAH and to determine them collectively. Samples are collected on sorbent-backed filters followed by gas chromatographic/mass spectrometric analyses. ISO 16362 [64] specifies a sampling and analysis procedure for PAH that involves collection from air onto a filter followed by analysis using high performance liquid chromatography usually with fluorescence detector (FLD).

Standardized methods available for dioxins and furans have been developed for constant emission sources and then are difficult to apply in fire-related environment. The most important methods for air phase are those developed for constant emission according to EN 1948-3 [90] or for interior air according to ISO 16000 parts 12 to 14 [91–93], generally using gas chromatography coupled with isotopic dilution. However, although dioxin concentrations in the atmosphere are often not able to generate dangerous conditions for populations, contamination of soil, water and ultimately food is more critical, which is why these other phases of analysis are more important for such species than atmosphere.

Particulates and aerosols are of first importance in fire plume and sometimes far from fire. Parameters of interest are their total concentration, their optical properties (often represented by their extinction coefficient), their size distribution (often represented by their aerodynamic diameter distribution), the morphology of the particles and their chemical composition. Depending on the objective and sampling possibilities, there are many different techniques applicable. These analytical methods are described in ISO 29904 [62]. Some methods are also used to monitor air quality and air pollution stations may be a good tool to assess ground concentration of aerosols, often through PM_{10} and $PM_{2.5}$ values. In air quality measurements, the reference method used for the sampling and measurement of PM_{10} and $PM_{2.5}$ is that described in EN 12341 [94].

Long-Distance Atmospheric Measurements

LIDAR and infrared spectroscopy (open field) have been used for the analysis of fire gases and provide valuable semi-quantitative data [95]. LIDAR consists of emitting laser pulses into the atmosphere and analysing the backscattered radiation at the same wavelength using a telescope, using the absorption and scattering properties of the laser light by particles and molecules. Differential absorption LIDAR (Differential absorption Lidar, DIAL) is the most widely used. The laser source emits simultaneously in the atmosphere at two wavelengths, one is strongly absorbed by the gas considered and the other is weakly absorbed. By applying the Beer-Lambert law, the concentration of the desired gas as a function of distance is determined by difference. LIDAR is able to provide quantitative data on particles through long-distance light-scattering coefficients along the fire plume. In addition to airborne particles, LIDAR can also detect, for example, the following gases: benzene, toluene, xylene, styrene, ozone, sulphur dioxide, carbon monoxide, nitric oxides.

More recently, terahertz analysis has been performed on fire plumes and has been shown as valuable for gases such HCN [96, 97]. Validation has been made compared to sampling methods in laboratory. The results shown the feasibility of portable systems used as gas sensors in fire disasters.

In addition to being devastating for local ecosystems and economies, wildfires significantly alter air quality, sometimes on regional to hemispheric scales, and are an important component of the climate system. Satellite analysis is suitable for such purpose. Instruments such Infrared Atmospheric Sounding Interferometer (IASI) on board METOP-A satellite has demonstrated the possibility to assess carbon monoxide (CO) during extreme fire events several hundred kilometres far from the fire, giving quantitative results of the concentration of atmosphere columns [98]. Authors presented also feasibility on Indonesia wildland fires for CO, CO_2, CH_4, PM_{10}, $PM_{2.5}$ and black carbon, using MODIS Aqua satellite, and compared to field measurements [99].

5.4.3 Analytical Techniques Suitable for Water Run-Off

Analytical methods used for water run-off are listed in Table 5.6. Currently, the most sensitive and practical means for measuring low concentrations of trace elements are by graphite furnace atomic absorption spectrophotometry as proposed in ASTM D3919 [100], by direct current plasma atomic emission spectroscopy (DCP) as covered by ASTM D4190 [101] or by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) according to ASTM D5673 [102].

Cyanides in water environment are often a consequence of water run-off. Sampling, preservation and mitigation of interferences for water samples intended to be analysed for cyanides is covered in ASTM D7365 [103]. As speciation is of first importance with cyanides, analysis of free cyanide (HCN and CN^-) in natural water, saline waters, and wastewater effluent is covered by ASTM D6888 [104] by gas diffusion separation and amperometric detection. ASTM D7284 [105] is used for free cyanides that are free and strong-metal-cyanide complexes that dissociate and release free cyanide when refluxed under strongly acidic conditions.

Metals are frequent contaminants to water from massive fires, as released from ancient construction products soils, mines or vegetation, which can concentrate specific metals. ISO 11885 [106] specifies a method for the determination of dissolved elements, elements bound to particles ("particulate") and total content of elements in different types of water (e.g. ground, surface, raw, potable and waste water) for the following elements: aluminium, antimony, arsenic, barium, beryllium, bismuth, boron, cadmium, calcium, chromium, cobalt, copper, gallium, indium, iron, lead,

Table 5.6 Guidance available for water analyses of pollutants from fires

Species	Reference method
Cyanides (free and metal-complexed)	ASTM D6888 [104] ASTM D7284 [105]
Metals and elements	ISO 11885 [106]
Polycyclic aromatic hydrocarbons (PAH)	ASTM D5412 [81]
Volatile organic compounds (VOC)	ISO 15680 [111] ISO 20595 [112]
Polychlorinated biphenyls (PCB) Perfluorinated compounds (PFC)	ISO 6468 [113]
Polychlorinated dibenzodioxins and furans (PCDD/PCDF)	ISO 18073 [114]

lithium, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, selenium, silicon, silver, sodium, strontium, sulphur, tin, titanium, tungsten, vanadium, zinc and zirconium. Methods specific of several metals are also described, such ASTM D2972 [107] for arsenic in water through the photometric and atomic absorption method. ASTM D3558 [108] covers dissolved and total recoverable cobalt in water by atomic absorption spectrophotometry. ASTM D3559 [109] concerns dissolved and total recoverable lead in water by atomic-absorption spectrophotometry and differential pulse anodic stripping voltammetry. ASTM D3859 [110] covers the dominant species of selenium reportedly found in most natural and wastewaters, including selenities, selenates, and organo-selenium compounds.

ASTM D5412 [81] covers a means for quantifying or characterizing total polycyclic aromatic hydrocarbons (PAHs) by fluorescence spectroscopy (Fl) for waterborne samples. The characterization step is for the purpose of finding an appropriate calibration standard with similar emission and synchronous fluorescence spectra.

Volatile organic compounds in water may be analysed by Gas-chromatography using purge-and-trap and thermal desorption according to ISO 15680 [111]. The most highly volatile species could be analysed using gas chromatography and mass spectrometry using a static headspace technique (HS-GC-MS) according to ISO 20595 [112].

Polychlorinated biphenyls (PCB) or perfluorinated compounds (PFC) in water can be analysed using gas chromatography after liquid-liquid extraction according to ISO 6468 [113]. This method is adapted to water containing suspended solids. For dioxins and furans, as quantities may be very low, method using isotope dilution from ISO 18073 [114] is recommended.

5.4.4 Analytical Techniques Suitable for Soils

Contamination of soils from fire effluents is probably the most important pathway in terms of long-term contamination. Analytical techniques listed in Table 5.7 are applicable for soils include sediment, soil, and fire debris. ISO 22892 [115] may be

Table 5.7 Guidance available for soil analyses of pollutants from fires

Species	Reference method
Metals and elements	ISO 11047 [116]
Polycyclic aromatic hydrocarbons (PAH)	ISO 18287 [117] ISO 13859 [118]
Hydrocarbons	ISO 16703 [119]
Volatile organic compounds (VOC)	ISO 15009 [120]
Polychlorinated biphenyls (PCB)	ISO 10382 [121] ISO 13876 [122]
Perfluorinated compounds (PFC)	ISO 22155 [123]
Polychlorinated dibenzodioxins and furans (PCDD/PCDF)	ISO 13914 [124]
Endocrine disruptors (EDC)	ISO/TS 13907 [125] ISO 13913 [126]

used as a guidance for the identification of target compounds that could be extracted and analysed through mass spectrometry. A large part of compounds of interest, including metals, are analysed through ISO 11047 [116] using atomic absorption or by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS).

Polycyclic aromatic hydrocarbons (PAH) are analysed through ISO 18287 [117] and ISO 13859 [118], respectively through GC-MS and HPLC techniques. Hydrocarbons in the range C10-C40 are covered by ISO 16703 [119]. Volatile aromatic hydrocarbons, naphthalene and volatile halogenated hydrocarbons are covered in ISO 15009 [120] through purge-and-trap method with thermal desorption.

Polychlorinated biphenyls (PCB) analysis in soils is covered in ISO 10382 [121] and ISO 13876 [122]. Perfluorinated compounds (PFC) are analysed through ISO 22155 [123]. ISO 13914 [124] specifies a method for quantitative determination of 17 2,3,7,8-chlorine substituted dibenzo-p-dioxins and dibenzofurans and dioxin-like polychlorinated biphenyls in sludge, treated biowaste, and soil using liquid column chromatographic clean-up methods and GC/HRMS.

Endocrine disruptors (EDC) in soils are of first interest. ISO/TS 13907 [125] describes the gas chromatography with mass selective detection (GC-MS) method to analyze nonylphenols (NP) and nonylphenol-mono- and diethoxylates in soils. ISO 13913 [126] covers phthalates using capillary gas chromatography with mass spectrometric detection.

5.5 Metrology of Measurement

5.5.1 Range of Analysis – Limits of Detection and Quantification

Data on the environmental impact of fire effluents may be required from a variety of sources by the environmentalist and for a variety of end uses (e.g. calculations to estimate health hazards to local populations). It is important to ensure that the sampling and analysis procedures and methodologies employed should reflect the required limits of concentration, quantification, accuracy and precision of the end use of the results. Thus, there is probably little value in employing a range of highly sophisticated (and possibly expensive) instrumentation to determine the concentrations of a large number of species to a high degree of accuracy and precision when the data will be used for estimations of hazard using far less sophisticated calculations with relatively wide "error bands". In presenting chemical analysis results therefore, it is clearly of importance to be able to state for a particular sampling and analysis regime, the limits of detection (LoD) and limits of quantification (LoQ) for specific compounds. ISO 12828-1 [127] covers these two aspects within fire effluents and is especially adapted to airborne effluents in fire plume. The range of the method is also of first importance. It is defined as the values between where a quantitative analysis is feasible and can be achieved in practice. Its lower limit is mainly characterized by the limits of detection and quantification for the particular species with the chosen method.

5.5.2 *Accuracy, Repeatability and Reproducibility*

It is necessary to choose a methodology, which has been proven to be repeatable and reproducible and not overly sophisticated and/or expensive for the required particular end use. This includes uncertainties estimates.

Accuracy is defined as the difference between the real value and the true value, where this last quantity is never really known in the field of fire emissions. Trueness, although a key parameter, is difficult to measure in fire effluent analysis. Repeatability is the coherence between results obtained on a given measurement in one laboratory, by one operator and one piece of equipment. Reproducibility is the coherence between results obtained in various laboratories for the same published method. For both repeatability and reproducibility, it is also essential to separate the processes involved in the chemical analysis with the processes involved in the fire event itself. As uncontrolled fires are by nature supposed to be unique, only the first cited component from the method may be evaluated. So, these notions are generally verified on small scale experiments. A proper analytical method shall have been evaluated in the range and matrix similar to those for the expected analysis. Effects of sampling are difficult to assess in such conditions.

ISO 12828-2 [128] presents examples of complete method validation for fire effluents, at intralaboratory level. ISO/TS 12828-3 [129] provides tools to interpret interlaboratory trials within fire effluents.

ISO 20988 [130] provides more general guidelines for estimating measurement uncertainty and may be used for generic airborne pollutants. Water analyses uncertainties are described in ISO 11352 [131].

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Chapter 6
Fires in Enclosures

Robert McNamee and Markus Sandvik

6.1 Introduction

The occurrence of fires in enclosures is probably as old as the combined use of fire and enclosures. The environmental effects of fires in enclosures, are in several aspects, different compared the environmental impact of fires out in the open. The fire dynamics are altered by the enclosure and the enclosure itself contributes in a variety of ways to the environmental impact of the fire event. This chapter will explore the environmental impact of enclosure fires. In this context we will also consider the potential environmental benefits of avoiding or limiting an enclosure fire.

In recent years, a significant amount of focus and effort has been spent on improving the societal sustainability, in part by a reduction of carbon emissions. In the case of buildings or enclosures this reduction can be achieved through judicious choices which can be made in different parts of the building life cycle, for example:

(i) Construction phase: optimization of the materials and building systems used and the methods of construction;
(ii) Use phase: Improvements in energy efficiency and design for flexibility can improve the ability to repurpose an existing building to improve building longevity; and
(iii) End-of-life phase: design for demolition can improve recyclability of materials and products.

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In the construction phase, significant work has been done on the development of green buildings and green building attributes, although the fire implications of these construction choices have only recently come into focus [1–3]. In the use phase, questions of energy efficiency, renewable energy sources and the ability of the building to be repurposed over time without large rebuilding are examples of important factors to consider. Finally, in the end-of-life phase, it is important to consider recycling costs and the environmental impact of replacing the buildings due to, e.g. a fire. In a traditional investigation of the environmental impact of a building, the event of fire incidents is not included in the overall analysis of the environmental impact, but methods to include fire in the life cycle analysis have been under development for almost 20 years although they are not yet mainstream [4–6]. A more detailed description of this type of tools can be found in Chap. 9 – Tools and Techniques for impact analysis. The main focus of the present chapter is effects more directly related to the enclosure.

6.2 The Environmental Context of Enclosure Fires

There are several parameters that influence the environmental impact of fires in enclosures which relate to the life cycle of the building as identified in the introduction. To give the full picture of the influencing parameters it is important to reach beyond the initial release of smoke and the related contamination of air. As an example, when assessing the global warming potential of fires in enclosures, in terms of carbon dioxide equivalents or carbon footprint, we will need to consider:

(i) Fire dynamics (to understand the size of the fire and associated emissions)
(ii) Incident response (to understand the impact of response tactics)
(iii) Post-fire remediation (to understand the impact of replacement of material and structures, and restoration of the fire site).

In recent years, factors such as the environmental impact from replacement of the suppressant and, to a certain degree, factors related to the intervention made by the fire and rescue service involved in the response to a fire event, have been recognised as influencing the environmental impact of fires in terms of the carbon dioxide equivalents [7, 8]. Similarly, Amon et al. [7] found that remediation activities, such as handling of contaminated material and soil, can lead to substantial environmental costs expressed as carbon dioxide equivalents. Emissions in terms of carbon dioxide equivalents can be related to the global warming potential caused directly or indirectly by the fire event.

Some factors influencing the environmental impact, both in terms of global warming and contamination of air, water and soil, from fires in enclosures, are summarized in Fig. 6.1.

The type and amount of fuel in an enclosure influences the amount of combustion products and the damage caused by the fire, in a more global perspective the size of compartmentation is directly influencing these factors. Further, the

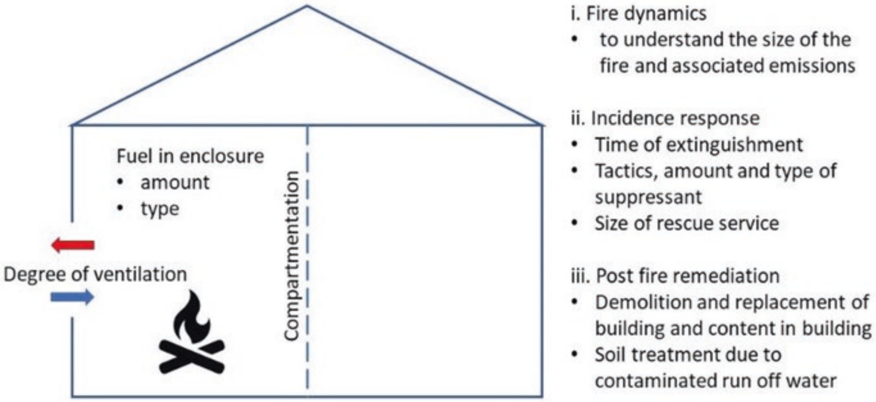


Fig. 6.1 Factors influencing the environmental impact from fires in enclosures

ventilation conditions influence the composition of the combustion products, where under-ventilated fires in general give rises to more products of incomplete combustion which are the most ecotoxic gases. Finally, the response time and tactics during extinguishment are also important in relation to the production of fire emissions. Rapid response times can reduce the extent of the fire, by stopping the fire before all available fuel is consumed. The response time and tactics also relate directly to the amounts of contaminated run off water produced, with or without additives, that can potentially pollute the ground water, soil and the community water handling system. Additionally, the size of the rescue service operation (including vehicles involved) influences the environmental impact.

Further, factors not directly related to the combustion process are included in Fig. 6.1. The demolition, replacement of the building and the contents inside the building. In some cases, remediation of the soil around the enclosure is necessary which will also have an environmental impact which needs to be considered. In several cases, it has been found that the environmental cost of rebuilding the structures and replacing the contents in the building are significant [2, 7, 9].

There are, however, other environmental effects from fires in enclosures, beyond their global warming potential. Toxic compounds with both short- and long-term effects are released in an enclosure fire, influencing both the local environment in the immediate vicinity of the fire with the potential to spread in the biosphere. The influences on the environment can be divided in local, regional, national and global effects depending on the character of the spread [10]:

- **Local effects:** The spread of contaminated water from fire interventions can be a threat to the local environment in the water run off zone [11, 12]. In this context, the choice of suppression media, including additives in the suppression water, is an important factor to include when an analysis of the environmental impact is to be made [13, 14]. Such emissions can cause soil or water contamination. Further,

direct contamination from the fire plume and deposition of heavy particulates falling from the plume may have an impact on the local environment.
- **National Effects:** When a river is contaminated due to a fire event, the environmental impacts may have implications on a national level, e.g. contamination of the Rhine river after the Sandoz fire in Basel, see more details regarding this fire in Chap. 2.
- **Global effects:** When greenhouse gases are released from fire or released indirectly from actions related to the fire, their influence is not restricted to local or national effects. Such emissions give a contribution to the global warming by influencing the energy balance for globally.

In Chap. 2 of this handbook an overview of historically significant fires can be found, but the question of environmental effects from fires in enclosures is larger than specific events. Based on fire statistics, estimates on total CO_2 emissions from for all fires in different categories can be made [15]. Using this information, and complementary information on the carbon dioxide emissions from rebuilding different enclosures based on LCA data, it is possible to make informed decisions concerning fire protection measures taken to obtain the lowest overall environmental impact. In the case of using sprinklers this optimization has been done in several studies [2, 7, 16–18].

In the remainder of this chapter, fire dynamics, incidence response and post-fire remediation will be examined in more detail. Further, a case study of the impact of installation of sprinklers in schools will be given. Finally, some research into the environmental impact of fires including industrial chemicals will be summarized.

6.3 Fire Dynamics

6.3.1 Influence from the Enclosure on Fire Growth

Usually, fires in enclosures starts when something is ignited followed by some type of fire growth. The potential of this initial fire to develop into a larger fire can be influenced in two ways by the enclosure. First there is a geometrical effect making flame heights close to walls much higher than a free burning flame with the same heat release rate. This growth in flame height is because the entrainment of oxygen to the flame zone is limited on one side by the wall, more fuel will be transported further up from the fuel source before it ignites. Based on the same physics, flames in the corners of a room are even higher than flames close to walls. The second effect the enclosure has on flames is that the material in the wall will influence the fire development, either due to different thermal properties of the wall leading to more or less cooling of the flame and whether the wall material is combustible and can interact in the spread of flame thereby contributing to the heat release of the fire. Non-combustible linings limit the potential for fire growth and the related environmental effects from fires in enclosures.

An example of how combustible wall linings are considered in regulations is the European classification system, where one of the tests required is the Single Burning Item (SBI) test, EN 13823 [19]. This SBI test is designed to evaluate the potential of the material to contribute to a fully developed fire in a larger reference enclosure, based on a room corner setup [20]. The actual SBI test is an intermediate scale test setup where two test samples, 0.5 × 1.5 m^2 and 1 × 1.5 m^2 are mounted in a corner configuration exposed to a gas flame as an ignition source as shown in Fig. 6.2. The shape of the heat release curve is then the main evaluation parameter evaluated by the FIGRA (Fire Growth Rate) value according to Fig. 6.3. A high slope indicates a material that in the reference scenario will proceed rapidly to a fully developed fire. The correlation between the SBI test and the reference scenario is empirical and are described more in detail by Sundström [21].

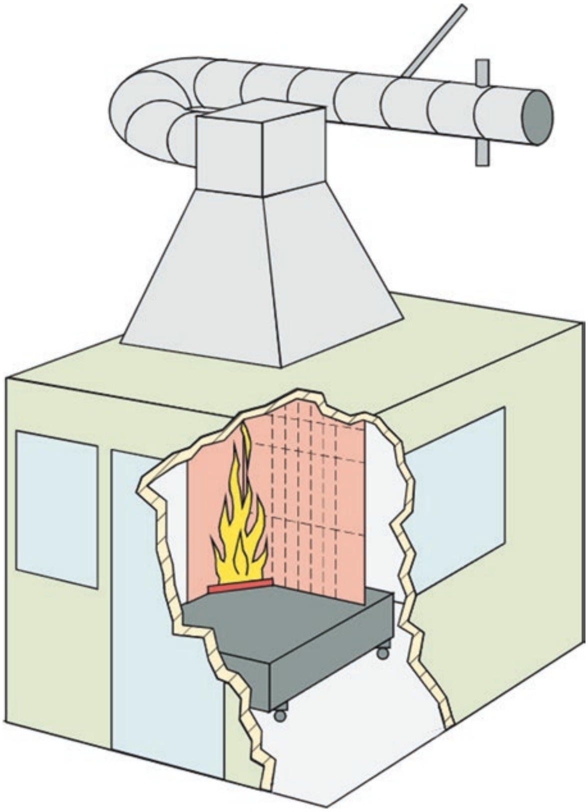


Fig. 6.2 The SBI (Single Burning Item setup). (Reprinted with permission of RISE Research Institutes of Sweden)

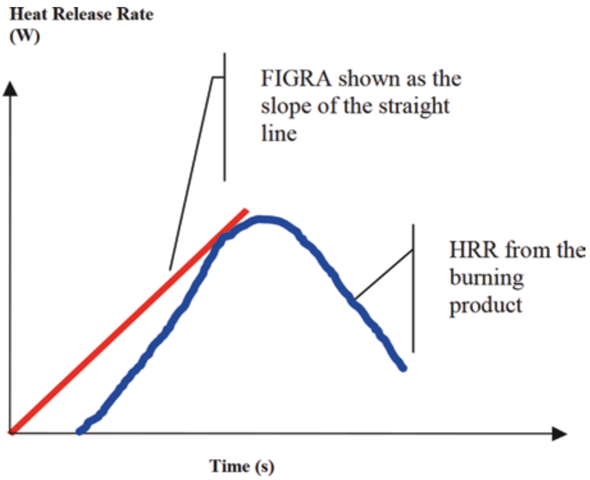


Fig. 6.3 FIGRA (Fire Growth RAte) value for evaluation of potential for fire growth according to the European system. (Reprinted with permission from [21])

6.3.2 Fully Developed Fires

Let us begin by defining an enclosure as a boundary separating a volume (the inside of the enclosure) from its surroundings. The enclosure itself can also be separated in several sub-enclosures, commonly called compartments. There are two main factors determining the fire dynamics in a fully developed fire in an enclosure:

(i) The compartment size and fire load
(ii) Combustion conditions in the compartment

This section will discuss these two parameters.

Compartment Size and Fire Loads

When the small fire develops to a larger fire involving the whole room the enclosure can act as a boundary for the fire. If the enclosure or sub-enclosures (termed compartments) have a certain resistance to spread the fire further, and/or maintain its load bearing capacity for a certain time, a building element in the enclosure is said to have a certain *fire resistance*. The most common classes to rate the fire resistance is “REI” where: *R* is the load bearing capacity during fire exposure, *E* is the integrity of the element, and *I* is the ability to thermally insulate the fire on one side of the element from an enclosure on the other side of the element.

The definition of the “fire” in fire resistance ratings is usually the so-called standard fire curve, being a prescribed temperature-time curve representing the fire scenario that the element is exposed to. From the beginning, the concept of the standard fire curve defined about a century ago, was based on limited experience of fire dynamics in enclosures [22]. Due to this lack of knowledge regarding the coupling between real fires and fire resistance, as defined by exposures to the standard fire curve of different duration, Ingberg [23] performed a series of 14 burnout tests. These tests were performed in two, one story test buildings, representing two different compartment sizes. The openings in the building were covered with pivoted shutters that were regulated to give the most severe fire conditions in the buildings. No detailed information has been preserved regarding how the opening factor of the enclosure was changed during the experiments, other than that it was optimized to increase the fire severity. The results from the series of burnout tests were used to create tables for converting the amount of combustible content per square meter floor area to an equivalent fire resistance time with the standard temperature-time exposure.

The conversion to the standard fire curve was conducted using an equal area assumption, i e. the area under a measured temperature curve during the experiment corresponds to the area under the standard fire curve above a baseline of 150 or 300 degrees. Ingberg was well aware of the fact that this equal area concept was an approximation, but confessed in his paper to “have so far found no better measure of comparison that can be conveniently applied” [23].

This concept of having a reference fire exposure, the standard fire curve for fire resistance ratings, has been questioned on many occasions during the last half century [24–29]. Despite these apparent and recurring concerns, the concept of fire resistance ratings is ubiquitous on the market, in part due to the simplicity of the approach and in part due to the fact that despite voiced concerns no workable alternative has been put forward. An alternative to designing enclosures, based on testing and classification using the standard fire exposure, is to calculate the fire resistance based on material models such as the ones found in the Eurocodes. When doing this, the fire resistance can also be calculated for other thermal exposures than the standard fire curve. But this type of calculations is by its very nature only suitable for relatively simple structures, i e. it is not suitable for complex components such as doors, window assemblies or other components including several materials or/and geometrically complex cross-sections.

By designing the external and internal walls with different fire resistance ratings, so called fire cells are created. A fire cell is a compartment specifically designed to keep the fire inside the enclosure or sub-enclosure where it begins. To make this compartmentation effective, all building components breaking the boundaries of the fire cell require a commiserate fire resistance rating, to ensure that the overall fire rating of the enclosure is not compromised by installation of the building component. In practice this means that, e.g. doors, cable penetrations, ventilation system and other building components that cross enclosure boundaries must be fire rated in a similar way to the fire boundary itself. Openings need to be able to close in the case of a fire, leading to the installation of door closure mechanisms and fire blockers in ventilation of cable openings. The choice of the size and nature of the components for the compartmentation has a direct influence on the total carbon footprint of the building in the construction phase.

Given that we now have a building, it has a specific fire rating, what happens if there is a fire despite our best efforts to avoid its ignition and spread? To understand what happens when an ignition is allowed to grow unchecked and develop to a fully developed fire, the size of the compartment determines in theory how large the area influenced by the fire will be. In this context, it will be important to understand whether the fire is confined to a single compartment or spreads to include several compartments or fire cells.

An important measure is also the fire load present in the compartments/fire cells [9]. In fire safety engineering, the fire load is one of the measures used to determine the characteristics of the fire. This fire load is a combination of variable and permanent fixed combustible materials [30]. There is a link between the fire load (available fuel), and the environmental effect of the fire, if it is not extinguished before burnout by the occupant, a sprinkler system, or the fire and rescue service. Further, when focusing on direct and indirect environmental effects of fires, it is important to also consider the environmental cost of different compartment sizes, e.g. should a space be divided into a single or multiple compartments. When comparing scenarios for a 2500 m^2 Swedish school building, built in a single storey, it was found that a division in two fire cells instead on one was favourable from an environmental point of view [2]. The study was based on an analysis of statistics from fires and environmental costs from adding an extra fire wall.

Combustion Conditions

There are two main differences between a free burning fire and a fire in an enclosure. Firstly, the enclosure may change the thermal exchange between the fire and the surroundings, and secondly, the enclosure may alter the availability of oxygen to the fire (also called the ventilation conditions). How much these effects influence the fire behaviour depends on the size, geometrical configuration, and thermal properties of the enclosure as well as on the actual size of the fire.

The ventilation and mode of burning are key factors influencing the production of emissions from the fire. Modes of burning can be divided in three main categories: smouldering, free burning fires, and ventilation limited or vitiated fires [31].

- During smouldering fires, the oxidation process take place in the solid phase and compared with flaming fires, the burning process is slow [32].
- The energy release from free burning fires is dependent on the type of fuel, amount of fuel and how the fuel is distributed geometrically (in the 3D space).
- The burning rate of the fuel in a fully developed fire where the ventilation limits the combustion process is strongly dependent on the shape and size of the ventilation openings. Fundamental research in this area was presented by Kawagoe [33] and summarized by Thomas [34].

A rough estimate of the burning rate of the fuel inside enclosures during ventilation-controlled fires can be made with Eq. 6.1 [35]:

$$HRR = 1.518^{*} A_0 \sqrt{H_o} \tag{6.1}$$

where *HRRHRR* is the heat release rate (MW), A_0A_0 is the opening area (m^2), and H_o is the average opening height (m). More detailed descriptions of fire dynamics in enclosures have been published in different chapters in the SFPE handbook [36] and in a number of seminal textbooks [35, 37, 38] and even in Chap. 3 of this handbook since the seminal work by Kawagoe.Not only the burning rate is dependent of the ventilations conditions. The specific chemical species released from a fire event in an enclosure are determined by the ventilation conditions within the enclosure [12]. The generation of carbon monoxide (CO), soot and unburnt hydrocarbons are considerably greater during conditions with limited ventilation compared with those exhibiting well-ventilated combustion [39]. Indeed, during smouldering conditions where ventilation is typically very limited, very high levels of CO can be created [32].

Taking the production of CO as an indicator of incomplete combustion, one can follow the release of CO as a function of the ventilation conditions as shown in Fig. 6.4. In this figure, values of the equivalence ration greater than 1 indicate conditions of limited ventilation. These conditions give rise to substantially higher production of CO from the fire.

During ventilation-controlled conditions the smoke and the ash includes highly toxic compounds due to the incomplete combustion. Depending on the material that is burning and the burning conditions, hydrogen cyanide (HCN) and elevated levels of carbon dioxide (CO_2) may also be created [12]. Other compounds cause sensory

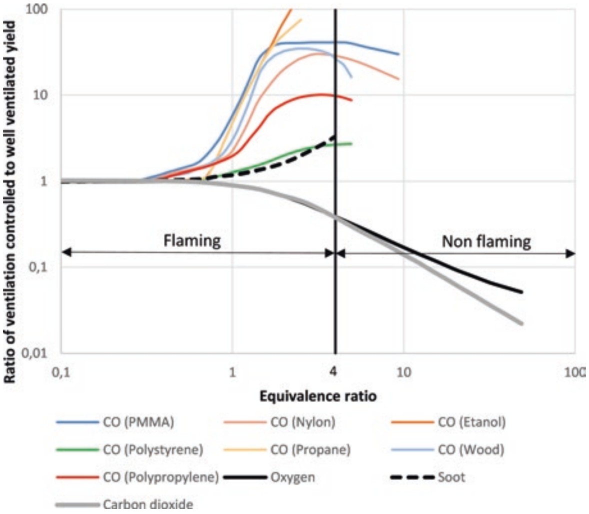


Fig. 6.4 Yields versus combustion equivalence ratio (redrawn from [40]). Note that an equivalence ratio < 1 is well ventilated while an equivalence ratio > 1 indicates limited ventilation

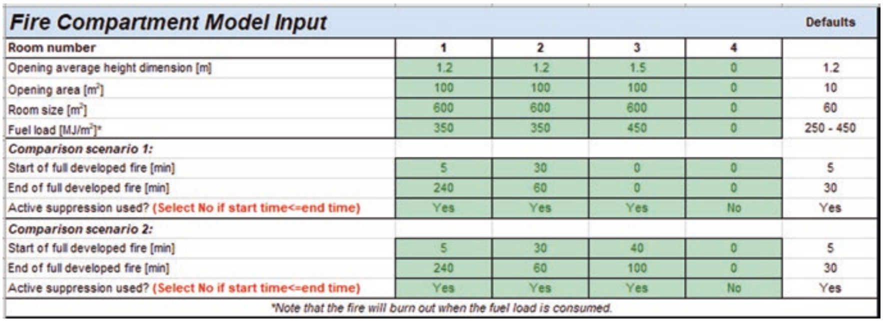
irritation to eyes and upper respiratory tracts, such as acid gases, and a variety of organic compounds.

6.4 Incident Response to Fires in Enclosures

An important factor influencing the environmental impact from a fire is the firefighting tactics. Firefighting operations can include changes to the ventilation conditions of the fire, limitation of the spread of fire or extinguishment of the fire. The choice of tactics influences both the direct environmental effect from release of toxic smoke and the indirect positive effect from limiting the spread of the fire. The response itself in terms of vehicles and water use, also has an impact on the environment. There are cases, for example, when contaminated water from the firefighting operation can lead to negative local environmental effects.

To illustrate the variety of factors influencing the environment during and after an enclosure fire a case study in the Fire Impact Tool will be used to create an example of how choices concerning the response change the overall environmental impact [7]. The Fire Impact Tool was developed to illustrate the consequences of different tactical choices during firefighting. The basic idea with the tool is to be able to compare the environmental impacts from different tactical choices. Due to the complexity of fires, a considerable amount of simplification needs to be made, but the results are useful for capturing trends and provide necessary insights to initiate discussion of tactical choices. This is very useful when educating the rescue service to be more aware of the different environmental impacts that their tactical choices give. The tool has three interdependent parts: the fire model, an environmental risk assessment (ERA) model, and a life cycle assessment (LCA) model. There are currently two applications available in the tool: a vehicle fire and an enclosure fire. In the application for an enclosure fire, the case illustrated is based on a school fire scenario for a Swedish school with up to 4 compartments involved in the fire.

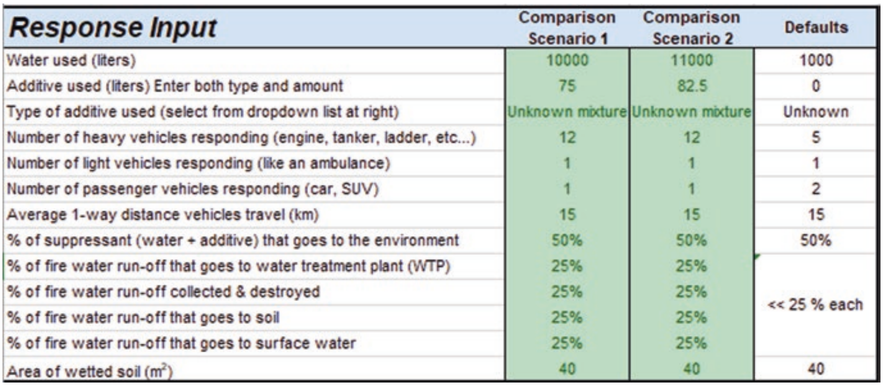
The parameters in the example are set to replicate, as well as reasonably possible, a fire event occurring in the Grillby school in Sweden [41]. A more detailed description of the case study summarized here can be found in Amon et al. [7]. During the fire event the initial strategy of the rescue service was to limit the fire to one of three enclosures, but in the end two of the three enclosures were lost in the fire. During the response firefighters used water and a compressed air foam system (CAFS), along with ventilation, a cutting nozzle, and a backhoe to extinguish the fire. The incident report does not specify the amount of foam and water, or the type of foam used. At the peak of the response there were 32 people, 2 engines, 5 basic vehicles, 3 tankers, 1 ladder truck, 1 smoke safety container, and at least 1 passenger car at the incident site. Due to limitations in the information regarding the incident response, several assumptions needed to be made when using the tool. Nonetheless, the example illustrates the methodology.



Fire Compartment Model Input					Defaults
Room number	1	2	3	4	
Opening average height dimension [m]	1.2	1.2	1.5	0	1.2
Opening area [m^2]	100	100	100	0	10
Room size [m^2]	600	600	600	0	60
Fuel load [MJ/m^2]*	350	350	450	0	250 - 450
Comparison scenario 1:					
Start of full developed fire [min]	5	30	0	0	5
End of full developed fire [min]	240	60	0	0	30
Active suppression used? (Select No if start time<=end time)	Yes	Yes	Yes	No	Yes
Comparison scenario 2:					
Start of full developed fire [min]	5	30	40	0	5
End of full developed fire [min]	240	60	100	0	30
Active suppression used? (Select No if start time<=end time)	Yes	Yes	Yes	No	Yes

*Note that the fire will burn out when the fuel load is consumed.

Fig. 6.5 Input parameters defining the enclosure fire in Grillby using the Fire Impact tool [7]. Two alternative scenarios are prescribed where scenario 1 was the real fire, and scenario 2 an alternative scenario where one more enclosure was lost in the fire



Response Input	Comparison Scenario 1	Comparison Scenario 2	Defaults
Water used (liters)	10000	11000	1000
Additive used (liters) Enter both type and amount	75	82.5	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture	Unknown
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	12	12	5
Number of light vehicles responding (like an ambulance)	1	1	1
Number of passenger vehicles responding (car, SUV)	1	1	2
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	25%	25%	<< 25 % each
% of fire water run-off collected & destroyed	25%	25%	
% of fire water run-off that goes to soil	25%	25%	
% of fire water run-off that goes to surface water	25%	25%	
Area of wetted soil (m^2)	40	40	40

Fig. 6.6 Input parameters defining the incidence response fire in Grillby using the Fire Impact tool [7]. Two alternative scenarios are prescribed where scenario 1 was the real fire and scenario 2 an alternative scenario where one more enclosure was lost in the fire

The user of the tool prescribes the fire development in the enclosures. The real scenario during the Grillby school fire is represented as scenario 1 in the example, and an alternative scenario where also the third enclosure is included in the fire is scenario 2. In Fig. 6.5 the parameters for the fire are set. Other parameters related to the incident response was set according to Fig. 6.6.

In the tool a LCA model illustrating the global impact from the fire response operation according to two defined scenarios including:

- replacement of the building and content from a typical Swedish school building
- replacement of suppression media
- treatment of waist suppression media
- response travel
- smoke
- the persistent effect of foam in water (if used)

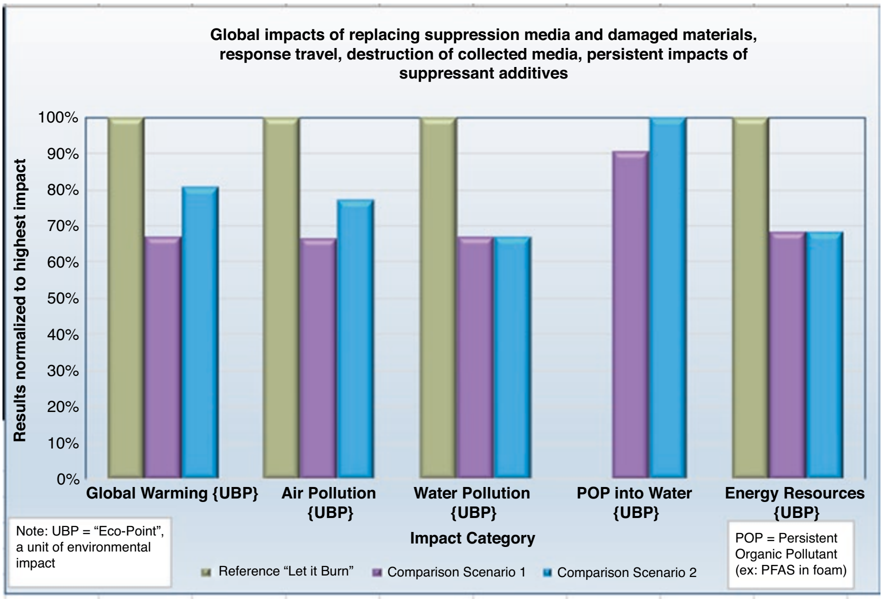


Fig. 6.7 Example of global environmental impact results from the Fire Impact Tool when analysing the Grillby fire [7]

- treatment of excavated soil

In Fig. 6.7 an example of global environmental impact results from the tool are shown. The two chosen tactical response scenarios in the previous figures are compared with a "let it burn" scenario with no intervention from the rescue service. The plots show values normalized to the highest value in each comparison. The results show that the impact in the categories Waste Pollution and Energy Resources, are not sensitive to changes in amount of water and foam used in scenario 1 and 2 but that differences are present in the local impacts.

The ERA model in the tool is used to illustrate the local impacts for the scenarios. Therefore, the ERA model provides quantitative data concerning three types of environmental impacts resulting from fire water run-off:

- the amount of dilution water needed to reduce the concentration of pollutants in surface water to an acceptable level,
- the distance contaminated groundwater must travel through soil until it is degraded to an acceptable level, and
- the volume of contaminated soil that must be excavated to remove contamination.

In scenario 2 the use of water and foam was increased by 10% giving slightly higher local impacts as shown in Fig. 6.8. The figure also illustrates the substantial impact that additives can have on the local surface water. As can be seen, in this example the additives are more toxic than the contaminated fire water.

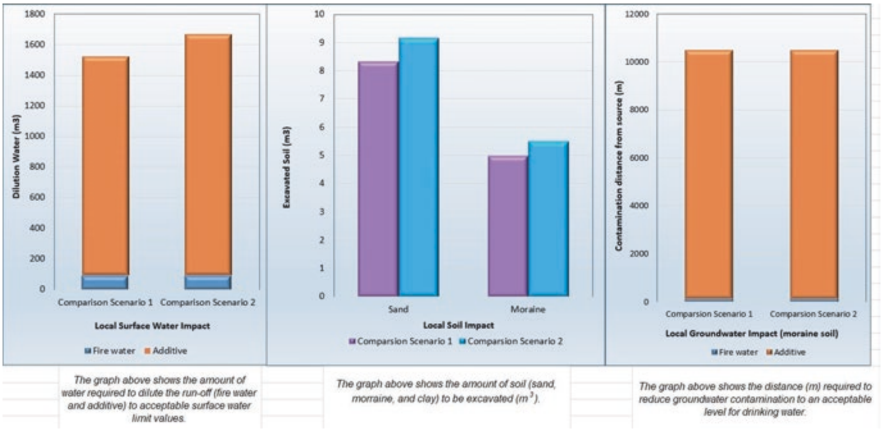


Fig. 6.8 Local impacts for scenario 1 and 2 in the example. Scenario 2 includes 10% more water and additives [7]

6.5 The Application of Life-Cycle Analysis to Sprinkler Systems in Enclosures

There are several studies looking at the environmental trade-off between including sprinkles to limit the fire damage and the environmental cost of this inclusion. The benefits from including a sprinkler system include: a reduction of CO_2 emissions from the fire, reduced quantities of water used in firefighting and CO_2 savings from less need of replacement of the structure and the content in the buildings. In this study fire statistics are used to estimate the occurrence of fires for the building type included in this case.

In case studies performed by Bureau Veritas it was found that there was a net carbon benefit of installing sprinklers in warehouses greater than 5000–10,000 m^2, if the lifespan of the building is assumed to be 30 years [42]. In a similar study by BRE (the UK Building Research Establishment), the environmental effects from including sprinklers in a 15,000 m^2 warehouse were investigated using a 45 yeas lifetime perspective [43]. It was found that the inclusions of the sprinkler system increased the environmental cost measured in CO_{2e} by 10%, when the benefits from reducing the fire damages by including the sprinkler system were not included. When including the beneficial effect of reducing the fire damage, the analysis showed a net gain of 3730 tons of CO_{2e} for the investigated building.

The environmental benefits from using sprinkles in residential homes has also been studied by FM Global [16, 17, 44]. It was found that fire events contributed between 0.4–3.7% to the total carbon emissions of residential homes without sprinklers installed. With sprinklers installed this contribution from fire events was reduced to 0.2% according to their model.

In a handbook written by the Swedish consultancy company Bengt Dahlgrens, the environmental impact of introducing a sprinkler system in 2500 m^2 school was investigated [2]. When estimating the environmental impact from using a sprinkler system, assuming that it will reduce the fire damage with it's commiserate environmental cost, the overall environmental impact of adding this measure was found to be clearly favorable to their inclusion.

An estimation of the potential benefit of including sprinklers in all Swedish schools was investigated in the Fire Impact tool project [7]. The main idea was to compare the environmental effects from fires with and without installed sprinkler systems according to Fig. 6.9.

The study was based on statistics of fires in Swedish schools and due to the nature of this type of investigation a number of assumptions were made regarding influencing factors. Two of these assumptions are included as parameters in the results:

(i) the lifetime of the sprinkler system and
(ii) the damage from activating the sprinkler system.

The lifetime of the sprinkler system is difficult to estimate, as this is a mix of the technical lifetime and the lifetime based on major changes of the schools. Included in the damage parameter are both the water damage due to activation of the sprinklers and the damage from fires not controlled by the sprinkler system. The results shown in Fig. 6.10 indicate that if the lifetime of the sprinkler system in Swedish schools is more than 20 years there is an environmental gain to introduce sprinkler in all schools [7].

6.6 Enclosure Fires Including Industrial Chemicals

When storing industrial chemicals in enclosures the occurrence of fires has the potential to release large amounts of toxic compounds. This release of the compound to the surroundings can be directly as a leakage of the compound itself or

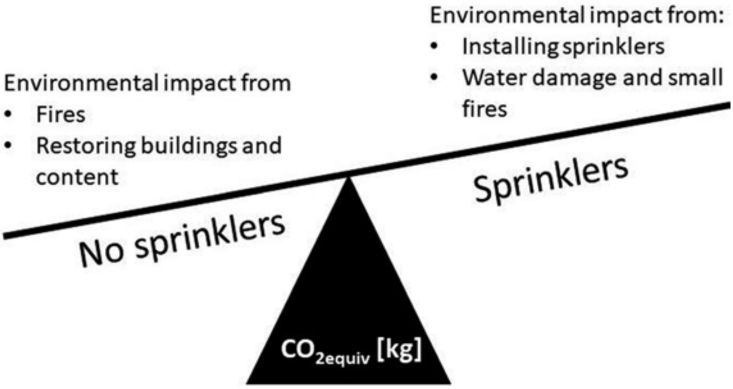


Fig. 6.9 The environmental balance measured in CO_{2e} during the lifetime of sprinkler systems in Swedish schools [7]

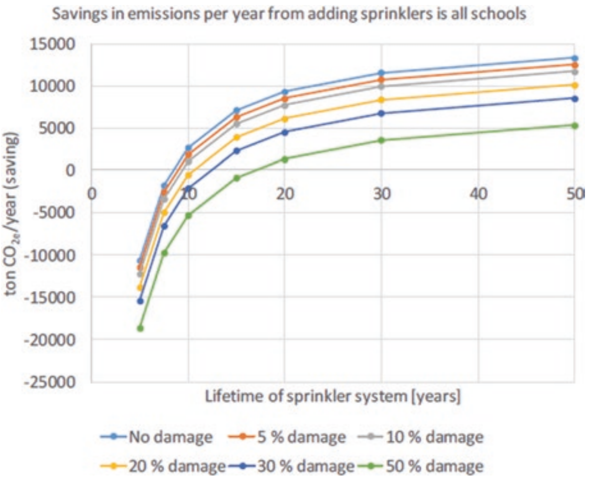


Fig. 6.10 Environmental cost of all Schools fires in Sweden minus the environmental cost of introducing sprinklers in all Swedish schools. Percentage of damage include water damage from sprinkler activation and from small fires (the reference 100% is total fire damage without sprinklers) [7]

indirectly as a component in the fire gases or as contamination from the water used in the firefighting operation. One of the most cited events where this happened was the Sandoz fire in Basel, Switzerland 1986 [45]. The fire occurred in a warehouse where 1.25 million kg of chemicals and packing material was stored. The fire plume spread sulfur and other inorganic substances in the Basel area causing anxiety and discomfort among the population. There was also a substantial release of contaminated water from the firefighting operation and direct from the chemicals spread in the river Rhine. This led to extensive damage of the flora and the fauna od the river. More details on this event can be found in Chap. 2 of this handbook together with numerous other industrial fire incidents.

Two large European research projects have focused on the characterization of the hazards from fires including industrial chemicals, the COMBUSTION project and the TOXFIRE project. In the COMBUSTION project, the outcome was a database called FIRE where data on warehouse fire accidents including industrial chemicals were summarized [46] and in the TOXFIRE project an extensive experimental study on the combustion behavior of industrial chemicals was performed [47]. The project included experimental studies focusing on the characterization of combustion products produced in different setups, fire modelling and risk assessment focusing on both human health and environmental effects. Guidelines were developed, both for fire safety engineers and fire brigades. The main structure of the TOXFIRE project is presented in Fig. 6.11.

In the TOXFIRE project the burning behavior of the following chemicals was investigated in an extensive experimental series in different scales (micro scale, bench scale, 1/3 room and room scale):

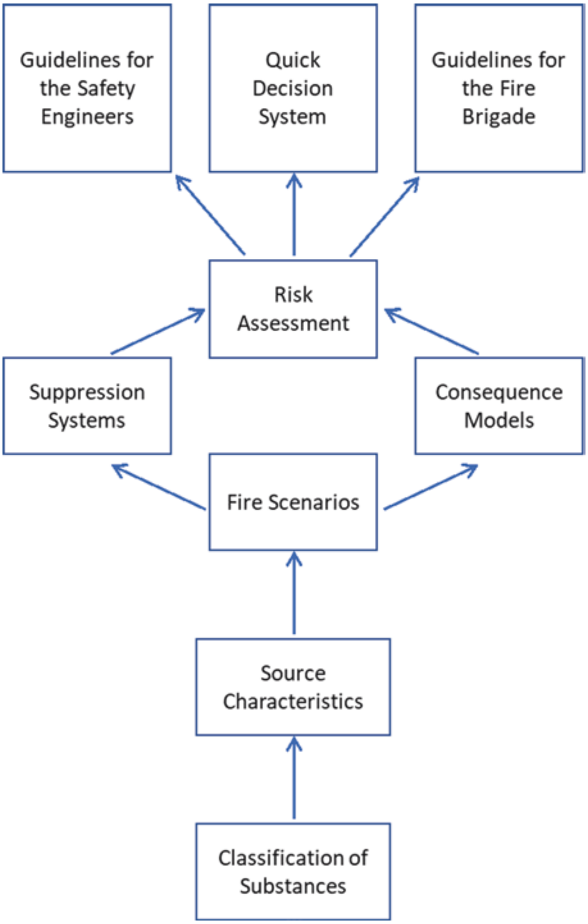


Fig. 6.11 The structure of the project TOXFIRE (Guidelines for Management of Fires in Chemical Warehouses) (redrawn drawn from [47])

- Polypropylene, $(C_3H_6)_n$
- Nylon 66, $(C_{12}H_{22}N_2O_2)_n$
- Tetramethylthiuram monosulphide (TMTM), $C_6H_{12}N_2S_3$
- 4-chloro-3-nitro-benzoic acid (CNBA), $C_7H_4NO_4Cl$
- Chlorobenzene, C_6H_5Cl

In the documentation of the project extensive data on yields of different species under different ventilation conditions are given, see for example numerous publications from the TOXFIRE project [39, 48–55]. The impact of enclosure size and ventilation conditions are explored to develop a variety of emission factors or yields for different conditions.

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Chapter 7
Wildland Fire

Alexander I. Filkov, Jane Cawson, Matthew H. Swan, and Trent D. Penman

7.1 Introduction

Wildfires can have profound impacts on humans and the environment [1]. They are important to the functioning of many ecosystems globally, influencing the distribution, abundance and structural form of many plant species and vegetation communities [2]. Yet, they also threaten human life, property and the environment, with people killed, homes destroyed [3, 4], and ecosystems services like water supply severely disrupted [5].

The most devastating impacts are often associated with extreme fires that result from dynamic fire behaviours [6–8].These extreme fires carry particularly high human costs when they occur in the Wildland-Urban Interface where urban sprawl into more natural areas puts people and their dwellings in proximity of flammable vegetation [9, 10]. Ecological values in many areas are under threat from altered fire regimes, whether it be an increase in the frequency, severity, and extent of wildfire or the absence of fire in a system that is well-adapted to fire [11–13].

Climate change has the potential to amplify the social, environmental and economic impacts of wildfires [14]. In many parts of the world, we are already seeing longer fire seasons as the number of dry and hot days increases [15, 16] and more extreme fires occur [17]. This was especially apparent during the 2019/2020 fire season in south-eastern Australia, where record temperatures and drought conditions contributed to the most extensive forest fires in this region in recorded history [18].

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In this chapter we examine the impact of wildfires on a range of values:

- communities – human life and property,
- biodiversity – particularly plants and animals,
- soil and water, and
- air quality.

We then highlight the role of dynamic fire behaviours and their disproportionate contribution to wildfire impacts. The chapter closes within a reflection on Australia's 2019/2020 wildfire season (Black Summer fires hereafter). We describe these fires and their impact on people and the environment.

7.2 Impacts on Communities

Wildfires result in widespread destruction and damage to a range of economic and social assets and functions. Their impacts include losses of human life and property, livestock and crops, loss of tax revenues, property value and unemployment [19]. Wildfires also impact upon social systems causing psychological distress [20], social disruption [21] and preventing the use of recreational land [22].

Wildfire impacts on private property and public lands have increased dramatically during the past few decades [10]. They threaten many lives and cost billions of dollars in damage (Table 7.1). Many of the most destructive fires have occurred in south-eastern Australia, California USA, the Mediterranean region of Europe, south-western Canada, and Siberia and Far East of Russia.

A number of recent wildfires have impacted communities in locations where historically fires are rare or extraordinary events. For example, wildfires occurred in the tropical and temperate rainforests of Chile in 2014 and 2017 with 12 people killed and hundreds of homes destroyed [40, 41]. In Bolivia in 2017 wildfires resulted in 3 deaths, 1479 people injured, and 3000 homes lost [42]. There were wildfires close to the Arctic circle in Sweden, Norway, Greenland and Scotland [43–45]. In 2014 wildfires in Sweden killed one person, damaged or destroyed 71 buildings, and over 1000 people were evacuated [46]. In 2019 hundreds of people were forced to evacuate due to an extraordinarily high number of extreme wildfires in Norway and Sweden [44].

Wildfires cause the greatest loss of human life and damage to property in the Wildland-Urban Interface (WUI) compared with the broader vegetated landscape. The WUI is "the line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetation fuels" [47]. Greater losses occur due the density of people and houses within this zone. In some parts of the world a large proportion of the population lives within the WUI. For example, it is estimated that in Australia about 20.3% of addresses are within 700 m and 4.1% within 50 m of forested areas in major capital cities and surrounding areas [48].

Analysis of wildfire related life loss in WUI area of Australia over the past 110 years (1901–2011) showed that over 78% of all fatalities occurred within 30 m

Table 7.1 Examples of wildfires with large social, economic and environmental impacts from 2010–2020

Name	Region	Impact
2019 black summer fires	Australia	33 people killed and over 3000 houses destroyed [23]
2018 camp fire	USA	85 fatalities and nearly 19,000 structures destroyed [24]
2018 Attica fires	Greece	102 fatalities and approximately 3000 houses burned [25]
2017 Thomas fire	USA	1300 structures lost and 2.2 billion USD in damages [26]
2017 British Columbia fires	Canada	1.2 million hectares burned and 65,000 people evacuated [27, 28]
2017 wildfires	Portugal	112 human lives lost with 424,000 hectares burned [29]
2016 Fort McMurray wildfire	Canada	2400 houses lost and 6 billion CND in damages [27, 28]
2016 wildfires	Portugal	4 people killed and more than 1000 evacuated [30]
2015 wildfires	Russia	33 people killed and 1300 houses burned [31]
2015 South Australia fires	Australia	2 lives lost and 88 houses burned [32]
2013 red October fire	Australia	224 structures destroyed and 1 person died [33, 34]
2012 Chios fire	Greece	9 villages evacuated and 7000 hectares burned [35]
2011 slave Lake fire	Canada	374 properties destroyed and 700 million CND in damages [36]
2011 Bastrop County complex fire	USA	2 deaths and 1645 homes lost [37]
2010 wildfires	Russia	53 fatalities and 2500 houses lost [38, 39]

of the forest [3]. For wildfires occurring under extreme weather conditions, fatalities within structures represented over 60% of all fatalities. It was shown [49] that there is a correlation between life loss and house loss. These findings highlight the importance of fire performance of structures in reducing life loss. The impact of wildfires on communities is expected to increase dramatically with the rapid expansion of population in the WUI [50] and because changing climate will likely increase the occurrence and intensity of wildfires [51].

The ignition of structures in communities is caused by exposure to heat fluxes (convective and radiative) from flames or firebrands generated by the wildland fire itself or from adjacent houses already burning [52]. The majority of houses are burnt at peak levels of fire danger [53]. Firebrand generation is the process through which wildland fuels, such as shrubs and trees are heated and broken into smaller burning pieces during combustion. In wildland fires a huge amount of smouldering and flaming firebrands are produced and transported by the convection column and the wind over long distances [54–56], leading to the formation of new spot fires and the ignition of structures. Firebrands deposit and accumulate on the outer surface of a building or find a way through the structure to reach easy-to-ignite fuel or structural elements within [57]. The intense exposure to firebrands in the vicinity of a fire front is called a firebrand shower (Fig. 7.1). This is the main condition of exposure from firebrands in the WUI [58]. Studies show that most house loss during a wildfire occurs via ignition from firebrands [10].

7.3 Impacts on Biodiversity

Fire is an important global force, shaping the distribution of biomes and driving biodiversity [2, 59]. Biodiversity is defined as the variety of all life including species, ecosystems and genes. Fire influences biodiversity in various ways such as killing individual organisms, disrupting competition and providing conditions for certain species to thrive [2, 60]. Fire is crucial for maintaining the structure and function of fire-prone ecosystems and many species across the globe require fire for their ongoing persistence.

A single wildfire can have wide-ranging effects on biodiversity. The effects of a single fire will depend on properties of the fire *event* such as fire behaviour, intensity and extent. However, knowledge of the history of preceding fires is often required to fully comprehend the effects of individual fire events. Together the properties of fire frequency (interfire interval), intensity, season and spatial extent define the *fire regime* of an area and are crucial to understanding the effects of fire on biodiversity [61–63]. Chemicals used for fire suppression also affect biodiversity (see Chap. 8).

Here we describe major effects of wildfires and associated fire regimes on biodiversity with a focus on plants and animals as two important and widely studied groups of organisms in the context of fire.

7.3.1 Plants

Wildfires consume an enormous amount of plant biomass across the globe with between 300 to 500 million hectares of vegetation burnt each year [64]. Plants and plant derived material typically provide fuel for fire, but as sessile organisms they also are vulnerable to its lethal effects. Fire affects two fundamental parts of plant

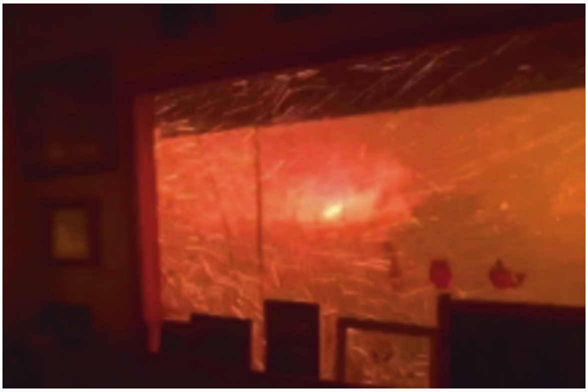

Fig. 7.1 Firebrand shower from a passing wildland fire, Western Australia. (Credit: Department of Fire and Emergency Services)

life cycles; causing mortality of existing plants and promoting recruitment of new plants. This leads to four conceptual, contrasting responses of plants to individual fire events: high recruitment-low mortality, high recruitment-high mortality, low recruitment-low mortality and low recruitment-high mortality [65]. The first three can be considered either fire dependent or fire tolerant whereas fire would result in local extinction of plants in the latter category.

Survival mechanisms include insulating sensitive tissues from the heat of fire in thick bark or soil and resprouting from underground or aboveground tissues [66]. Recruitment involves either germinating from stored seed buried in soil or held on the plant [65]. Plants that do not possess recruitment or survival strategies are vulnerable to local extinction in the event of fire and as such are reliant on dispersal to recolonise areas after fire [61].

The effects of wildfires on plants is dependent upon interactions between the fire regime and species response traits. Where species responses are adapted to a particular fire regime, local extinction may occur where it experiences a regime that is outside its tolerance for survival or reproduction [67]. This is clearly epitomised by serotinous species (plants that store seeds in the canopy) that are sensitive to multiple fires occurring at short intervals. Serotiny is a fire adapted trait that is common across the different biomes of the world including many coniferous forests in the northern hemisphere, and shrublands in the Mediterranean climate regions of Southern Australia and South Africa [68]. Plants showing this trait typically require crown fire to trigger the opening of woody cones or fruits before they subsequently germinate in ash beds [69]. Where fires occur at short intervals there may not be sufficient time for juvenile plants to produce enough seed before they are killed in the second fire, risking local extinction. For example, the dominant overstorey *Eucalyptus* species in mountain wet forests of south-eastern Australia are killed by high intensity fires and only reach sexual maturity after approximately 20 years [70]. Large areas of alpine ash (*Eucalyptus delegatensis*) forest burnt in three successive wildfires from 2003 to 2014 resulted in regeneration failure across multiple stands [71]. Similarly, lodgepole pine (*pinus contorta*) forests in North America have reduced regeneration and ultimately marked changes in structure and function after short-interval wildfires [72]. Ecosystems with a high incidence of serotinous species are also vulnerable to the long-term absence of fire [62]. However, increasing fire frequency and intensity with climate change poses greater risk of abrupt state-change due to loss of key species through short intervals between wildfires [73].

Climate change has the potential to compound the ecological effects of fire regimes with increasing temperatures and rainfall variability. Climatic conditions can both make plants more vulnerable to severe fires and affect plant establishment and ongoing survival after fire [74]. Rainfall in the years following wildfire is a major determinant of the trajectory of plant and ecosystem succession [75]. Post-fire drought in widespread areas of Conifer forests across North America placed increased stress on juvenile or fire damaged plants and affected subsequent recovery, increasing the risk of forest conversion to shrublands or grasslands [76]. Furthermore, drought conditions preceding fire can make certain plants more vulnerable to mortality and damage [77, 74].

Recently, there has been increased occurrence of wildfires in ecosystems that have rarely encountered fire associated with shifts towards a warmer climate [42, 78, 79]. While the long-term impacts of this are yet to be fully understood, increased fire frequency may pose a risk to biodiversity where systems include plant species that are fire sensitive and do not readily survive or reproduce after fire. For example, pencil pines *Athrotaxis cupressoides* are a rare, slow-growing paleo-endemic relict that occupy high elevation and high rainfall regions of Tasmania. This species occupies forests that are usually too wet to burn and lacks adaptations for surviving fire and reproducing in the aftermath. Climate change induced drying and increase in fire weather contributed to recent wildfire-driven loss of entire stands of this species [80], threatening its ongoing survival.

Another risk that wildfires pose to plant biodiversity is through the promotion of invasive plants. In the aftermath of a wildfire, conditions are ideal for many invasive species, such as ample light, a nutrient rich ash bed and reduced competition from established species [62]. The management of invasive, fire-promoted plants is a serious management challenge across the globe. Where invasive species dominate, they can alter fire regimes at the expense of other species [81]. For example, gamba grass *Andropogon gayanus* increases fuel load and fire severity in northern Australian savannahs, resulting in increased mortality of overstorey trees and thus more favourable conditions for its persistence and spread [82]. Invasive species can even promote fire where it otherwise rarely occurs, resulting in large shifts in structure and function of these ecosystems [83].

7.3.2 Animals

Animals, unlike plants, do not have structural or physiological mechanisms that allow them to survive the heat of fire. Individual animals rely on mobility or behavioural strategies to avoid death or injury in a fire event [84]. The immediate effects of a single fire on individual animals are influenced by the traits of the animals such as their size, mobility and life stage [85]. Larger mammals and birds that are highly mobile may be able to escape the immediate effects of fire [86]. Many fossorial animals survive fire by burrowing into soil however their ability to do so will depend on fire intensity and associated depth of heat penetration into the soil [87]. Animals with reduced mobility such as small reptiles, amphibians and invertebrates that live in substrates that regularly burn such as leaf litter may be especially vulnerable to immediate fire effects [88, 87].

The direct effects of wildfire on animal populations is likely to be dependent upon fire intensity, season and extent. Extensive high intensity wildfires reduce the ability of many individual animals to survive fire and may pose an extinction risk for species with restricted distributions [87]. The negative effects of wildfire on animal populations may be attenuated by refugia within fire boundaries [89]. Refugia can include patches of unburnt vegetation associated with less flammable vegetation such as those in riparian zones or vegetation types with less flammable plants or even areas burned at low severity within a wildfire boundary [90]. The extent to which moisture and fuel properties influence fire severity and the creation of refugia is dependent upon fire weather and under extreme conditions the abundance of unburnt patches or lower severity patches is diminished [91].

In many cases the aftermath of fire is of greater risk to many animals than fire itself [84]. For example, a large proportion of an elk (*Cervus canadensis*) population survived a large wildfire in Yellowstone National Park but mortality was high in the year after fire [92]. Fire results in resource depletion and many predators increase activity [93] posing risks of death by predation and starvation to many species. The risk from predators to animal populations after fire may be particularly acute where species are vulnerable to invasive predators [94].

The ability for animals to recover as conditions become suitable after wildfire is critical for sustaining populations. Recovery can take place in-situ, from refugia or from outside the fire boundary [85, 89]. After fire, movement is critical for recolonization and for maintaining genetic diversity of populations but may be impaired where fire occurs among fragmented landscapes where an inhospitable matrix inhibits movement [86, 95].

Arguably the most important effect of fire regimes on the long-term persistence of animal populations is the effect on habitat features that provide critical resources such as food, shelter and protection from predation [96]. Fire can affect specific resources that species require. For example, woodland caribou (*Rangifer tarandus*) forage on lichen in boreal forests to help survive winter months [97]. This food resource is reduced until approximately 50 years after fire and as such this species prefers older stands for foraging. Wildfire can also affect habitat features that are important for suites of organisms such as leaf litter and woody debris that take many years to recover, yet high intensity fire is important for creating suitable habitat conditions for many species [98]. Many important habitat features and resources are influenced by properties of fire regimes. In many ecosystems, animal species rely on habitat elements that are at risk of short or long fire intervals such as leaf litter, hollow logs or tree hollows [99]. Short intervals between wildfires can remove tree canopies and habitat features such as hollows in some systems, risking local extinctions of arboreal fauna [10v0].

Animals and plants are likely to be affected by climate change and its interactions with fire regimes. More frequent, intense wildfires may threaten certain vulnerable species such as those with restricted distributions or that occupy habitat types that are sensitive to such regimes. Furthermore, post-fire growing conditions affects subsequent recovery of plants which affect the resources used by many animals. Drought alone has negative consequences for many animal species [101, 102] and wildfires can potentially compound the effects of this and other threatening processes, resulting in population declines.

7.4 Impacts on Soil and Water

Globally, a significant number of people depend on water supplied from forests, grasslands or peatlands [103]. Many of these catchment areas are prone to wildfires. Wildfires can alter the movement of water and sediment on burnt hillslopes [104]. In some circumstances, this can have very serious implications for downstream water quality and yield, posing a threat to water security for the people and aquatic wildlife downstream [105]. In other circumstances, wildfires have seemingly little impact on soil and water. The degree of impact is determined by a complex interaction of factors and thresholds [106]. Understanding these factors and their interactions is critically important for predicting and managing the potential threat of wildfire to water security.

Streamflow in vegetated catchments is mostly provided by subsurface flow, with the soil acting as a filter for contaminants [107]. Surface runoff and erosion rates are low due to the combined effects of vegetative cover, high soil organic matter, and high soil porosity. Vegetation intercepts precipitation, reducing the amount of water available to infiltrate into the soil or become surface runoff [108]. Transpiration from living plants regulates the amount of moisture in the soil, while leaf litter on the soil surface reduces soil evaporation. Vegetation (particularly leaf litter) also protects surface soil from erosion caused from the impact of raindrops and overland flow [109]. Soil organic matter acts as a binding agent for soil particles, providing the soil structure that is crucial for water movement and water storage in the soil [110]. Macropore spaces created by cracks, old root channels and earthworm holes, provide preferential flow channels for more rapid infiltration of water into the soil, reducing the amount of water available to become runoff [107].

Increased runoff and erosion following wildfires is caused by several interacting factors. Rainfall interception by vegetation is reduced, which means there is more water available to potentially become runoff [104]. This is compounded by a reduction in the infiltration capacity of the soil caused by a combination of reduced soil organic matter, soil sealing, and soil water repellency. The combustion of soil organic matter reduces soil aggregate stability, pore size and total porosity [110, 111]. Soil aggregates are further destroyed by the impact of raindrops on the bare soil surface, which can lead to soil sealing [110, 112, 113]. Soil water repellency is another important contributor to enhanced runoff on burnt hillslopes [114, 115]. It can be created, strengthened, relocated or destroyed as a result of soil heating during wildfires. Low infiltration rates post-fire are often attributed to strong soil water repellency, though it can be difficult to quantify its influence on runoff rates relative to other factors, especially at larger spatial scales [113, 116, 117]. Without the protection of a layer of leaf litter, erosion caused by rain drop impact and runoff is enhanced [112]. In some circumstances, ash protects the soil surface from rain drop impact and acts as a water store, reducing runoff [118]. Conversely, it can contribute to soil sealing by clogging macropores and therefore contribute to increased runoff.

Wildfire impacts on runoff and erosion vary widely depending on a range of factors including fire severity, soil type, rainfall intensity and hillslope gradient. The largest impacts are observed where a high severity wildfire intersects [119] with an intense rainfall event in steep terrain [120]. These conditions can produce debris flows, a particularly destructive form of post-fire erosion [121, 5]. In areas of high fire severity, a large proportion of the vegetation cover can be consumed by the fire, maximising exposure of the soil surface [122, 123]. Furthermore, soils can be exposed to high temperatures for long durations, leading to the loss of soil organic matter [111, 112] and intensification of soil water repellency [124]. In contrast, lower severity fires, generally have lower runoff and erosion rates [125, 126]. These lower severity fires require a higher threshold of rainfall and steeper slopes for substantial amounts of runoff and erosion to occur post-fire [127, 128].

Vegetation type and its rate of recovery also determines the magnitude of post-fire runoff and erosion. Forests are susceptible to the largest increases in runoff and erosion while grasslands and shrublands generally exhibit the smallest changes [129]. This reflects lower fire severities and faster rates of vegetation recovery in grasslands and shrublands. The magnitude of post-fire runoff and erosion also declines with time since fire. This is sometimes referred to as the ‘window of opportunity’ before the vegetation recovers following a fire, with the greatest amounts of runoff and erosion most likely when intense rainfall occurs within 1–2 years of the fire [130, 131].

Higher rates of runoff and erosion within burnt catchments can have detrimental consequences for water quality in streams and water reservoirs [105]. Concentrations of a range of water quality constituents may be elevated, such as suspended sediments, ash, nutrients (N, P) and metals. Increased suspended sediment is the most commonly reported. Trace elements, bacteria and nutrients have a high affinity to fine sediment, so their levels are often correlated with levels of suspended sediment. Although most studies report an increase in suspended sediment, the magnitude increase is highly variable (e.g. from 11 to 500,000 mg L^{-1}) [105]. This reflects the complexity of factors influencing both post-fire erosion (as discussed above) and sediment movement through the catchment, most notably post-fire rainfall. In some forest systems, debris flows are considered the dominant risk to downstream water quality [132].

Elevated constituent concentrations in streams may pose problems for aquatic ecology [133, 134], water supply for domestic and agricultural purposes [105], recreation and aesthetics [105]. For example, domestic water supply was disrupted following the 2003 and 2006/2007 wildfires in south-eastern Australia resulting in boil water notices, water restrictions, water carting and the costly installation of new water treatment facilities for some towns [135]. Following an intense fire in Yellowstone National Park in 1988, aquatic macroinvertebrate richness, total density and composition fluctuated for the duration of a 10 year study rather than reaching a constant equilibrium [136].

Loss of vegetative cover may also impact streamflow and catchment water yields. Initially, reductions in rainfall interception and evapotranspiration, coupled with lower rates of soil infiltration, can equate to higher streamflow [137, 138]. Peak flows, including flash floods, can occur more frequently during this initial phase, with small, steep, severely burnt catchments being the most vulnerable [139].

Long-term trajectories for evapotranspiration and streamflow following fire are highly variable and depend on a range of factors including fire severity, vegetation type, regeneration mechanisms, and post-fire climatic conditions [140–142]. For example, forests with eucalypt trees that resprout via epicormic buds can recover rapidly following fire, with evapotranspiration and streamflow returning to pre-fire levels within 8–12 years, after a period of higher evapotranspiration [143]. In contrast, reduced streamflow can persist for 100–150 years, peaking 20–30 years post-fire, in Mountain ash (*Eucalyptus regnans*) forests that regenerate from seed following high severity fire [144]. In areas where the wildfire causes a substantial shift in vegetation type from forest to shrubland or grassland, reduced evapotranspiration and increased streamflow can persist for at least 10 years [145].

7.5 Impact on Air Quality

Wildfires release large amounts of smoke, which can pose a hazard to human health by impacting air quality. Global average wildfire emissions were estimated to be 2.2 billion tons per year from 1997 to 2016 [146]. In addition, chemicals in plastics and other materials are released into the air when structures and furnishings burn. Air pollution from wildfires affects visibility, human health and contributes to climate change [147]. Globally, average annual mortality from fire smoke is estimated to be 339,000 deaths, with the worst impacted areas being sub-Saharan Africa and South east Asia [148].

Smoke from wildfires is made up of small particles, gases and water vapor. Carbon dioxide and water vapor are the main constituents, generally contributing over 90% of total emissions [149]. The remainder includes carbon monoxide, nitrogen oxide, irritant volatile organic compounds, air toxics and very small particles (particulate matter or PM). The particulate matter in wildfire smoke is the sum of all solid and liquid particles suspended in air and includes both organic and inorganic particles. The particulate matter tends to be divided into two principal groups: coarse particles (PM_{10}) and fine particles ($PM_{2.5}$). The barrier between these two fractions of particles is fixed by convention at 2.5 μm in diameter. $PM_{2.5}$ is the most abundant constituent in terms of the number of particles, but only contributes a few percent of the total mass of smoke due to its small size [150]. It has been attributed to adverse health outcomes and mortality [148].

Smoke composition and quantity varies depending on the fire intensity (the amount of heat released) and rate of spread of the fire [151]. Wildfires with rapid rates of spread and high intensity but relatively short duration, burn at high temperatures and produce only small amounts of smoke. In contrast, wildfires with longer burning durations consume a larger portion of biomass through smouldering, which results in high levels of smoke production relative to the fuel consumed. Smouldering produces a large amount of carbon monoxide, hydrocarbons, nitrogen oxides, and sulfur oxides, all of which increase the toxicity of smoke [149].

Wildland fires (especially peat fires) can smoulder for months and accumulate high concentrations of smoke near the ground. For instance, the Capital of Central Kalimantan (Indonesia) in 2015 experienced 2 months of smoke. Daily average PM_{10} levels during these fires exceeded 3800 μg/m^3, shockingly higher than the World Health Organization air quality guideline (50 μg/m^3 24-h) [152]. During active wildfire periods, levels of carbon monoxide can increase 30–40% and polycyclic aromatic hydrocarbons can be 15 times higher compared with periods with no fires [153]. As a result, wildfires can cause severe levels of human exposure to toxic compounds.

Many wildfire emissions can have acute or long term health implications on the exposed populations [147, 151]. $PM_{2.5}$ is the principal air pollutant in wildfire smoke of concern for public health and it has various effects on human health [148, 151]. Fine particles may reach the alveoli in the lungs, and if not sufficiently cleared, may enter the bloodstream or remain in the lungs, resulting in chronic lung disease such as emphysema. Other wildfire emissions like volatile organic compounds may cause skin and eye irritation, drowsiness, coughing and wheezing, while others like benzene may be carcinogenic [150].

Among wildfire emissions, PM_{10} and $PM_{2.5}$ are the most studied in terms of their effects on human health. Daily and hourly $PM_{2.5}$ and PM_{10} concentrations can be increased dramatically by wildfires burning hundreds of kilometers away because of the ability of the aerosol to be transported long distances [154]. In terms of health, several studies have found a significant association between PM and respiratory symptoms, increased respiratory hospital admissions and increased emergency department visits [150]. Fine particles have been observed to cause changes in lung function, leading to increases in respiratory and cardiovascular mortality and morbidity including asthma. Studies have also found an association between daily mortality from wildfires for all-causes of death, including cardiovascular disease [155].

Not everyone who is exposed to thick smoke will have health problems. The level and duration of exposure, age, individual susceptibility, including the presence or absence of pre-existing lung or heart disease, and other factors play significant roles in determining whether someone will experience smoke-related health problems [151]. The elderly, people with pre-existing cardiopulmonary conditions, smokers and people with smaller airways may experience more severe short-term and chronic symptoms [150]. Additionally, fire fighters are at higher risk due to their level of exposure [156].

Population exposure and respiratory health impacts of wildfire smoke is likely to grow in the future as global wildfire activity and human population growth both increase. It is estimated that $PM_{2\ 5}$ exposures due to wildfire smoke in the western US for 2046–2051 under moderate climate change will be 160% higher than currently observed [157]. Liu et al. [158] found that both climatic change and projected increases in population will increase the number of respiratory hospitalizations due to wildfire smoke exposure. They estimated that premature deaths attributable to wildfire-generated $PM_{2.5}$ will double by late twenty-first century compared to early twenty-first century under climate change.

7.6 Disproportionate Impact of Extreme Wildfires

Extreme wildfires pose a disproportionate risk to environmental and human assets and result in enormous impacts [23]. Their occurrence and behaviour are driven by complex processes. Fire propagation can be significantly affected by dynamic feedback processes that result in unpredictable behaviour, and the continual escalation of fire spread rates and intensities even when environmental conditions are consistent. The erratic behaviour and difficulty of control of extreme wildfires means they can result in the worst impacts, burn larger areas and cause loss of human life. The trend for the occurrence of extreme wildfires appears to be increasing each year [16, 159–161].

Dynamic feedback processes or dynamic fire behaviours (otherwise known as "extreme fire behaviours", EFB) can occur within any wildfire [17, 162–164]. According to Filkov et al. [8, p.3] dynamic fire behaviour (DFB) is a *"physical phenomenon of fire behaviour that involves rapid changes of fire behaviour and occurs under specific conditions which has the potential to be identified, described and modelled."* DFBs can influence the intensity, rate of growth and impact of wildfires [6, 7, 165, 166]. Fires in which DFBs occur contribute disproportionately to damage statistics. For example, in the 2003 Canberra fires in southeastern Australia, two separate fires (the McIntyre's Hut and Bendora fires) merged and created a series of violent pyro-convective events and a fire tornado [7]. The merging fire apex spread rapidly, becoming extremely destructive and resulting in four deaths, many injuries and property losses valued at $AUD600 million to $AUD1 billion [167]. The 2016 Fort McMurray wildfire in Canada is another example. It cost $6 billion CND and caused the largest Canadian wildfire evacuation on record, 88,000 residents [27]. Approximately 2400 buildings were destroyed. Record-breaking temperatures (>30 °C) and strong wind (about 72 km/h) created ideal conditions for DFBs [168]. The high amounts of energy released by this fire resulted in a pyroconvective event and the transport of firebrands up to 40 km ahead of the flame front. Multiple spot fires and fingers of fire front merged together and produced fast rates of spread and high fire intensity.

There are nine recognised DFBs, see Table 7.2 [8].

DFBs are relatively frequent in medium to large fires. Analysis of historical fires greater than 1000 ha in Australia that occurred between 2006 and 2016 [8] revealed that more than half of the fires had at least one DFB (overall 60%). Spotting and crown fires were the most frequent DFBs, making up a total of 50% of all DFB observations (Fig. 7.2). Pyro-convective events (PyroEvs), eruptive fires and conflagrations were observed to have similar frequencies of occurrence, accounting for 39% of the remaining observations. Junction fires, fire tornado/whirls, fire channelling and downbursts combined accounted for 11% of DFBs in total. The low frequency of the last four DFBs was assumed [8] to reflect limited understanding of them in the fire community and therefore challenges with identification.

Table 7.2 Dynamic fire behaviours [8]

Type	Definition
Spotting	Spotting is a behaviour of a fire producing firebrands or embers that are carried by the wind and which start new fires beyond the zone of direct ignition by the main fire [47].
Fire whirls	A fire whirl is a spinning vortex column of ascending hot air and gases rising from a fire and carrying aloft smoke, debris, and flame. Fire whirls range in size from less than 0.3 m to over 150 m in diameter. Large fire whirls have the intensity of a small tornado" [47].
Fire channelling	Fire channelling/lateral vortices is a rapid lateral fire spread across a steep leeward slope in a direction approximately transverse to the prevailing winds [170].
Junction fires	Junction fires/junction zones (jump fires previously) are associated with merging of two fire fronts intersecting at an oblique angle, producing very high rates of spread and with the potential to generate fire whirls and spotting [163].
Eruptive fires	Eruptive fires are fires that occur usually in canyons or steep slopes and are characterised by a rapid acceleration of the head fire rate of spread [163].
Crown fires	Van Wagner [171] recognized three types of crown fires according to their degree of dependence on the surface fire phase: passive, active, and independent. Active and independent crown fires are recognised as dynamic fire behaviours [8]. Active crown fire is "a fire in which a solid flame develops in the crowns of trees, but the surface and crown phases advance as a linked unit dependent on each other" [47]. Independent crown fires "advance in the tree crowns alone, not requiring any energy from the surface fire to sustain combustion or movement" [47].
Conflagrations	Conflagrations are raging, destructive fires [47] that occur when several fires grow up and unite. Their interaction will increase the burning rates, heat release rates, and flame height until the distance between them reaches a critical level [172].
Pyro-convective events	A pyro-convective event is an extreme manifestation of pyroconvection, the buoyant movement of fire-heated air. A flammagenitus cloud, generated by the heat of a bushfire, often rises to the upper troposphere or lower stratosphere [173], and transforms into cumulus (CuFg) or cumulonimbus (CbFg) cloud (also known as PyroCu or PyroCb).
Downbursts	Downbursts are violent and damaging downdrafts associated with cumulonimbus flammagenitus clouds [173], that induce an outburst of strong winds on or near the ground [174]. These winds spread from the location of the downbursts and may result in a fire spread contrary to the prevailing wind direction.

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Fires with DFBs tend to exhibit two or more different types of DFB [8]. This association between DFBs could reflect a causal relationship between some types of DFB, e.g., crown fires and PyroEvs could facilitate long distance spotting and fire tornados/whirls. DFB can happen at any scale, even smaller fires can have multiple DFBs [8].

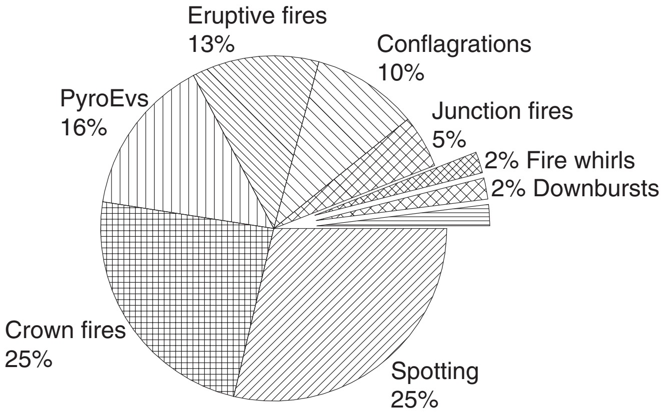

Fig. 7.2 Relative frequency of each dynamic fire behaviour phenomenon. The sum of all DFBs is 100% [8]. (Open Access paper. Under the terms and conditions of CC BY license)

7.7 Case Study - Black Summer Fires of 2019/2020 in South-Eastern Australia

Arguably, the 2019/2020 fire season in southern Australia is the worst on record. In September 2019, wildfires started in New South Wales and Southern Queensland, one month earlier than the typical start to the fire season. These fires, and others which ignited later in other states, continued to burn for months, culminating in approximately 10 million hectares burnt in south-eastern Australia, 33 people killed and over 3000 homes destroyed.

7.7.1 Preconditions

The Black Summer fires occurred during a period of unprecedented weather conditions. Record breaking temperatures were recorded across the continent, with 2019 declared Australia's warmest year on record (Fig. 7.3) [175].

Rainfall was extraordinarily low, comparable only to the driest periods in Australia's recorded history (Fig. 7.4). Across much of Australia, 2019 was the driest year on record and this followed an extremely low rainfall period starting from 2017 for much of New South Wales and southern Queensland [175].

The impact of low rainfall over the period was exacerbated by the record high temperatures, which caused higher rates of evaporation. Low rainfall also led to very low soil moisture across large areas of Australia during 2019 (Fig. 7.5). The combined effects of high temperatures, rainfall deficit and prolonged drought resulted in increased fuel availability and very high fire danger indices [176, 18].

The Forest Fire Danger Index (FFDI) is used to estimate the difficulty of fire suppression in Australian forests [179, 180]. It combines wind speed, temperature and humidity with a long term drought factor based on rainfall and evaporation. By Spring 2019, more than 95% of Australian territory had accumulated FFDI values that were very much above average, including almost 60% of the country that was highest on record [181]. The accumulated FFDI for Australia in spring 2019 was significantly higher than any other season on record (Fig. 7.6).

7.7.2 *Impact*

The Black Summer fires were unprecedented for south-eastern Australia in terms of the amount of forested land burnt. The fires burnt about 10 million hectares, destroyed over 3000 houses, killed 33 people and more than 1 billion animals [23] (Table 7.3). With fires burning across several states and territories, fire-fighting resources were stretched and smoke impacts widespread.

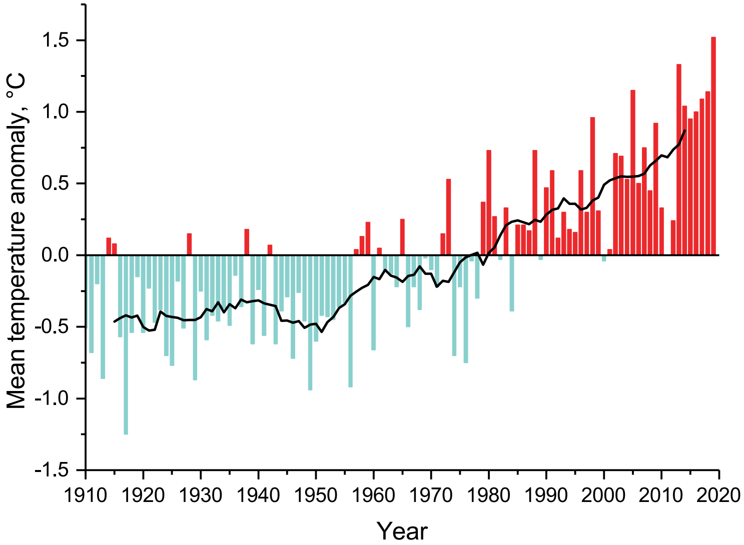

Fig. 7.3 Mean temperature anomalies averaged over Australia. The black line shows the 11-year moving average [175]. (Source: This figure was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020)

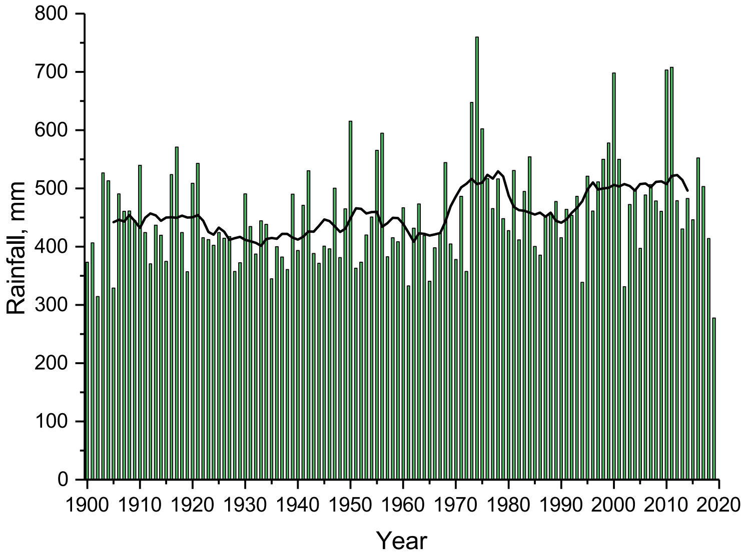

Fig. 7.4 Annual mean rain. The black line shows the 11-year moving average [175]. (Source: This figure was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020)

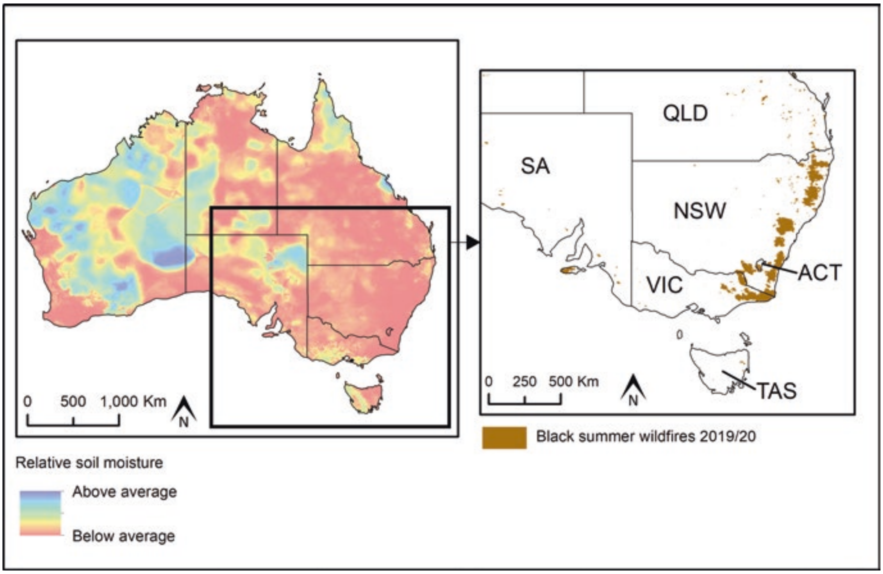

Fig. 7.5 Modelled soil moisture on 30th December 2019 relative to historic patterns (data acquired from AWRA-L water balance model [177]) and wildfire extent in south-eastern Australia for the Black Summer wildfires (data acquired from [178])

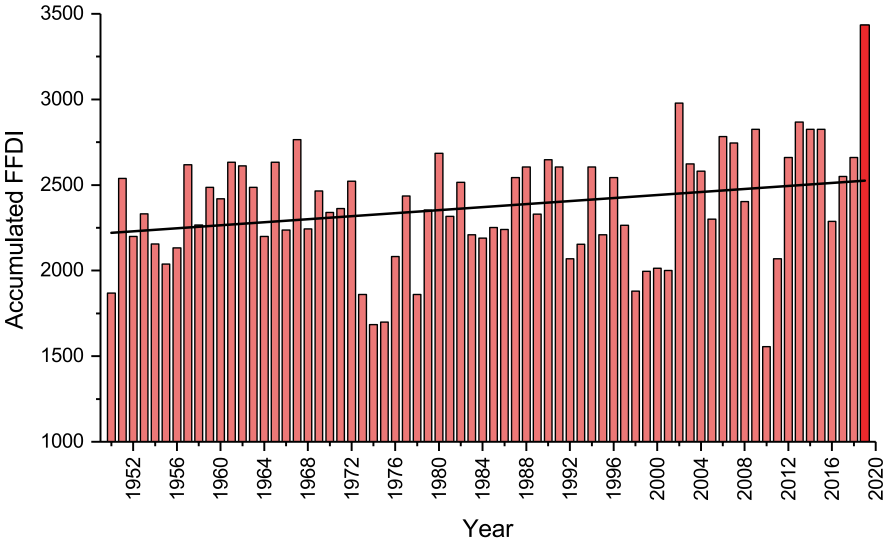

Fig. 7.6 Spring accumulated FFDI values for Australia from 1950 to 2019 [181]. Accumulated FFDI for spring 2019 shown in dark red. Linear trend line shown in black. (Source: This figure was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020)

Impacts on Communities

New South Wales (NSW), Victoria (VIC), and South Australia (SA) were the most impacted States in terms of lives and houses lost [23]. The fires impacted many coastal towns and parks during the peak summer holiday season, when many tourists were visiting the area.

NSW. A total of 10,520 fires were recorded during the 2019/2020 fire season in NSW (Table 7.3). These fires resulted in 5,595,739 hectares burnt, 25 lives lost, and 2475 houses damaged or destroyed (Table 7.3). Two mega-blazes were recorded. The Gospers Mountain fire started on 26 October 2019 and burned approximately 512,626 hectares, becoming the largest forest fire in Australian history [176]. By 11 January, three fires on the border of NSW and Victoria, the Dunns Road fire, the East Ournie Creek, and the Riverina's Green Valley merged and created a second mega-fire which burned through 895,744 hectares. Fires in NSW burned more area than any single fire season in NSW during the last 20 years (Fig. 7.7).

VIC. 3500 fires in Victoria resulted in 1,505,004 hectares burnt, 5 lives lost, and 396 houses damaged or destroyed (as of 20 March 2020) (Table 7.3). The number of fires and the burned area were one of the biggest in Victorian history. One of the most destructive fires was around the town of Mallacoota in the far east of the State, where 300 homes were lost. A small fire started on 29 December 2019, 30 kilometres west of the coastal town of Mallacoota. The fire spread rapidly in the following

Table 7.3 Fire statistics for 2019/2020 wildfire season across Australia

State	Burned area, ha	Number of fires	Houses lost	Lives lost
Victoria	1,505,004	3500	396	5
New South Wales	5,595,739	10,520	2475	25
Queensland	2500,000	NA	48	0
Tasmania	36,000	NA	2	0
Western Australia	2,200,000	NA	1	0
South Australia	286,845	1324	186	3
Northern Territory	6,800,000	NA	5	0
Australian Capital Territory	60,000	NA	0	0
Total	18,983,588	15,344	3113	33

NA = data is not available

Source: This table was published in Journal of Safety Science and Resilience, volume 1, Alexander I. Filkov, Tuan Ngo, Stuart Matthews, Simeon Telfer, Trent D. Penman, Impact of Australia's catastrophic 2019/2020 bushfire season on communities and environment. Retrospective analysis and current trends, p 44–56, copyright Elseiver, 2020

These figures are preliminary and may be revised when official statistics are released at the end of the 2019/2020 financial year [23]. Statistics for areas burnt in northern Australia are included, however, these areas are not considered part of the Black Summer fires. The fire season in the northern parts of Australia is typified by frequent, low intensity fires during the dry season (April to November) and vast areas burnt annually

Fig. 7.7 After bushfire. Armidable Road, Clouds Creek, NSW. (Photo is taken on January 4, 2020. ©Photo by Elena Filkova, used with permission)

days, leaving thousands of people (both locals and tourists) stranded on the boat ramp and in the surrounding water as the fire reached the water's edge [182]. Roads to Mallacoota were blocked for 37 days due to wildfires and fallen trees and as a result, many people had to be evacuated on two naval vessels.

SA. The 2019/2020 fire season resulted in a total of 1324 wildfires in South Australia. These fires caused 286,845 hectares burnt, 3 lives lost, and 186 houses damaged or destroyed (Table 7.3). On 20 December 2019, a series of lightning strikes ignited the Cuddle Creek fire in the Adelaide Hills [183]. This fire killed one person, burned 23,295 hectares, destroyed 84 homes and hundreds of other buildings and thousands of livestock. This fire also burnt through world famous viticulture and winery areas, and large parts of the water catchment for Adelaide, the state's capital city.

On 30 December 2019, another band of lightning in the remote Ravine de Casoars Wilderness Area on Kangaroo Island ignited fires that became known as The Kangaroo Island Fire [184]. Two people were killed, 89 homes destroyed and hundreds of other buildings including high visitation tourism assets. There were significant livestock losses for local farmers [185] and $100 to $900 million of plantation timber burnt [186]. The Kangaroo Island fires were officially contained on 21 January 2020 after burning 210,000 hectares and lasting for more than three weeks [185].

Impacts on Biodiversity

The scale and intensity of the black summer fires have resulted in a range of impacts on the biodiversity of eastern Australia. Approximately three billion vertebrate animals were estimated to have been killed in the fires [187], not to mention the countless invertebrates, plants, fungi and microorganisms directly affected.

Fires have occurred in many areas that have previously burnt in recent wildfires. For example, in Victoria the fires have led to a dramatic increase in the area of forest that has been burnt more than twice since 2003 (Fig. 7.8). This includes obligate seeder Alpine Ash forest, that is vulnerable to regeneration failure with short intervals (<20 years) between high intensity fires [71]. Such high frequency and high intensity fire regimes may also lead to a decrease in resprouting success and regeneration of trees in fire-tolerant mixed-species Eucalypt forests [188].

The extremely low soil and fuel moistures resulted in the fires affecting large areas of vegetation types that rarely experience fire, especially high intensity fire, such as subtropical and temperate rainforest. About 37% of the total area of NSW rainforests were affected, including 54% of the extent of the Gondwana Rainforests of an Australia World Heritage Area [190]. While some rainforest plants have adaptations that allow them to survive or reproduce after a single fire, repeated high intensity fires at short intervals may result in shifts towards open forest and promotion of more flammable vegetation [191].

The effects of the fires on many individual species are not yet clear, but ecologists fear some endangered species have been driven to extinction [192]. Forty-nine species listed as threatened under the national Environment Protection and Biodiversity Conservation Act have more than 80% of their distribution within the fire boundary [193]. While there is yet to be extensive post-fire monitoring, 486 plants, 213 invertebrates, 92 terrestrial vertebrates and 19 threatened ecological communities are considered to be at increased risk of extinction due to the wildfires and require urgent management intervention according to the Department of Agriculture, Water and the Environment [193].

The scale and severity of the fires has resulted in large impacts on many species with restricted spatial distributions (Fig. 7.9). This is exemplified by the species that

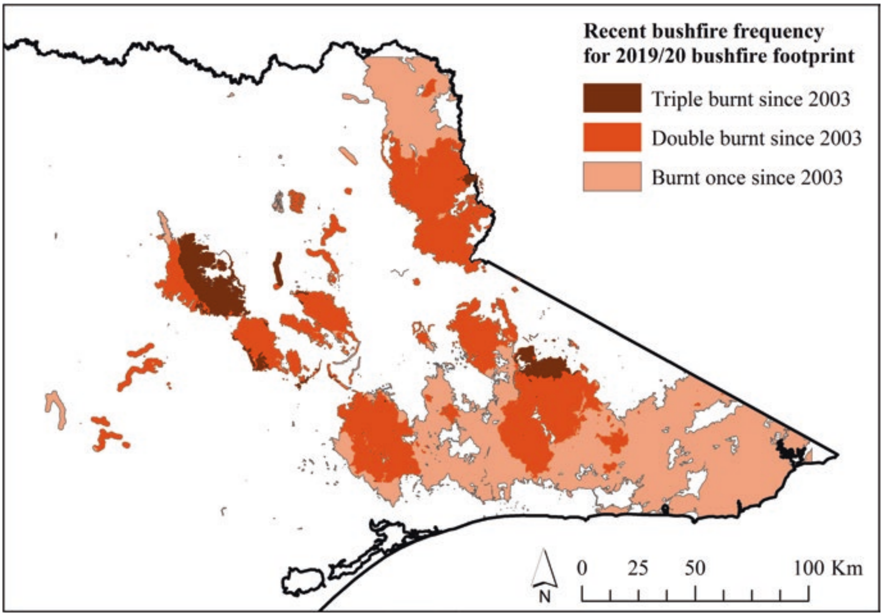

Fig. 7.8 The footprint of the Black Summer Bushfires in Victoria, Australia showing areas that have been affected by recent wildfires [189]

were impacted by the wildfire on Kangaroo Island off the coast of South Australia. More than a third of the island was burnt including most of the native vegetation reserved in protected areas. Experts have expressed concerns over the survival of several endemic endangered species on the island including the Kangaroo Island Dunnart (*Sminthopsis aitkeni*) and a subspecies of the Glossy Black-Cockatoo (*Calyptorhynchus lathami*) [194] that already had small population sizes prior to the fire.

Impacts on Soil and Water

Heavy rainfall following the Black Summer bushfires resulted in elevated levels of surface runoff and erosion in burnt areas, with downstream impacts for water supply and aquatic ecosystems (Fig. 7.10). In Lake Burragorang (Warragamba Dam), Sydney's major water supply, sediment, ash and debris were seen floating on the water surface following heavy rainfall [195]. Water authorities took precautionary action to minimize potential water quality impacts including installing two booms with silt curtains to limit the amount of ash and debris near the dam's supply off-take point [195, 196] and switching the water supply for Sydney to an alternative source following heavy rainfall.

Fig. 7.9 Impacted forest in north-eastern Victoria following the Black Summer fires. (©Photo by Rowhan Marshall, Department of Environment, Land, Water and Planning, used with permission)

Fig. 7.10 High sediment load in the Upper Buffalo river in north-eastern Victoria after the 2019/2020 Black Summer fires. (©Photo by John Costenaro, Department of Environment, Land, Water and Planning. Used with permission)

Numerous measures had to be taken to maintain water supply to towns in the Bega Valley on NSW's south coast following the bushfires [197]. Turbidity levels in the Brogo river and reservoir, a key water supply in the region, were more than 100 times above the safe limit for drinking. The local water authority responded by implementing water restrictions, trucking water into the region at a cost of AUD$30,000 per day, recommissioning water supply from alternative sources and installing additional water treatment facilities [198].

There were severe impacts on aquatic fauna. Tens of thousands of fish were killed in the Macleay River in northern NSW and hundreds of fish killed in Tilba Lake on the south coast of NSW [199]. Critical habitats for threatened aquatic species were damaged by the fires, e.g. Macquarie perch in Mannus Creek [200]. These impacts on fish populations were caused by elevated levels of suspended sediment, which can clog fish gills and smother physical habitat [134] as well as reduced level of dissolved oxygen. Fisheries officers undertook rescue efforts in some catchments to remove threatened fish species from these waterways to repopulate these waterways after water quality conditions improve [200]. However, the combined effect of drought, fire and flood on these systems is expected to have a long-lasting impact on some fish populations [201].

Impact on Air Quality

Smoke from the wildfires shrouded much of Australia's south-eastern coast (Fig. 7.11). According to early estimates from the Global Fire Emissions Database, the wildfires likely contributed 900 million metric tons of carbon emissions [202, 203]. Borchers Arriagada et al. [204] estimated population exposure to $PM_{2.5}$ for NSW, Queensland, the ACT and Victoria between 1 October 2019 and 10 February 2020 and found that $PM_{2.5}$ concentrations exceeding the 95th percentile of historical daily mean values were recorded in the study area on 125 of 133 days. Wildfire smoke was estimated to be responsible for 417 excess deaths, 1124 hospitalisations for cardiovascular problems, 2027 for respiratory problems and 1305 presentations to emergency departments with asthma. Liu et al. [205] estimated that such increases in daily $PM_{2.5}$ concentration could induce an increase of at least 5.6% in daily all-cause mortality, 4.5% in cardiovascular mortality, and 6.1% in respiratory mortality.

Thick smoke covered populated areas of coastal New South Wales and Victoria (Fig. 7.12), including Sydney and Melbourne, particularly from November through to January. Westerly winds continued to blow smoke from fires burning further inland towards the coast, resulting in poor air quality in the Sydney Basin and many

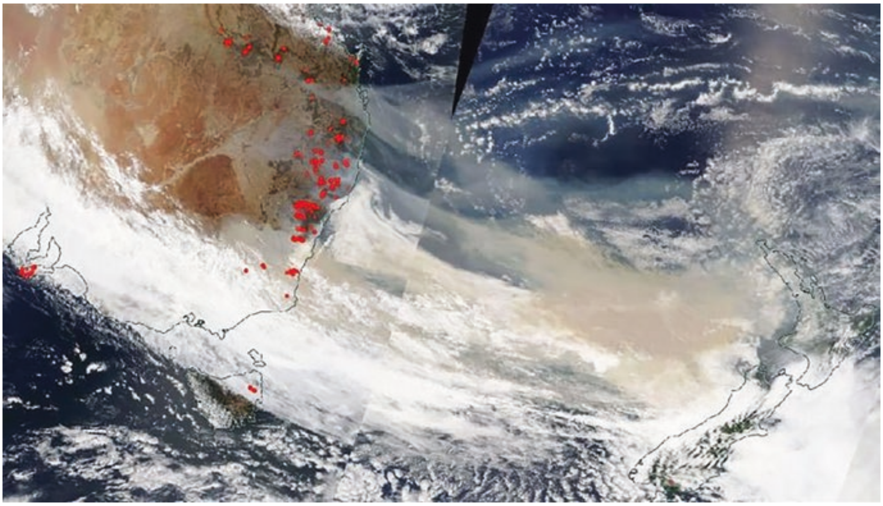

Fig. 7.11 Smoke from wildfires. Red areas represent active fires. This image was taken by NASA's Aqua satellite using the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument on 05 January 2020 [206]. (Open access from https://earthdata.nasa.gov/learn/toolkits/wildfires)

other areas along the New South Wales coast. Sydney experienced 81 days of poor (above 100 μg/m^3) or hazardous air quality in 2019, more than the last 10 years combined. According to Yu et al. [207], in most areas of Sydney, 24-h average of $PM_{2.5}$ concentrations in December 2019 exceeded 100 μg/m^3 (5 times lower before wildfires), which is four-times higher than the World Health Organisation guideline value of 25 μg/m^3. The national capital, Canberra, was also impacted by thick smoke. It experienced poor air quality for 33 days (Civic station) and at one point it had the world's worst 24-h average of $PM_{2.5}$ concentration (714 μg/m^3) [208].

Smoke from the Australian fires covered the whole South Island of New Zealand on 1 January 2020 [209]. The smoke moved over the North Island the following day and affected glaciers in the country, giving a brown tint to the snow. By 7 January 2020, the smoke was carried approximately 11,000 kilometers across the South Pacific Ocean to Chile, Argentina, Brazil, and Uruguay [210].

Impact of Extreme Wildfires

Unprecedented weather conditions and prolonged drought resulted in multiple extreme wildfires. They caused several dynamic fire behaviours, e.g. formation of pyro-convective events, dry thunderstorms and lightning, massive spotting, and fire whirls. At least 18 PyroCb were recorded between 29th December and fourth January in south-eastern Australia [211]. Massive spotting and lightning resulted in two mega fires (>500,000 hectares each) [23]. In NSW flames with 60–70 m height and fire tornados were recorded [212]. One of them flipped a 10-ton fire truck, killing a firefighter. Fast and unpredictable propagation of extreme wildfires resulted in tremendous environmental impact. Further research is being undertaken to fully understand the occurrence and impact of these behaviours.

Fig. 7.12 View of smoke plume from Ovens fire complex in north-eastern Victoria on 16th January 2020. (©Photo by John John Costenaro, Department of Environment, Land, Water and Planning. Used with permission)

Economic

Damage from the wildfires is estimated to have had a $20 billion impact to the economy, greatly exceeding the record A$4.4 billion set by 2009s Black Saturday fires [213, 214]. According to AM Best credit rating agency, wildfires resulted in A$1.7 billion in insurance losses and this is expected to rise [215]. Consulting firm SGS Economics estimated that smoke produced by wildfires caused between A$12 million and A$50 million worth of daily disruption of Sydney [216]. All of the above is likely to make a record impact to the Australian economy.

7.8 Summary

Australia's 2019/2020 wildfire season showed a new level of impact on the environment. Every year in different parts of the world the weather breaks new high temperature and rainfall deficit records. Climate projections show further increases in occurrence and intensity of wildland fires [51, 161].

The effects of wildfire on biodiversity are nuanced and often involve complex interactions between fire regimes and species traits. Fire is in principal, a positive force for biodiversity that has directly driven the evolution of many plants and to a lesser extent animals [217], continuing to be a crucial driver of the life cycles of many species. The greatest risks to biodiversity conservation in fire-prone ecosystems is the emergence of novel fire regimes with climate change and human activities that may push species to extinction and leave certain ecosystems at risk of collapse. Furthermore, interactions between wildfires and other threatening process such as drought, fragmentation and invasive species may compound deleterious effects in the future.

Runoff and erosion from areas burnt by wildfire can have significant impacts on downstream water quality. However, substantial effects are only evident in some instances, particularly when a high severity wildfire intersects with intense rainfall in steep terrain. Streamflow and water yield can also be impacted by the initial loss of vegetative cover and its subsequent regeneration. The level of impact depends on a range of factors including the vegetation type and the severity of the fire.

Smoke from wildfires is seen a significant problem in the future [157, 158]. It impacts on people with cardiovascular and respiratory problems and increases mortality. It also has indirect impact on the economy resulting in disruption of settlements [216] and climate change [147].

Recent increases in the number of extreme fire events [16, 159, 169] and the rapid expansion of the WUI areas [50] is likely to increase their impact. Multiple DFBs in extreme events can manifest simultaneously and at any scale [8] contributing disproportionately to damage and environmental impacts.

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Chapter 8
Firefighting Chemicals

S. J. González-Prieto

8.1 Introduction

8.1.1 Definition and Frequently Used Synonyms

The fire-fighting chemicals (FFCs) are substances, either natural or synthetic, which are used as additives aiming to improve the fire extinguishing effectiveness of water and, therefore, to reduce the social, economic, and environmental impacts of wildfires (see preceding Chap. 12). These chemicals increase the ignition delay time and reduce fire intensity from flaming to smoldering combustion; moreover, they also slow-down the spread of fire, decrease the consumption of fuel and delay the recovery of the combustion process [1–3]. Besides fire-fighting chemicals, (some of) these products are also called aqueous film-forming foams, extinguishment agents, extinguisher agents, fire extinguishers, fire-fighting additives, fire-fighting foams, fire-fighting gels, fire retardants, fire suppressants, flame inhibitors, flame retardants and water enhancers.

8.1.2 Brief History

From almost a century ago, the FFCs are used to fight fires in wildland and built-up areas because of their advantages over the use of water alone [1–4]. In the 1930s, the U.S. Forest Service tested the fire suppression ability of potassium carbonate [5] and then up to 40 different products, based on either single or combined chemicals, being ammonium phosphate the most effective [6].

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By the middle of 1950s, the Operation Firestop in California concluded that sodium calcium borate was the best available FFC [see Davis et al. [7]], promoting the use of FFCs primarily effective by their physical effects (higher or longer moisture retention) on the fuels [8]. However, subsequent studies demonstrated that borates, due to limited or no effect on pyrolysis, are less effective than ammonium phosphate; as they are also corrosive, abrasive, difficult to handle an toxic to plants, their use was discontinued [4, 8].

From late 1950s to early 1970s, several studies demonstrated that viscous or thickening agents improve water extinguishment effectiveness by creating larger droplets [8]. Consequently, the U.S. Forest Service conducted field tests to compare the effectiveness of water modifying retardants and flame inhibiting chemicals [7]. Among the former, bentonite foam (swelling bentonite plus a foaming agent) and several kinds of thickening agents (CMC, sodium carboxymethylcellulose; sodium alginate without or with calcium chloride) were assayed, while the chemical fire retardants tested were ammonium phosphates without or with CMC thickening agent.

Although superabsorbent polymers are available from the early 1960s [9], their fire retardancy properties were fortuitously discovered in 1993 [10], leading to the development of different brands of FFCs based on superabsorbent polymers, usually polyacrylates [9].

Nowadays, synthetic foams and gels, as well as nitrogen- and phosphorous-based compounds are still the most widely used FFCs, although in the last decade increasing efforts have been undertaken to develop more environmentally friendly FFCs (see Sect. 8.4).

The use of FFCs is raising rapidly in the developed countries. Carratt et al. [11] reported a twofold increase for long-term FFCs in California between 2012 and 2015, and pointed out the lack of data on the use of foams. Similarly, from 2009 to 2018 the amount of FFCs employed in the USA increased around 2.7 millions of gallons annually [12]. Worldwide, the consumption of long-term FFCs is around 40,000 Mg year^{-1}, mainly in the USA, Canada, Australia, France and Spain [13].

8.1.3 Mechanisms of Action

The FFCs can enhance fire retardancy of fuels through either chemical or physical actions which can be explained by six basic mechanisms/theories [3, 14]. The first mechanism is to form a fire-fuel glassy barrier which reduces the evolvement of volatile gases, the contact oxygen-fuel and the temperature at the fuel surface. The second mechanism is to reduce the temperature of the fuel surface (thus preventing its ignition) either by enhancing thermal conductivity of fuel, i.e. distributing the energy to the whole volume of fuel, or by adsorbing energy through endothermic reactions of FFCs during their thermal decomposition. A third mechanism is the decomposition of FFCs, evolving non-combustible gases which dilute both the flammable gases from fuel pyrolysis and the oxygen available, helping to quench the flames. The fourth mechanism is to trap the volatile free radicals released by the burning fuel so the propagation of flames is interrupted. The fifth and sixth mechanisms, which operate simultaneously, are to reduce the pyrolysis temperature – so more char and less volatile gasses are produced – and the heat content of the volatile gasses.

8.1.4 Application

All FFCs can be applied from ground or aerial equipment, as fire-trucks, portable devices, fixed-wings airplanes and helicopters [4, 7, 8, 15]. Adequate fuel covering by the FFCs is more easily achieved by ground application which, however, is frequently restricted by the accessibility of trucks and crews to the wildfire. After World War II, first successful applications of FFCs from aircrafts were attained [4, 8], although aerial fire-fighting operations are frequently hazardous due to the smoke and erratic winds. Once a large proportion of FFCs became aerially delivered, their formulations were adjusted to reduce abrasion and corrosion of metals used not only in fire-trucks but also in aircrafts, as well as to improve droplet size and final ground distribution which, besides flight and wind conditions, largely depends on the rheological properties (viscosity, elasticity) of FFCs [2, 4, 16] (Fig. 8.1).

Fig. 8.1 Application of ammonium phosphate (long-term FFC) with ground equipment to create a chemical fire-break

8.2 Types of FFCs

8.2.1 Long-Term FFCs

The distinctive characteristic of long-term FFCs is that their effectiveness, which mainly relies on the dose of retardant applied, remains even after the evaporation of the carrying water used for achieving a good dispersal [17]. A variety of chemicals, each one with different purpose, are included in the formulations of commercial FFCs [16–19]. In the most widely used long-term FFCs, the main components are nitrogen and phosphorous salts (DAS, diammonium sulphate; DAP, diammonium phosphate; MAP, monoammonium phosphate) which retard fire ignition and propagation. To facilitate their application with aerial and ground-based devices, these salts are mixed with thickeners (agar gum, carboxylmethyl cellulose, bentonite or attapulgite clay) to ensure a good and uniform delivery, as well as colouring agents (iron oxide) to mark out the drop sites; moreover, to prevent chemical and biological degradation of the storing and application devices, corrosion inhibitors (sodium dichromate, sodium ferrocyanide, tolyltriazole) and bactericides have been also included in the FFCs mixtures. Recently, the flame retardancy of ammonium polyphosphate and its effectiveness to reduce fuel mass loss have been improved by adding it with 3-(methylacryloxyl) propyltrimethoxy silane [20].

When heated above 166 °C, the ammonium-bearing sulphates and phosphates release ammonia, which contributes to evaporative cooling of the fuels, and either sulphuric or phosphoric acid (and phosphorous pentoxide); these acids react with cellulose from the heated fuels modifying its thermal decomposition pathway, increasing the production of char and decreasing that of volatile compounds [3, 17, 21, 22]. Lignin decomposition, by the contrary, is not significantly affected [3]. In the case of phosphate-based FFCs, fire retarding effectiveness is directly related to their phosphorous content and it is highest in the case of ammonium salts because those with other cations, as sodium, calcium, potassium and magnesium, do not decompose so easily to phosphoric acid [21, 23]. Among the ammonium salts, phosphates are more effective than sulphates in reducing the mass loss of heated fuels, likely because the former decompose at a higher temperature [21]. As a consequence of the incomplete combustion of fuels, the emissions of smoke and airborne particulates can increase when FFCs are used [1]. According to this latter author, more smoke (and blacker) is produced when mono- and di-ammonium phosphate retardants, which reduce glowing combustion, are applied; by the contrary, ammonium sulphate retardants slightly decrease the production of smoke.

According with Loane and Gould [24], long-term FFCs are effective in fires with intensities up to 2000 or 3000 kW m^{-1} (without and with support of ground crews, respectively), but are no useful for high-intensity wildfires (> 5000 kW m^{-1}).

8.2.2 Short-Term FFCs

These retardants are also a water solution of several chemicals but, unlike long-term FFCs, their effectivity disappears once the carrying water is evaporated or drained out [18]. Aiming to improve the effectiveness of water as fire extinguisher, which was limited by its high surface tension, a variety of short-term FFCs containing foaming agents, wetting agents (anionic surfactants alone or mixed with non-ionic synthetic surfactants), foam stabilizers, dispersants, superabsorbents and corrosion inhibitors have been formulated [9, 11, 17, 18, 22]. Regardless of being foams or gels, the efficacy of the short-term FFCs depends mainly on their ability to increase water retention by fuels (but see Class B foams below), so they remain more time insulated from the other two elements of the fire triangle: the sources of ignition (heat) and oxygen (air).

Foams enhance the extinguishing capacity of water by slowing its evaporation and increasing its adherence to the fuels, thanks to the foaming agents, as well as by increasing water penetration into fuels, thanks to the wetting agents [17, 18, 22, 25, 26]. While Class A foams are based on hydrocarbon surfactants, Class B foams contain both hydrocarbon and fluorocarbon surfactants. Class A foams are employed to fight all types of wildfires, whereas Class B foams are specifically used in fighting hydrocarbon-fuel fires and, thus, could be occasionally used in wildland-urban interphase fires [11, 27]. Class B foams are a mixture of anionic and amphoteric fluorocarbon surfactants, hydrocarbon surfactants and corrosion inhibitors (tolyltriazole) dissolved into glycol ether [27]. Unlike the hydrocarbon ones, fluorocarbon surfactants are not only hydrophobic but also oleophobic and their halogenated compounds trap the volatile free radicals released by the burning fuel, helping to interrupt the propagation of flames; fluorocarbon surfactants also showed a higher thermal and chemical stability and, consequently, a longer-lasting persistence in the environment [27, 28].

The third type of short-term FFC, called water enhancers in some publications, are based on water superabsorbent polymers. Several products have been formulated with sodium or potassium polyacrylate as primary ingredient, but others use trade secret ingredients or mixtures of synthetic terpolymer (based on acrylic acid, acrylamide and acrylamidopropane-sulfonic acid sodium salt) with an oil-phase, fatty acid ester. Like the related hydrogel superabsorbent additives developed for improving soil water retention capacity, these FFCs are able to absorb several hundred times their weight in water and to produce a sticky aqueous gel which, unlike foams, does not contain air bubbles but a bubble-like shell encasing water droplets. By cutting-off the oxygen supply to the combustion process and through thermal diffusion, these FFC smother the flames and cool the burning material (Fig. 8.2).

Fig. 8.2 Superabsorbent polymer (short-term FFC) applied with ground equipment 20 h before to create a chemical fire-break

8.3 Side Effects of FFCs

During wildfire fighting, FFCs may enter into contact with all components of the target ecosystem, from soil to water and air, as well as all living organisms, people included [1]. Therefore, care must be taken when using FFCs because they contain a wide variety of chemical elements (mainly phosphorus, sulphur and nitrogen, but also aluminum, antimony, boron, bromine, chlorine and fluorine) and synthetic compounds which can have deleterious effects on humans and the environment.

8.3.1 Environmental Effects

Besides in wildland-urban interphase fires, the FFCs are mostly employed to fight fires in wildland areas with high ecological or landscape values; consequently, all their possible impacts on the environment must be carefully taken into account [1, 16, 17, 29–31].

Among the chemicals widely used at present in long-term FFCs, higher environmental adverse effects can be expected from the ammonium, phosphate and sulphate radicals [1, 15], although some performance ingredient can also be deleterious for sensitive species and the mixtures of individual ingredients can present additive risks [15]. Regarding short-term FFCs, their surfactant ingredients showed the highest detrimental effects, especially in aquatic systems [16].

In addition to the respective chemical compositions, the environmental impacts of FFCs are influenced by both biotic and abiotic factors. Among the first ones, the species and biological communities must be considered [15, 16]. The abiotic factors ranged from site-specific characteristics, such as the topography of the surrounding land, to the size, water level and geographical isolation of water bodies [1, 32, 33], and quality and hardness of water [18, 19, 25, 34]. Moreover, the environmental persistence of FFCs is also largely dependent on soil type, soil organic matter content and cation exchange capacity [2, 15, 35], as well as on weather patterns, particularly above or below average rainfalls after FFCs applications [2, 16, 22, 33, 36–39].

Aquatic Ecosystems

Even though moderate toxicity of long-term FFCs to algae have been reported [34], these kind of FFCs containing large amounts of nitrogen and phosphorous can stimulate algae growth [17], leading to changes in water characteristics (pH, transparency, and levels of dissolved oxygen and chlorophyll a) indicative of aquatic ecosystems eutrophication [1, 29, 32].

Aquatic bottom-dwelling fauna can be physically affected by the accumulation of thickener additives from long-term FFCs, which can both impair its fixation to the substrate and clog their respiratory systems [19, 34].

According to the most up-to-date assessment of the ecological risks of long-term FFCs [15], acute toxicity for aquatic animals would be unexpected in the case of runoff from land receiving long-term FFCs. By the contrary, toxic effects will be detected in sensitive species if long-term FFCs are accidentally applied across small streams, and all long-term FFCs showed toxicity to both sensitive and non-sensitive species in the case of accidental spills into small or large streams [15]. Toxicity of long-term FFCs for aquatic fauna is due to either unionised ammonia – to which fish are less tolerant than macroinvertebrates – or hydrogen cyanide [8, 18, 19, 35]. Ammonia and free cyanide originate, respectively, from the dissociation of ammonium salts and sodium ferrocyanide (a corrosion inhibitor phased out in some modern formulations); dissociation of the former increases with water pH and temperature while that of the latter increases in the presence of water and UV-B. The concentration of ammonium in long-term FFCs is up to 120 times higher than the US EPA threshold to protect aquatic organisms from unionized ammonia [34]. According to US EPA terminology, the acute toxicity of ammonia is high for diverse aquatic invertebrates and the aquatic stages of amphibians, and very high for freshwater bivalves and fish [15], which explain the massive fish mortality after accidental spills into waterbodies reported from the mid twentieth century [2]. Moreover, ammonium and unionized ammonia have a joint toxicity effect enhanced by water hardness [19, 34]. The entry of phosphate-based FFCs into seasonal or salt wetlands modifies the structure of their invertebrate communities, with a decrease of abundance, taxonomic richness and biodiversity as the FFC dose increases, the reduction being much higher in lonely wetlands [33].

The main responsible for the deleterious effects of short-term FFCs on aquatic ecosystems are the surfactant ingredients [16] – more specifically their anionic portion [18] – to which invertebrates are more sensitive than fish [19, 34]. Several authors have reported a moderate toxicity of short-term FFCs to algae, as well as negative impacts on mobility and oxygen uptake of aquatic animals, leading to a decrease or even local extinction of some taxa [19, 34], particularly among those that use the water surface [16]. Moreover, the surfactants modify the permeability of biological membranes and, therefore, can enhance the uptake of pollutants already present in the waterbodies [2]. To be safe for aquatic organisms, surfactants from short-term FFCs must be diluted by 3–6 orders of magnitude [16, 19], because their toxicities for zooplancton and several fish life phases is 10–100 times higher than that of long-term FFCs, and can increase with time [18, 19]. The exception seems to be the river macroinvertebrates adapted to harsh natural conditions because their assemblages showed no effects of FFCs foams on composition and species richness [16]. Little is still known about the effects of foams containing fluorocarbon surfactants on aquatic ecosystems. While other ingredients of these foams are biodegradable (alkyl sulphate surfactants; butyl carbitol solvent), the fluorinated compounds showed high stability to temperature and most acids, alkalis, oxidants and reductants, so only the non-fluorinated fraction of the molecule seems to be biodegraded [27]. It is suspected that fluorocarbon surfactants can adversely affect the groundwater microbiota and feather waterproofing in birds; moreover, the available information points to a moderate or high toxicity for marine and freshwater organisms, bioaccumulation in fish, and diseases, or mortality, on waterfowls [27].

Even taking into account the negative impacts on all trophic levels previously discussed, a risks/benefits analysis on the use of FFCs in aquatic ecosystems will likely show that they can be considerably lower than those derived from the massive entry of ashes and sediments eroded from the burnt areas [2]. Nevertheless, care to prevent accidental applications or spills into wetlands – in its broadest sense – and their surroundings is strongly recommended.

Terrestrial Ecosystems

As recently as in 2006, Couto-Vázquez and González-Prieto highlighted their surprise by the scant studies about the effects of FFCs on soils, in spite of their key role as the base of all terrestrial ecosystems. Transient acidification and salinity increase have been reported in soils receiving long-term FFCs based on ammonium sulphates and phosphates [40]. A substantial fraction of the ammonium contained in these FFCs is volatilized by the fire, but up to a third of it is leached from soils, mainly after its nitrification [41]. A variable proportion of phosphate from long-term FFCs also reached the subsoil by lixiviation [40, 42]. Basanta et al. [43] reported a decrease of net nitrogen mineralization, and even net immobilization, in soils receiving a superabsorbent-based FFC. Conversely, increased availability was recorded during 1 year for nitrogen [29] and 10 years for phosphorous [31] in a soil where an ammonium-phosphate long-term FFC was applied. Similarly, the

Fig. 8.3 Image of the area burnt by the Laza wildfire (NW Spain, 2010) where ammonium phosphate (long-term FFC), containing a red colouring, was aerially applied during the fire-fighting operations

application of an ammonium-sulphate FFC increased temporarily sulphur availability in soils [40] (Fig. 8.3).

The FFCs-derived ammonium can enhance silicates weathering and displace some cations from the soil exchangeable complex (sodium, iron and silicon, but not aluminium, manganese and copper), leading to increased concentrations in the soil solution and leachates [44]. Leachates from soils with diammonium-phosphate FFC became more acidic and, thus, can solubilize macronutrients and trace elements (calcium, copper, manganese, lead and zinc, but not chromium); conversely, magnesium carbonate FFCs lead to alkaline media, lowering calcium, copper, magnesium and zinc solubility [45, 46].

In the so-called Tomiño experiment set-up in an Atlantic heathland where a retardant, a foam and a water enhancer gel were applied, the prescribed fire triggered short-lived changes in the availability of manganese and zinc (increase), and iron and cobalt (decrease), which were enhanced by the three FFCs [47]. The effect on manganese availability and the iron/manganese ratio persisted after 5 years [30], but not after 10 years [31].

Also in the Tomiño experiment, the impact of the prescribed fire on soil microbial communities seemed to be stronger than that of the assayed FFCs, although persistent effects of the long-term retardant and the superabsorbent-based gel were recorded [48, 49]. In addition, the retardant showed a long-lasting effect on an enzymatic activity of the carbon cycle (β-glucosidase), but not in other of the nitrogen cycle (urease), while the superabsorbent gel was apparently difficult to biodegrade [48] and induced changes in the soil microbial diversity [50].

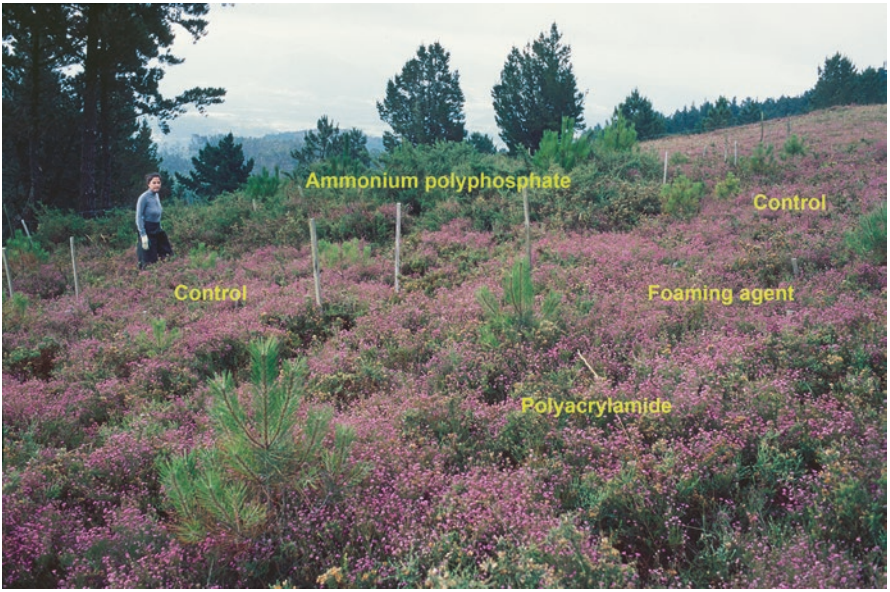

Fig. 8.4 Tomiño experimental field after 5 years [30]. Burned plots without (control) or with a long-term (ammonium polyphosphate) and two short-term (foaming agent and polyacrylamide-based water enhancer) fire-fighting chemicals. *Image previously published in* [52]

Across all vegetation strata of Australian heathlands, Bell et al. [51] reported quick and extensive death of shoots and plants from key species receiving long-term FFCs with ammonium salts of phosphate and sulphate; although overstorey plants recovered rapidly, 1 year later the coverage of many understorey species was still low. The high levels of ammonium supplied by these FFCs inhibited the growth of some leguminous and triggered changes in species richness which could be advantageous for some weeds and invaders [17, 51], leading to changes in the composition and structure of the vegetation community [39].

Seed germination and viability are reduced by low osmotic potentials in the surrounding solution, as in the case of high salts concentrations after the application of long-term FFCs rich in ammonium and phosphates [38, 39]. While seed germination can be stimulated by moderate concentrations of available nitrogen [38], in the case of herbaceous plants it was completely inhibited by the very high initial levels of ammonium and phosphorous supplied by a retardant FFC [29]. Moreover, the excessive concentration of these two macro-nutrients could impair the plant assimilation of some micro-nutrients, as iron and zinc [47].

Contrasting with the short-term negative effects on seeds, the nitrogen- and phosphorous-rich FFCs can benefit plant growth at the medium-term [39] acting as fertilizers that enhance plant cover and biomass [17, 30].

Some foams employed as short-term FFCs are phytotoxic in laboratory conditions, but only little and transient effects of foams have been documented in field experiments [30, 53]. Nevertheless, Adams and Simmons [17] found that FFCs

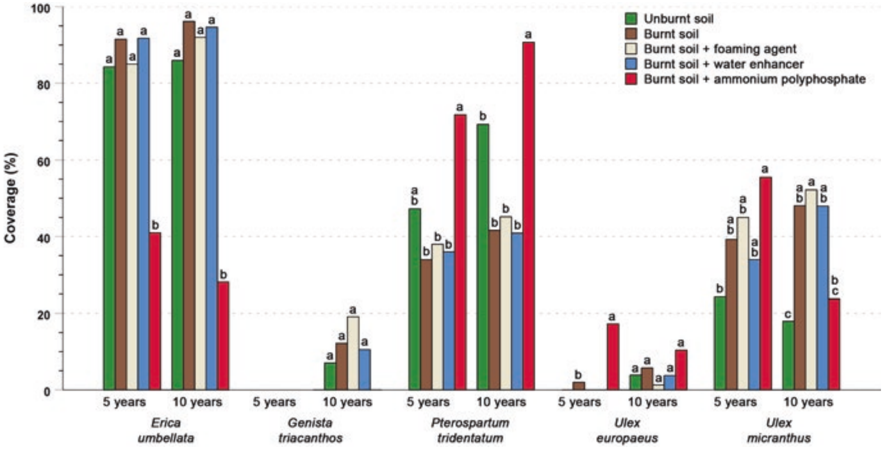

Fig. 8.5 Cover of the shrub dominant species at the Tomiño experimental field 5 and 10 years after a prescribed fire and the application of a long-term (ammonium polyphosphate) and two short-term (foaming agent and water enhancer) fire-fighting chemicals. For each species and year, different letters indicate significant differences among treatments. Based on the data of [30, 31]

foams can damage shoots, suppress flowering and cause foliage death, and there are inconclusive evidences of decreased pine viability by a water enhancer gel [30, 31] (Fig. 8.5).

Concerning terrestrial animals, early assessments suggested that FFCs, either short- or long-term, were not hazardous for ants, earthworms, adult birds (a raptor, a ground nester and a songbird) and a rodent [54, 55]. However, recent studies showed that all tested single ingredients of long-term FFCs pose individual or additive risks to sensitive vertebrate species, a few ingredients posing risks also to some non-sensitive species [15]. Risks of the commercial long-term FFCs are most frequent for omnivore small mammals, followed by songbirds and raptors, ground nester birds and small herbivore mammals, and large herbivore mammals [15]. No risks for carnivore mammals or ruminants were detected, while data on long-term FFCs toxicity to reptiles and terrestrial stages of amphibians are still insufficient to assess the risks for them [15].

8.3.2 Human Health

A large proportion of substances included in FFCs are also commonly used in agricultural and domestic activities (fertilization, cleaning, painting), as well as in products intended for direct human contact or consumption (cosmetics, food preservatives). Consequently, low or no adverse effects on human health are expected [1, 2, 56]. The review by Kalabokidis [1] showed no evidences of systematic toxicity, carcinogenic, reproductive or mutagenic effects of FFCs, except after ingestion or prolonged contact. The highest exposure is expected for fire-fighters, or eventually civilians, accidentally receiving a drench of FFCs aerially delivered, but only the latter would be at risk [11, 56]. Usually, health risks would be negligible for people entering to areas where long-term FFCs have been applied, but, as nitrates levels in soils and some plants can be temporarily high, vegetables from areas where FFCs residues are apparent must not be consumed [56]. During fire-fighting operations with long-term FFCs, people can suffer transient breathing difficulties and irritation of lungs and throat [2] due to higher levels of smoke and airborne particulates, because of the incomplete combustion of fuels, and to the ammonia evolved from thermally decomposing ammonium-bearing FFCs.

Some foams, especially Class B aqueous film-forming foams employed to extinguish fires involving flammable liquid fuels, contain per- and polyfluoroalkyl substances or PFASs [11, 27, 57]. These family of fluorinated molecules, with over 240 individual compounds identified, is known by its chemical and thermal stability and its persistence in soils, sediments and groundwater [27, 57]. Carratt et al. [11] highlighted that results about PFASs on human health are contradictory: while epidemiologic studies are inconclusive, a reduction in fecundity and weight at birth, as well as possible endocrine disruption have been reported for perfluorooctanoic acid and perfluorooctane sulfonate.

8.4 New Generation of Eco-Friendly FFCs

While potassium carbonate was initially considered a promising FFC [5], but latter displaced by ammonium phosphates [4], magnesium carbonate minerals have been recently proposed aiming to reduce the ecological impacts of long-term FFCs [3]. According with these authors, magnesium carbonates decompose endothermically at 200–400 °C, contributing to flame quenching by cooling and by evolving non-combustible water vapor and carbon dioxide which dilute the combustible gases from fuels; moreover, magnesium carbonates create a ceramic barrier which protects fuels from flames and heat. However, these minerals, which modify lignin decomposition, are less efficient to reduce fire spread than sulphate and phosphate based FFCs, which alter cellulose decomposition [3].

Like for long-term FFCs, in recent years there has been an important increase in research efforts for developing new environmentally friendly and biodegradable short-term FFCs. For example, compared to synthetic detergent-based foams, Kawano et al. [58] found that a natural soap-based foaming agent was significantly less toxic to aquatic organisms, including paramecia, hyacinth plants, freshwater snails and Odonata nymphs. In the same way, other research teams developed novel firefighting foams consisting of soaps, a biodegradable chelating agent and diluents [25, 59], natural surfactants [60] and a mixture of sodium alkylobenzenesulphonate and non-ionic surfactant poly(oxypropylenediol)–propylene glycol [26]. Regarding the highly specific fluorinated-FFCs, the only alternative proposed to date is a foam formulated with alkyl glucose amide and organosilicone surfactant [28].

8.5 Summary

Fire-fighting chemicals are a valuable resource for extinguishing wildfires, up to the point of being irreplaceable in some circumstances, but their confirmed or suspected effects on human health and the environment must be carefully take into account to decide when, what and how they must be employed. As a rule of thumb, the precautionary principle must be applied and prolonged or intense exposure of people to FFCs should be prevented and, unless their eco-friendliness have been verified, FFCs should not be used in valuable ecosystems harbouring sensitive or endangered species.

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Chapter 9
Tools and Techniques for Impact Analysis

Margaret McNamee, David Butry, and Joshua Kneifel

9.1 Introduction

Fire can impact the environment as a result of the fire itself, fire suppression activities and actions taken to restore or replace the material damaged in the fire. The initial source of the impacts are emissions from the fire, i.e. products of combustion that are carried in the plume and dispersed into the air. When these products settle into the ecosystem, aquatic and terrestrial impacts can follow. Impacts of fire suppression are largely aquatic and terrestrial, with firefighting water runoff carrying fire products and suppression agents (including chemical additives) into waterways and/or ground water, or directly into the soil. In terms of embodied impact, the impact of fires is primarily caused by the production and replacement of material lost due to fire damage. The damage caused by emissions will be highly dependent on the sensitivity of the recipient. Thus, any environmental risk evaluation must be built on an understanding of the source, emission pathways and vulnerability of the recipient environment. This can be exemplified in Fig. 9.1 below.

A variety of methods can be used to assess the relevance of different mitigation methods to minimize the environmental impact of human activities, including risk assessments, cost-benefit assessments, life cycle assessments and a variety of hybrid models. This chapter will consider the types of impacts through emissions, models for assessing the impact of these emissions and mitigation efforts to minimize these impacts.

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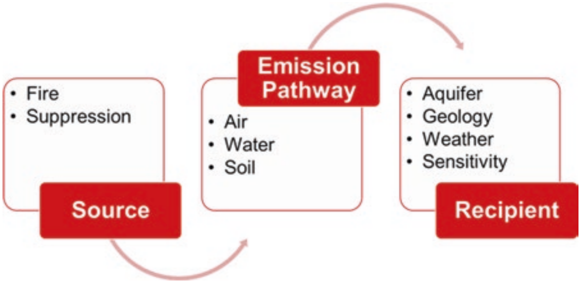

Fig. 9.1 Relationship between source and recipient in an environmental risk assessment of fires

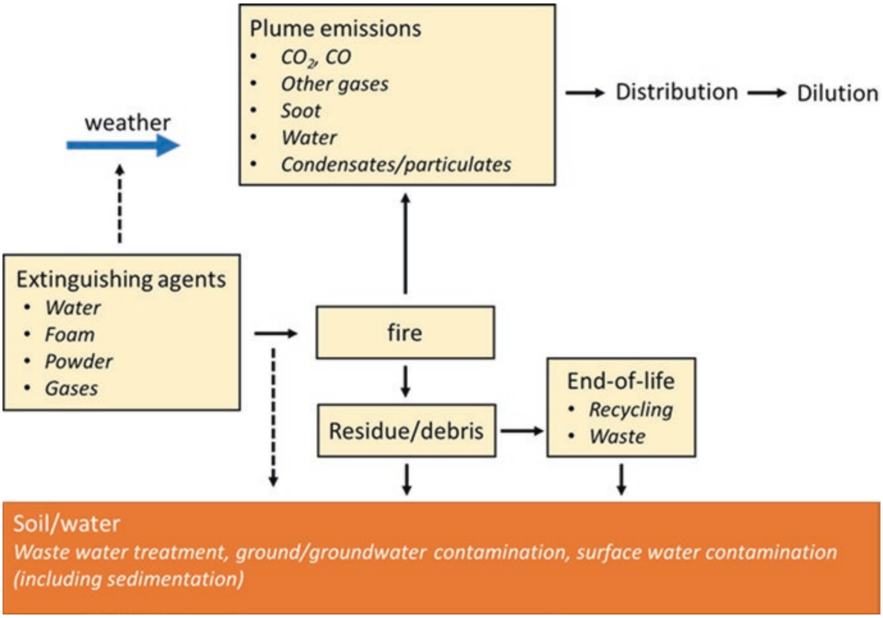

Fig. 9.2 Schematic representation of impact of fire on the environment [37]

9.2 Emission Sources

A significant amount of work has been done since the 1980s onwards to characterize the emissions of various chemical species fires and burning specific materials (see for example [1–6]). The vast majority of studies found through a literature search are related to material emissions or forest fire emissions (see for example [7–14]) with few being available for products that are relevant for the built environment (see e.g. [15–36]).

Emissions from fires are typically characterized as illustrated in Fig. 9.2. The fire emits gaseous species, particulates, and aerosols to the environment in the fire plume. The plume is distributed based on impact from the weather and geographical conditions. Those species not emitted to the fire plume will remain at the fire scene as debris. The weather or suppression activities can leach emissions to water or soil environments.

Suppression activities can impact the species produced by changing the combustion conditions (potentially producing a momentary increase in the products of incomplete combustion), can increase transport of species from debris into surface or ground water or in the shape of soil contamination, and can introduce new chemical species (such as firefighting foam or powder) to the ecosystem. The impact on the water cycle and/or soil will depend heavily on the geography of the ecosystem.

Key to developing an understanding of the environmental impact of emissions from fires is an understanding of emissions themselves, and the recipient to which they are emitted. The international standardization committee for Fire Safety (ISO TC92) sub-committee (SC3) focusses on developing a standardized methodology to assess the environmental impact of fires. Their standards represent a series of documents compiling important definitions and instructions concerning assessing the environmental impact of fires and represent an important starting point for the development of a methodology to assess the cost of environmental impact of fires, and are recommended reading. ISO TC92 SC3 has to date developed (or is in the process of developing) the following documents:

- ISO 26367 Guidelines for assessing the adverse environmental impact of fire effluents
- ISO 26367-1 Part 1: General (international standard, 2017, 2019)
- ISO 26367-2 Part 2: Compilation of environmentally significant emissions from fires (international standard, 2017)
- ISO 26367-3 Part 3: Sampling and analysis (working draft)
- ISO 26367-4 Part 4: Incorporating Fires into Models of Environmental Impact (working draft)
- ISO 26368 Environmental damage limitation from fire-fighting water run-off (international standard, 2012)
- ISO 19677 Guidelines for assessing the adverse impact of wildland fires on the environment and to people through environmental exposure (international standard, 2019).

Ecotoxicity is the result of an interaction between the eco-toxicant and the recipient. The ecosystem is the environment where the emission occurs. This includes flora and fauna, air, water, and soil. How toxic or ecotoxic an emission is will depend on the dose, exposure time and sensitivity of the recipient. Certain environmental toxins are extremely stable, persistent molecules with a significant potential to create exposure over a long time. Therefore, even if the dose is low, if the exposure time is sufficiently long there is a potentially significant risk to the environment. Numerous large organic species which can be emitted in a fire are characterized as persistent, bioaccumulative and toxic chemicals (PBTs). Due to their stable and long-lived nature in the environment, low concentrations can be accumulated along the biological food chain to a point where their concentrations have been increased to toxic levels, see Fig. 9.3.

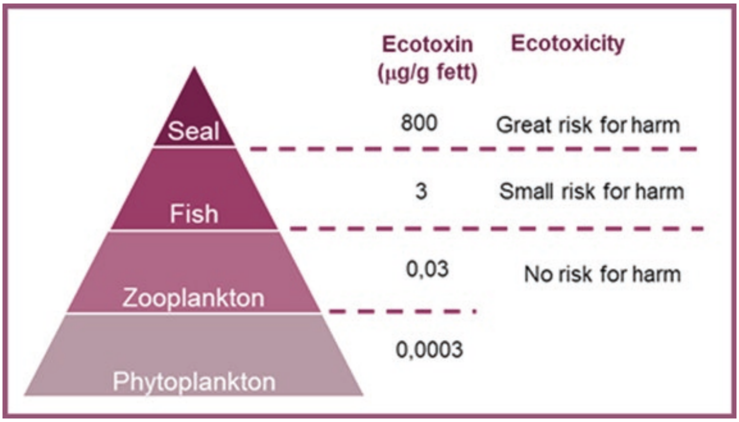

Fig. 9.3 Illustration of bioaccumulation and its impact on ecotoxicity

Table 9.1 Summary of main emissions from fires, impact categories and main recipients

Emission	Distance of greatest impact	Temporal window of greatest impact
Inorganic species (e.g. CO, HCN, acid gases, NO_x, SO_x) Irritant organics (e.g. aldehydes, isocyanates)	Local	Short-term (acute toxicity)
Firefighting agents (e.g. FF-foam additives, powder)	Local/Global	Long-term
Metals and metal salts	Local/Global	Long-term
Particulates (e.g. soot)	Local/Global	Long-term
Large organic species (e.g., dioxins, polyaromatic hydrocarbons (PAH), PCB, persistent organic pollutants (POPs), volatile organic compounds (VOC))	Global	Long-term
Greenhouse gases (e.g., CO_2, CH_4, N_2O)	Global	Long-term

Modified from [37]

Bioavailablity will depend at least in part on whether the emissions are to air, water or soil. Emissions to all three parts of the environment, air, soil and water, will be explained in more detail in the sub-sections below.

9.3 Emission Pathways and Recipients

9.3.1 Emissions to Air

Emissions from fires are typically divided into two main categories either based on geographic distance from the seat of the fire (i.e., local or global emissions), or based on their potential temporal impact (i.e., short-term effects or long-term effects). Table 9.1 gives a summary of common atmospheric emissions which are relevant to consider when investigating the environmental impact of fires. Note that the categories are not mutually exclusive and some species may be present in more than one category, e.g. some irritant organics are also large organic species, and some inorganic species are greenhouse gases. It is important to keep in mind that the impact (and potential cost) of emissions is also highly dependent on the sensitivity of the recipient.

An important part of understanding the environmental impact of emissions from a fire requires us to be able to estimate concentrations of different species at different distances from the source of the emissions. Plume modelling can be used to estimate distribution of emissions in the air. A variety of models are available which can account for weather and topology surrounding the emission source. Early work mainly considered integral models where the profiles of various physical quantities are assumed in the cross-sectional planes perpendicular to the external impact of wind. Wilson [38] and Turner [39] have both made summaries of such applications. In the early 2000s the National Institute of Standards and Technology (NIST) developed an open software ALOFT (a large outdoor fire plume trajectory) to predict downwind concentrations of smoke and combustion products [40]. Computational fluid dynamics programs have also been developed to include outdoor smoke movement although these can be computationally slow, e.g. Fire Dynamics Simulator [41].

9.3.2 Emissions to Water

Fire emissions to water can be due both to direct emissions from the fire and from firefighting activities which take place as an intervention trying to minimize the overall impact of the fire. Recently, a study of the impact of firefighter intervention on fire emissions and their environmental impact [42] addressed the question of how to assess the combined environmental impact in terms of local and global effects using the Fire Impact Tool. The work is based on division of the risk assessment into an Environmental Risk Assessment, which considers local impacts and the use of an LCA-based methodology to assess the global impacts.

Emissions to water can occur in a variety of ways, e.g.

- Deposition of emissions borne in the fire plume. The heavier the particle, the closer to the source of the fire it is be expected to be deposited.
- Leaching from fire debris through rain or extinguishing water.

The water cycle allows numerous points of interaction between a fire. See Fig. 9.4 for an overview of this interaction. The impact of rain or suppression on the interaction is to increase the risk of leaching from the fire into the water cycle. Once fire emissions have reached surface water, they can rapidly be distributed long distances depending on the rate of flow of the surface water. In this context a fast-flowing river can provide a highway for transport of emissions over long distances.

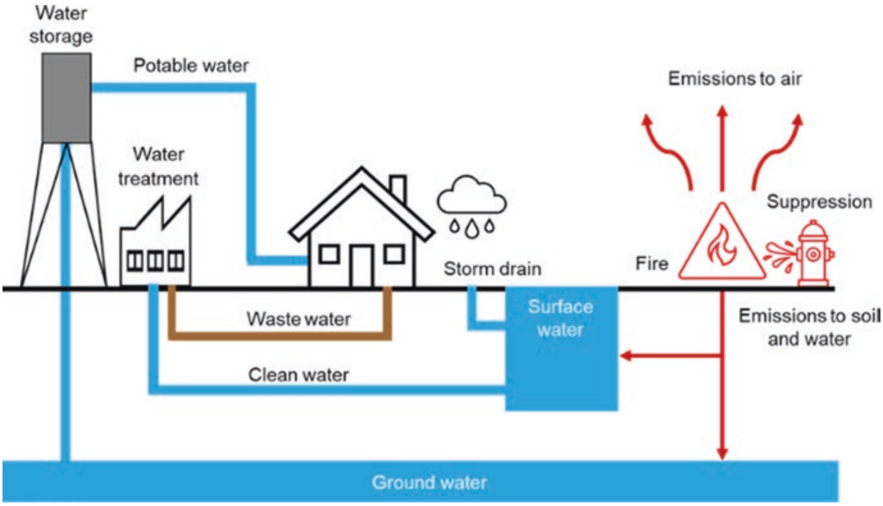

Fig. 9.4 Schematic overview of water cycle and access to it from a fire

While a high-water flow leads to significant risk of spread of eco-toxicants it also leads to rapid dilution of the emissions. Of particular interest in this context is the chemical stability of the eco-toxicant and risk of bioaccumulation through the food chain as explained in the previous section. Even very low concentrations can potentially cause lasting harm if they have the potential to build up in the ecosystem over a long time. The volume of water required to dilute different species in surface water can be calculated using a simple model based on concentration limits given by relevant agencies:

$$V_{dilution} \geq \frac{C_i \cdot V_{FW-SW}}{C_{i,tox}} - V_{FW-SW} \tag{9.1}$$

Where $V_{dilution}$ is the volume of dilution necessary to reduce the concentration below lethal levels, V_{FW-SW} is the volume of fire water run-off to the surface water, C_i is the concentration of toxicant i in the fire water run-off, and $C_{i,\,tox}$ is the toxic limit concentration for toxicant i according to local environmental regulation. This value should not be interpreted as a limiting value; but rather a value to obtain a sense of the risk for contamination of surface water. Factors such as bioaccumulation and eco-toxicity must be accounted for to develop mitigation schemes.

Access to ground water implies a risk for contamination of wells within a certain radius from the fire source. Models for the estimation of such contamination rely on an understanding of the retention capacity of the soil and ground water movement through the geology surrounding the emission. Therefore, exposure assessment of wells requires an understanding of the local geology and water system, including both groundwater and surface water. Typically, local maps containing this type of information will be available both from relevant government agencies in any country and the local fire and rescue services. Contamination of local wells should be based on the risk of exceeding acceptable guideline values for potable water. If we assume that the change in concentration of toxicants in the groundwater is only affected by dilution taking place due to groundwater flow, the distance to a contaminated well will be directly correlated to the dilution factor of the groundwater (DF_{GW}):

$$D_{GW} = \frac{L \cdot I_r \cdot W}{k \cdot i \cdot d_{mix} \cdot (2y + W) + (y + W) \cdot (L + x) \cdot I_r} \tag{9.2}$$

Where W and L are the dimensions of the emission source where it enters the aquifer, I_r is the groundwater recharge rate (m/year), k is the hydraulic conductivity of the soil (m/year), i is the hydraulic gradient (m/m), d_{mix} is the thickness of the mixing zone in the aquifer (m), y is the width of the aquifer at the well and x is the distance from the emission to the well (m). The parameter d_{mix} can be calculated using the length of the emission source (L) and the depth of the aquifer (d_{aq}):

$$d_{mix} = \sqrt{0{,}0112 \cdot (L + x)^2} + d_{aq} \cdot \left[1 - \exp\left(-\frac{(L + x) \cdot I_r}{k \cdot i \cdot d_{aq}}\right)\right] \tag{9.3}$$

where

$$y = \sqrt{0{,}0112 \cdot (L + x)^2} \tag{9.4}$$

Given all other parameters, an estimate of the distance to potentially contaminated wells (x) can be made. If such parameters are not available, a useful rule-of-thumb to identify a potential radius for contamination is approximately 250 m [43].

The sensitivity of water recipients will depend on a variety of factors, e.g. the presence of a water reservoir or the presence of protected aquatic species or environments. Table 9.2 provides a summary of some factors related to the sensitivity of water in relation to recipients. This table has been modified from Mulholland [44].

9.3.3 Emissions to Soil

The emissions from a fire to soil are both through leaching of contaminants from the fire debris through the impact of rain during or after the event, or through the impact of firewater used during the incident response. The porosity of the underlying geology is crucial to determine the risk of rapid spread of toxicants from the fire source.

Table 9.2 Overview of risk to recipient of emissions to water and soil

Risk/ Sensitivity	Recipient
High	Major aquifer
High	Designated water protection zone (groundwater or surface water)
High	Well, spring or borehole used for drinking water (within 250 m of such)
High	Shallow water table (<2 m)
High	Fissured rock, posing risk of rapid flow to groundwater or surface water
High	Important surface water for industrial or agricultural abstraction (<5 km upstream)
High	Commercial fishery site
High	National heritage site or high value amenity
Medium	Minor aquifer
Medium	Important surface water for industrial or agricultural abstraction (5–20 km upstream)
Medium	Medium value national heritage site or amenity
Low	Non-aquifer
Low	Outside water protection zones
Low	Deep water tables (>2 m)
Low	Clay
Low	Far from drinking water abstraction point (>20 km)
Low	Far from industrial or commercial water abstraction points (>20 km)
Low	Limited access to national heritage sites or amenities

Modified from [43]

This can be illustrated schematically as shown in Fig. 9.5. The time available for response (and potential mitigation of environmental impacts) varies depending on the geology in connection with the emission source. If the fire emissions to soil are above an area with significant clay deposits, movement of toxicants in soil will be slow. In contrast, if emissions are too porous a media then transport of emissions will be faster and commensurate time available for response and mitigation will be lower.

The depth of contaminated soil (D, measured in meters) can be related to the retention capacity of the soil (R_C, measured in m^3/m^3) and can be derived from Eq. 9.5.

$$D = \frac{V_{FW}}{A \cdot R_C} \tag{9.5}$$

Where A is the area of contamination (m^2) and V_{FW} is the volume of firewater run-off. In this context, the soil retention capacity is seen as the ability of soil to contain water when it is completely wetted [42]. This simple model provides the possibility to estimate soil depth for excavation if that is determined to be necessary.

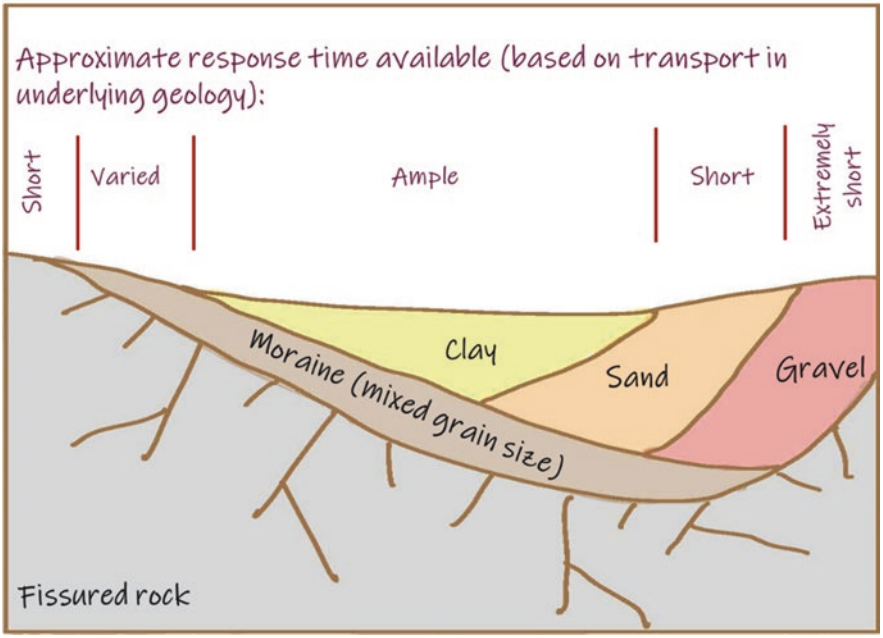

Fig. 9.5 Schematic representation of underlying geology in a specific site and the potential impact on movement of ecotoxicants

9.4 Risk Assessment

Risk assessment combines the likelihood or probability of an occurrence (e.g., event, incident) with its expected consequence (e.g., damage). In this form, it is similar to an expected value. Statistical models can be used to estimate occurrence probabilities and consequences as a function of explanatory variables, such as:

$$Risk_i = \Pr\left(Y_i = 1 \middle| \boldsymbol{X}_i\right) * f\left(\boldsymbol{Z}_i \middle| Y_i = 1\right) \tag{9.6}$$

Where *Pr*() denotes probability function, *Y* is a binary variable (1 = presence, 0 = absence, e.g., fire or no fire) conditioned on a vector of covariates ***X***, *f*() is a function mapping a vector of covariates ***Z*** to consequences, and *i* is the unit of observation. Note that the set of covariates found in ***X*** and ***Z*** could overlap, i.e., a factor that influences the incidence of wildfire could also influence the level of damage (e.g., weather or fuel moisture). The probability distribution could take many forms, and for example, it could follow a Poisson distribution, meaning the probability becomes an expected count of occurrence (e.g., number of wildfires).

ASTM E2506 *Standard Guide for Developing a Cost-Effective Risk Mitigation Plan for New and Existing Constructed Facilities* [45] describes a generalized (three-step) approach for developing a cost-effective risk mitigation plan and is broadly applicable for building and infrastructure systems. The three-steps include:

perform the risk assessment, identify the combination of risk mitigation strategies, and conduct an economic evaluation. ASTM E2506 Appendix X1 provides a list of risk assessment references and software applications. Measures of economic performance are referenced in ASTM 1185 *Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems* [46].

9.4.1 Three-Step Protocol for Economic Risk Assessment

An example of using the three-step protocol is detailed below. Another, more detailed example, can be found in ASTM E2506 Appendix X4 ('A case-study on using the three-step protocol to develop a cost-effective risk mitigation plan against intentionally-set fires'). The example here is based on Abt et al. [47], which evaluates the impact of wildfire prevention programs and law enforcement on human-caused wildfire starts on tribal lands in the United States.

In Abt et al. [47], a risk assessment was performed to statistically evaluate the relationship between the number of wildfire ignitions (by cause-type) and wildfire prevention and law enforcement activity, weather, fire weather, previous wildfire history (acres burned), and temporal and tribal unit fixed effects. The cause-types considered include: campfire, use fire, smoking materials, juveniles, equipment, and incendiary sources. A count model (negative binomial model – similar to a Poisson model, but with fewer methodological assumptions) was used to parameterize the statistical model.

Combinations of risk mitigation strategies were determined using the statistical output from the count model, which could be leveraged to estimate marginal reductions in wildfire ignition counts for a percent change in wildfire mitigation effort. Wildfire prevention programs were found statistically to reduce the number of campfires, use fires, fires set by juveniles, and equipment fires. Law enforcement effort was found statistically to reduce the number of incendiary and equipment fires. Because wildfire mitigation effort demonstrated differential impacts on wildfire cause-types (e.g., law enforcement has the largest impact on incendiary wildfires, prevention education has the largest impact on wildfire caused by use fires) and the expected avoided damages vary by wildfire cause-types, combinations of risk mitigation strategies could be identified to those with the largest economic returns.

Coupling cost data on prevention programs and law enforcement with estimates of wildfires avoided by wildfire-cause type, estimated from the statistical models, economic evaluation, such as benefit-cost analysis (see Sect. 9.5) was performed to determine the economic performance of wildfire prevention programs and law enforcement. In Abt et al. [47], the economic performance of mitigation varied spatially across tribal units, with the benefits outweighing costs by magnitudes from multiples of 4.5 to 38.4 times, demonstrating the significant positive economic returns to wildfire risk mitigation efforts.

9.5 Benefit-Cost Analysis (BCA) and Life Cycle Cost Analysis (LCCA)

Benefit-Cost Analysis (*BCA*) and Life Cycle Cost Analysis (*LCCA*) are two commonly used methods for evaluating the economic costs and benefits of investment decisions. Each of these economic valuation methods will be summarized in this section, including a tool that represents a good example of implementation of these methods for public sector economic analysis. Additional related models will also be mentioned and discussed briefly, e.g. net benefits (savings) (*NB*), internal rate of return (*IRR*) and payback period (*PB*) models.

9.5.1 Benefit-Cost Analysis (BCA)

Benefit-cost analysis is used to evaluate competing investments that have an associated stream of benefits and costs over their life cycle. Discounting normalizes the future streams of benefits and costs into present value equivalents to facilitate their comparison.

Based on ASTM E964 *Standard Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building System* [48], the benefit-to-cost ratio (*BCR*) is defined as:

$$BCR = \frac{\sum_{t=0}^{T} {(B_t - C_t)}\big/{(1+r)^t}}{\sum_{t=0}^{T} {I_t}\big/{(1+r)^t}} \tag{9.7}$$

Where *B* is benefits, *C* is costs, *I* is investment cost, *t* indexes time periods, *T* is total number of time periods (study period), and *r* is the discount rate. This version of the *BCR* calculation is effectively a net benefit to investment ratio. It provides a measure of economic performance of an investment. An alternative measure, which perhaps is the more classic variant, is to evaluate benefits compared to all costs (investment plus other costs). In this case the *BCR* takes the following form:

$$BCR = \frac{\sum_{t=0}^{T} {(B_t)}\big/{(1+r)^t}}{\sum_{t=0}^{T} {(I_t + C_t)}\big/{(1+r)^t}} \tag{9.8}$$

In both forms, a *BCR* greater or equal to unity is economical and a *BCR* below unity is not. However, the relative ranking of competing projects does depend on the form used and should be selected carefully.

In addition to the *BCR*, other (related) measures of economic performance exist, e.g.:

- ASTM E1185 Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems [46]
- ASTM E917 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems [49]
- ASTM E1074 Standard Practice for Measuring Net Benefits and Net Savings for Investments in Buildings and Building Systems [50]
- ASTM E1057 Standard Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems [51]
- ASTM E1121 Standard Practice for Measuring Payback for Investments in Buildings and Building Systems [52].

The Life Cycle Cost Analysis (*LCCA)* method is appropriate when comparing alternatives with similar, or no, benefits (savings). In this case the alternative with the smallest life cycle cost (*LCC)* is preferred. As the other major cost analysis method of choice, *LCCA* will be discussed in more detail in the following section.

The Net Benefits (*NB*) method subtracts present value costs from present value benefits, unlike comparing their ratio in the *BCR* method. Because the *NB* method is not a ratio, it has the advantage of providing a measure of project scale. The *IRR* is computed as the discount rate that yields a *BCR* of unity or a *NB* of zero. Like the *BCR* method, IRR does not provide a measure of scale; however, an advantage of the *IRR* method is that it does not require the selection of the discount rate. The *PB* method computes the length of time until the (net) benefits equal the initial investment cost.

In calculating a *BCR*, costs tend to be easier to estimate as often times they are known or the uncertainty may be better defined. For example, investment cost requirements may be known before the project is selected. Benefits, on the other hand, or *expected* benefits (savings), may be more difficult to estimate, particularly if they occur in out-years, which may increase the level of uncertainty surrounding their estimate.

NIST EDGe$ and Non-traditional Benefit-Cost Analysis

The Economic Decision Guide Software (EDGe$) Online Tool, published by the National Institute of Standards and Technology (NIST), provides a software platform to conduct *BCA* on investment alternatives for increasing community resilience (adaptation, mitigation, recovery) to natural disasters. While EDGe$ was designed to be hazard agnostic, NIST Special Publication 1260 [53] provides a detailed tutorial, illustrating its use, based on a fictitious example focusing on wildfire risk in the wildland-urban interface. The tool, which is based on the NIST 'Community Resilience Economic Decision Guide for Building and Building

Systems' [54], provides a few key features that extend beyond traditional benefit-cost analysis.

The EDGe$ approach encourages identifying and considering co-benefits, co-costs, and externalities. Co-benefits and co-costs are those positive and negative values, respectively, that occur regardless of whether a disaster or disruption occurs. For example, improved ecosystem health and increased forest tourism could be a co-benefit of a fuels management program. Externalities are impacts that accrue to a third-party. Considering externalities can assist in reducing unwanted disproportionate impacts or help achieve other non-risk goals (e.g., sustainability).

In the NIST SP 1260 example, a comparison is made evaluating the (1) retrofitting of a library of historic value by renovating its external envelope, improving its resilience to wildland fire encroachment, with the (2) relocation of the library to a nearby town, an area with significantly less wildfire risk.

The retrofit option included direct costs for improvements made to the rooftop, roof lining, exterior wall, landscaping and LEED-certified upgrades to the energy efficiency of the building (e.g., insulation, lightning). The indirect cost of downtime (loss of revenue) was also considered because the library charged an admission fee. Benefits from the retrofit option included a reduction in direct and indirect losses due to fire damage, partial avoided response and recovery costs, and fewer deaths and injuries.

The relocation option included direct costs of building construction and land acquisition. The annual operations and maintenance costs were also included. Additionally, the town from which the library was moved would incur a loss of a historic asset, and associated revenue generated from related tourism, but this would be in part offset by the resale of the structure and elimination of annual operation and maintenance costs. Benefits from the relocation option included the full reduction of direct and indirect losses due to fire damage, fully avoided response and recovery costs, and no resulting deaths or injuries.

Both options created non-disaster related benefits (benefits that occur in the absence of a wildfire incident) and induced externalities (impacts to third parties). For the retrofit option, non-disaster related benefits ('co-benefits') included increased asset value, reduced noise, energy savings, reduction in maintenance costs, increased staff productivity, and a positive economic shock to the construction industry. The resale of the building and its reuse would also induce some positive economic activity, but would result in lower tourism. For the relocation option, co-benefits included increased tourism and payroll, increased staff productivity, and also a positive shock to the construction industry. In terms of externalities, each option resulted in a change in life safety to the other town.

NIST's EDGe$ was used to conduct the economic analysis based on an assumed planning horizon, wildfire recurrence rate, real discount rate, and a value of a statistical life. The standard output included in an EDGe$-based analysis includes the net present value (i.e., NB), benefit-to-cost ratio (with and without externalities), return-on-investment (both total and just considering co-benefits, and with and without externalities), and internal rate of return. See NIST SP 1260 for more details.

9.5.2 Life Cycle Cost Analysis (LCCA)

Life cycle cost analysis (LCCA) is an economic method of project evaluation in which all costs arising from a capital investment project are potentially important to that decision, whether it is energy efficiency, water conservation, and alternative energy, sustainability and resilience, or safety and security (e.g., fire protection). LCCA is suitable for the evaluation of alternatives at different levels of project or program scope, whether it's a building system, facility or campus, or community scale project. LCC is the total cost of owning, operating, maintaining, and disposing of capital investment(s) over a given study period (usually related to the life of the project), with all costs adjusted to reflect the time value of money through discounting. Based on ASTM E917 *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems* [49], LCC (*LCC*) is defined as:

$$LCC = \sum_{t=0}^{N} \frac{C_t}{\left(1+r\right)^t} \tag{9.9}$$

Where C_t is the sum of all relevant costs, including initial and future costs, less any positive cash flows, occurring in year t, N is the number of years in the study period, and r is the discount rate used to adjust cash flows to present value.

The LCC of a system is generally used to compare with other investment alternatives that can perform the same function to determine which alternative is most cost-effective. These alternatives are called “mutually exclusive” alternatives because only one alternative for each system evaluated can be selected for implementation. Each viable alternative must satisfy all required levels of performance (safety, security, adherence to codes and engineering standards, reliability, resilience to predominant threats), but may have different initial investment costs, different operating, maintenance, and repair (OM&R) costs, and possibly different useful lives. LCCA can be applied to any capital investment decision in which higher initial costs are traded for reduced future cost obligations. An alternative formula used for LCC (*LCC*) provided in ASTM E917 is defined as:

$$LCC = IC + M + R + F - S \tag{9.10}$$

Where IC is the initial cost, M is present value of maintenance and repairs, R is the present value of replacements, F is the present value of fuel, and S is the present value of resale.

The use of LCCA may not stop when a cost-effective project has been identified. There are often several cost-effective design alternatives relative to the baseline scenario. In such cases, LCCA can be used to identify the optimal alternative for that application. This is generally the alternative with the lowest life cycle cost (LCC) or the largest net savings (NS), which is the LCC of the baseline alternative minus the LCC of the alternative being considered. LCCA can also be used to prioritize the allocation of funding to several independent capital investment projects within a facility, campus, or community when insufficient funding is available to implement them all. This application involves the ranking of projects by their savings to investment ratio (SIR) or by their adjusted internal rate of return (AIRR), both of which are supplementary measures of economic performance based on LCCA. These supplementary measures are defined in the following standards:

- ASTM E1074 Standard Practice for Measuring Net Benefits and Net Savings for Investments in Buildings and Building Systems [50]
- ASTM E1057 Standard Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems [51]
- ASTM E1121 Standard Practice for Measuring Payback for Investments in Buildings and Building Systems [52].

LCCA provides a significantly better assessment of the long-term cost effectiveness of a project than alternative economic methods that focus only on first costs or on operating-related costs in the short run (e.g., payback period). The payback method focuses on how quickly the initial investment costs can be recovered, and as such is not a measure of long-term economic performance or profitability. The payback method ignores costs and savings occurring after the point in time in which payback is reached. It also does not differentiate between project alternatives having different useful lives, and it often uses an arbitrary payback threshold. Moreover, the simple payback method, which is commonly used, ignores the time-value of money when comparing the future stream of savings against the initial investment cost.

LCCA is a powerful tool of economic analysis. As such, it requires more information than do analyses based on first-cost or short-term considerations. It also requires additional understanding on the part of the analyst of concepts such as discounted cash flow, constant versus current dollars, and price escalation rates. The alternative, however, is to ignore the long run cost consequences of investment decisions, to reject profitable investment opportunities, and to accept higher-than-necessary operational costs.

One of the most difficult parts of any analysis of capital investment is usually the estimation of future cost savings, particularly for potential savings that have some probability of happening (e.g., fire). Additionally, there is often unavailable information that may require a non-monetary metric or a non-quantitative approach to include in the analysis.

LCCA Analysis Example: Building Egress Design

NIST has provided an example for evaluation of fire-related building capital investments in Chapman et al. [55] and Butry et al. [56] where LCCA is used to evaluate the optimal egress (means of exit) design in several prototype buildings. Egress related measures are a major component of any fire protection strategy in buildings. Decisions on egress design should focus on performance and economic trade-off issues, such as designing for full building and phased-evacuation of occupants, provisions for the evacuation of individuals with disabilities, and counterflow issues between first responders accessing a building and occupants evacuating a building. The goal is to incorporate cost-effective fire protection and life safety systems that result in overall building safety that meets or exceeds the levels required by local building codes.

Egress-related measures entail significant investment costs. In addition to initial capital investments, egress-related measures may result in significant future costs associated with major replacements as well as operations and maintenance costs. In some cases, egress related measures may impinge on rentable floorspace, thus resulting in lost rental income. Therefore, any economic analyses must go beyond an evaluation of first cost considerations, because an alternative with higher first cost but lower future costs may be the most cost-effective choice. As a result, LCCA is appropriate to analyze the costs of selected egress-related requirements evaluating improved egress system designs that promote efficient and timely egress of occupants, including those with disabilities, and that facilitate more efficient fire department operations.

Chapman et al. [55] and Butry et al. [56] compared egress designs for four prototype buildings over 120 ft. (37 m) in height for a 25-year study period. Cost data on alternative configurations for exit stairs and occupant evacuation elevators were collected to support the economic analysis and to serve as an information resource for building owners, fire protection engineers, and other key construction industry stakeholders concerned about egress and life-safety issues in high rise buildings. LCCA results show that occupant evacuation elevators are a cost-effective alternative to the installation of additional exit stairs. For details on this analysis, see [55, 56].

LCCA Software Example: BLCC

An example of a tool that can complete LCCA is NIST's Building Life Cycle Cost (BLCC) which was developed, under sponsorship from the Department of Energy (DOE) Federal Energy Management Program (FEMP), to provide economic analysis of proposed investments in buildings and building systems intended to reduce long-term operating costs. BLCC is designed for evaluating costs and savings related to energy efficiency, water conservation, and renewable energy projects, and for selecting project alternatives with the lowest life-cycle cost. Comparative economic measures can be computed for any project alternative, including NS, SIR, AIRR, and payback period. BLCC complies with ASTM building economics standards and is appropriate for federal, state, and local government and private sector use and is available to the public, along with Life Cycle Cost Methodology for Federal Energy Management Program - Handbook 135 [57] and the Annual Supplement to Handbook 135 [58] that provides updated discount and energy price escalation rates, free of charge at FEMP's website devoted to life cycle costing for buildings [59]. BLCC is updated annually to include the current federal discount rates and the most recent DOE projections of energy price escalation rates published in the Annual Supplement to Handbook 135.

BLCC does not provide probabilistic cost estimates or probabilistic modeling, but cost estimates could be pre-processed and included as one time or recurring future cost(s) estimates. Therefore, BLCC is not optimally designed for fire-related building capital investments. However, BLCC could be used in the near-term and as a basis or template for how to develop fire-related LCCA tools, both for facilities as well as other fire related LCCA.

9.6 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a methodology that was developed in the 1960s and 1970s to investigate, estimate, and evaluate the environmental burdens caused by a material, product, process, or service throughout its life span [60]. An LCA is typically conducted in compliance with the procedures specified in the International Organization for Standardization (ISO) standards ISO 14040 and ISO 14044 [61, 62] or similar standards issued from national standardization bodies. Similarly, non-standardized life cycle thinking can be applied to virtually any situation where a holistic approach is used to estimate the environmental impact of the material, product, process or activity across its life-cycle or some portion of it. At the focus of an LCA is a functional unit, i.e., the material, product, process or service to be studied. Therefore, an LCA ostensibly gives you a complete picture of the functional units' environmental impacts. It lets you see which parts of its life cycle create the most negative impacts on the environment, e.g. the life cycle of an electronic product consumes much more energy during the use phase [63]. Likewise, an LCA helps to identify which impacts are the most significant across the life cycle, e.g., pollutant emissions to water may not be the worst impact at any individual stage of a product life cycle, but when summed across all stages may in fact have the largest impact. The tool is most powerful when comparing different alternatives, e.g. material or production choices, but in relation to fire can be used to examine the impact of tactical choices on the environment [42, 64].

A standard LCA study is structured to have four major components: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation of results, see Fig. 9.6. The development of an LCA is therefore typically an iterative

Fig. 9.6 Components of an LCA according to ISO 14040 [61]

process where each of component is revised as new information from other components is developed, adjusted and readjusted.

The life cycle phases of a product, process or activity are assessed with respect to their impact on the environment (both good and bad) within this structure. Typically, this includes the inception of the materials acquisition through manufacturing on to use, and end of life, which in turn delivers material back to the life cycle. Thus, an LCA is essentially equipped to consider both the environmental impacts from fires directly and from firefighting activities. However, an LCA is typically performed in an "accident-free" life cycle, meaning that fire is not traditionally included as part of the LCA. A Fire-LCA methodology was developed in the 1990s [65] which will be described in more detail later in this chapter.

The ISO methodology is process-based, sometimes termed P-LCA. In other words, inputs and outputs are optimized for every step in the product life cycle. Even for very simple products, this process-based approach can quickly include a significant number of "steps", see Fig. 9.7. A further challenge of P-LCA is related to the question of system boundaries. In essence, we create material, products, processes and services using other materials, products, processes and services. At some point it is no longer practicable to include all necessary aspects of production or use and a boundary must be drawn for the P-LCA, e.g. to produce a sofa, a factory must be built which in turn is built using other machinery and products. The sofa P-LCA should only include all inputs and outputs for those steps within the system boundaries. The data requirements of a full P-LCA are significant and a drawback often is that data quality is varied across the life cycle. Figure 9.7 gives an overview of the number of steps and interconnections between the steps in a simple P-LCA of a sofa.

In response to the challenges of data management and system boundaries associated with P-LCA, an alternative approach has been developed that is built on input-output tables for industry sectors. The methodology was first introduced by the Nobel laureate Wassily Leontief [67] using lessons learned from input-output analysis of economic trends. The basis for the method is that all economic transactions also have commensurate environmental repercussions. In the words of Leontief, "the quantity of carbon monoxide released in the air bears a definite relationship to the amount of fuel burned by various types of automotive engines; the discharge of polluted water into our streams and lakes is linked directly to the level of output of the steel, the paper, the textile and all the other water-using industries…". Input-output analysis describes and explains each sector of a given national economy in terms of the level of activities in all other sectors. Such information is regularly stored and can be associated with relevant emissions. In the IO-LCA methodology, boundary conditions are no longer an issue as whole sectors can now be included. Data requirements are still significant but altered as data needs can be bound to economic data that is traditionally tallied [68]. The environmental impact calculated by the IO-LCA model reflects the average consumption and emission levels of the sector, and has become a mainstream method for analyzing environmental impacts at the macro level for a country or industry sector [69].

Process-based LCA (P-LCA) and input-output analysis-based LCA (IO-LCA) both have their advantages and disadvantages. Presently, three main methods have

Fig. 9.7 P-LCA model for a sofa for domestic use, reproduced from [66]. Note the picture is reproduced to give an indication of the number of steps in the P-LCA of a relatively simple product, the various steps are too small to read

evolved to use LCA, i.e. P-LCA, IO-LCA and hybrid models that incorporate aspects of both P-LCA and IO-LCA, depending on data availability and system aims and scope [70]. The remainder of this chapter will present examples of specialized LCA-based models and Hybrid LCA models.

Common to most LCA-based methods is the presentation of results in a variety of environmental impact classes, e.g. the US EPA TRACI methodology that quantifies global warming potential, acidification potential, human health respiratory effects potential, ozone depletion potential, smog potential and eutrophication potential [71–73]. Which of these end-point impact classes is used will depend on the aim and scope of the application. Indeed, whether to use these endpoints or a variety of mid-point impacts will depend on the specific application [74].

9.7 Specialized LCA-Based and Hybrid Models

Specialized models may be useful in evaluating the environmental implications of fire. LCA-based models have been developed for fire applications, such as the ENVECO tool [64], the Fire Impact Tool [42], and Fire-LCA model [75]. Additionally, hybrid models – models that apply multi-criteria analysis – have been applied to the construction sector that may be directly or indirectly useful in evaluating fire, such as BEES [76, 77]. Multi-criteria models implement life cycle thinking for both economic and environmental analysis through the combination of LCCA and LCA. Although they are focused on sustainability in the built environment ranging from comparing individual building product substitutes to whole building design analysis, these models and their associated tools could be used to evaluate building-related economic losses and/or increased environmental damages from fire-related impacts on a building or building stock. Additionally, these approaches could be used as a basis for developing similar fire-related analysis, models, and tools. The following section will present examples of specialized LCA-based models (including hybrid models), both of which could be appropriate to apply to fire situations or which have been specifically developed for fire applications.

9.7.1 LCA and Hybrid Models in Building Evaluation

The building sector has begun to embrace LCA to improve environmental performance, initially at the individual product level and now at the whole building design level. Although the results target sustainability, these same approaches could be implemented in evaluating fire impacts. These models can be grouped into two categories: LCA models (process-based, input-output-based, or hybrid LCA) and "hybrid" models that include a combination of evaluation criteria and metrics (e.g., LCC and LCA).

Building Products

Numerous models for evaluating the environmental performance of building products have been developed and expanded over the last 30 years. Building product LCAs have been developed as far back as the 1990s and provided in tools such as NIST's Building for Environmental and Economic Sustainability (BEES) and Athena Sustainable Materials Institute's (ASMI) EcoCalculator. However, LCA has only recently begun to be adopted in decision-making by architects, designers, and contractors. Adoption has been driven by both the standardization in LCA modeling requirements by common product types and the growth of green building certification programs that credit documenting the environmental performance of installed materials.

The first and most widely known green building certification program, Leadership in Energy and Environmental Design (LEED), was first released in 2000 with 41 registered buildings. The green building industry has expanded year-over-year with LEED registrations of over 69,000 in 2019. As demand for more sustainable products and buildings has grown, so has the organized response by industry groups, which have been collaborating to develop a common set of rules for product LCA development known as Product Category Rules (PCRs) that are to be used to develop Environmental Product Declarations (EPDs) for specific products.

Several LCA-related tools have been developed to assist in more sustainable product selection. Two already mentioned are BEES (individual products) and EcoCalculator (building assemblies). Athena has also developed a tool focused on pavement (Pavement LCA). The Federal Highway Administration (FHWA) is currently developing an LCA tool and supporting Life Cycle Inventory (LCI) databases for pavement. The remainder of this section will focus on BEES as an example of how building product LCA tools are designed as well as discussion of the BEES hybrid model, which includes both LCCA and LCA analysis of individual building products.

BEES was developed by the Applied Economics Office (AEO) in the Engineering Laboratory (EL) of NIST to meet a need from building stakeholders for practical metrics, data, and tools to support decisions related to sustainable building products. The initial version of BEES was released as a desktop application in 1997 followed by several updated versions throughout the 2000s. In 2010, BEES was transitioned into a web-based application called BEES Online (NIST 2010). Through a combination of NIST-funded and privately-funded data development, over 230 product LCAs have been developed across 30+ product categories based on UNIFORMAT II classification. A complete redesign of BEES, named BEES Online 2.0 (now 2.1), has been completed using the BEES framework in combination with new and updated data sources, methodologies, and processes and easier-to-use interface to update the sustainability results for the building products available in BEES Online. In so doing, AEO is keeping BEES scientifically sound while maintaining consistency with current sustainability evaluation practices desired by industry stakeholders. The BEES Online 2.1 LCAs use the P-LCA approach and are developed based on existing PCRs to ensure the results are consistent with industry consensus LCA practices and has gone through a critical peer review to ensure confidence and acceptance of the results.

BEES is a hybrid model providing economic and environmental performance results. BEES measures economic performance using the life cycle cost (LCC) approach discussed prior. BEES Online 2.1 provides state-of-the-art impact methodologies including TRACI 2.1, Center of Environmental Science of Leiden University (CML) Impact Assessment Characterisation Factors (CML-IA), and

Cumulative Energy Demand (CED) while expanding impact categories to include water, land, and indoor air quality (IAQ). All products can be evaluated using one of three impact methodologies: TRACI 2.1, BEES, and PCR Impact Categories. TRACI 2 includes all TRACI 2.1 impact categories while BEES includes all TRACI 2.1 impact categories plus water use, land use, and IAQ. Selecting PCR Impact Categories will provide the user with only those impact categories specified in the product category's PCR, which could include TRACI and/or CML impact categories. A unique feature of BEES is that users are provided the option to synthesize environmental performance measures into an overall performance measure (Environmental Impact Score - EIS) using the ASTM Standard for Multiattribute Decision Analysis. Figure 9.8 shows the BEES Framework for developing the LCCA and LCA results. Even though this approach can assist some stakeholders by simplifying the comparison in environmental performance, the weighting of impact categories is not allowed by the ISO LCA standards because it includes a subjective approach. Therefore, users can exclude the EIS calculation if desired.

BEES Online 2.1 was released in 2019 with plans to expand available product categories with focus on interior design finishes. A focus on products that have minimal impacts on the relative performance of a building allows for direct comparison of products without the concern of interaction effects of the product with the rest of the building. Products that influence building performance should be evaluated as part of a whole building design.

Other tool development focuses on individual products or assemblies includes ASMI's suite of software tools, including EcoCalculator for Commercial

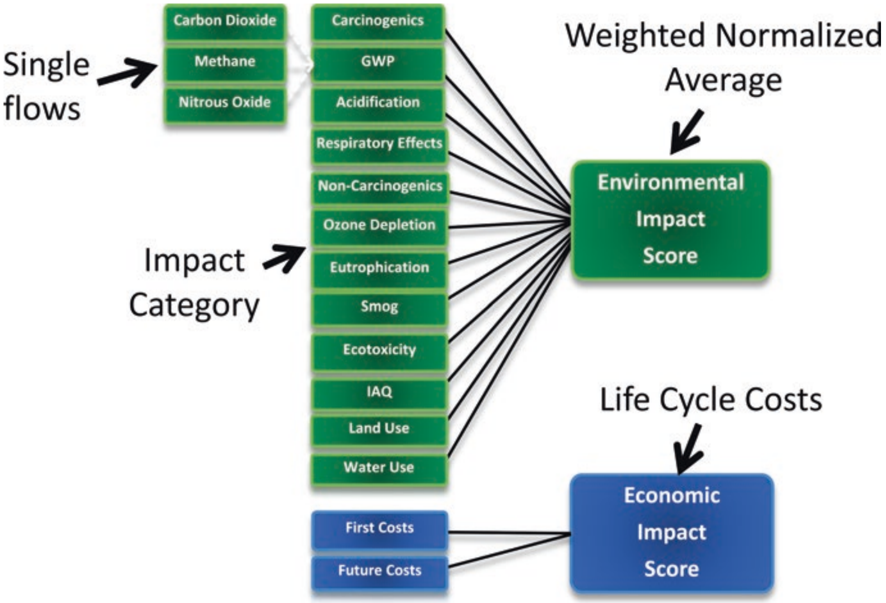

Fig. 9.8 BEES hybrid model framework

Assemblies, EcoCalculator for Residential Assemblies, and Pavement LCA, as well as software that aggregates EPD data (Tally and the EC3 Tool). Development is underway at DOE's Argonne National Laboratory to develop a building (individual product and whole building) LCA module for the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model.

Whole Buildings

Although product LCAs can assist in selecting between comparable products, such as for green purchase acquisitions, it cannot account for the integrated design nature of a building where products and systems interact and influence their relative performance. Therefore, evaluation of an entire building requires the inclusion of LCA results for the products installed in the building as well as activities related to the building during its service life (operational resource consumption, maintenance, repair, and replacement activities, and end-of-life).

To address this issue, tools are starting to be developed to provide a whole building life cycle analysis. Green building certification programs have introduced whole building LCA credits to encourage a more expansive view of the environmental impacts associated with a building. In most cases, P-LCA approach is implemented with a focus on quantifying the life cycle performance of the building structure and envelope by combining the embodied and operational energy LCA results for a buildings service life. For example, ASMI's Impact Estimator for Buildings (IE4B) requires inputs on every material layer in every assembly of the building, develops a "take-off" list of quantities for each material and aggregates the LCA results. Some tools provide an aggregation of LCA results for both generic material/products as well as EPDs for building structure and envelope assemblies, the most widely used of which are the EC3 Tool, Tally, and One Click LCA. These tools have been designed to meet the new whole building LCA credits, which encourages a more expansive view of the environmental impacts associated with a building. However, these tools currently exclude any building system (e.g., heating and cooling, electrical, hot water) related impacts.

An alternative approach is to implement a hybrid LCA model, where a combination of environmental input-output data (IO-LCA) and process-based (P-LCA) data are used to provide a whole building LCA. The U.S. Bureau of Economic Analysis (BEA) creates what are called Input-Output Accounts, or "I-O tables," for the U.S. economy that track economic value flowing across sectors in the economy. Academics have developed "environmentally-extended" I-O tables (Suh 2005, Hendrickson, Lave et al. 2006, Suh 2010) that associate environmental flows with these transactions to estimate flows across industries. A hybrid LCA approach can combine the advantages of both the P-LCA and IO-LCA approaches—namely the use of higher-resolution, P-LCA data and the use of regularly-updated, IO-LCA data without truncation (Suh, Lenzen et al. 2004, Suh and Huppes 2005), generally reducing uncertainty in the results by reducing truncation error in the former and increasing the resolution of the latter (Suh, Lenzen et al. 2004).

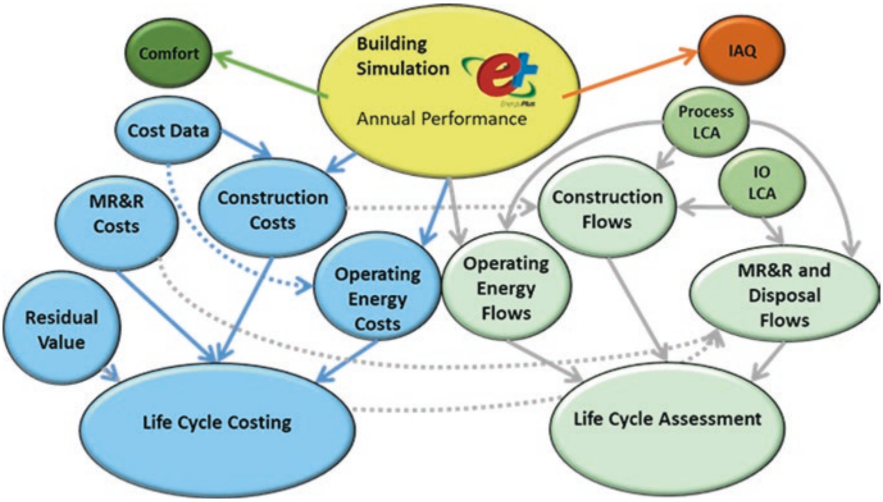

Fig. 9.9 BIRDS hybrid model framework

One example of such a hybrid LCA approach is used in NIST's Building Industry Reporting and Design for Sustainability (BIRDS) framework. "Top-down" IO data for a range of prototypical buildings is used to provide a baseline measurement from national environmental and economic statistics. Detailed "bottom-up" data compiled through P-LCA approaches as implemented in BEES is then then "hybridized" to reflect a range of improvements in building energy efficiency and resulting operational energy consumption.

As in BEES, BIRDS implements a hybrid model for evaluating the life cycle performance of whole buildings. As shown in Fig. 9.9, along with LCCA for the economics and LCA for the environmental impacts, BIRDS also includes building performance criteria and metrics for operational energy and indoor air quality through whole building simulations using DOE's EnergyPlus. By expanding to more criteria, the results can provide a broader scope of sustainability performance. The latest version of BIRDS, v4.1, includes three databases (standards-based commercial buildings database, code-based residential buildings database, and incremental energy efficiency measure residential buildings database).

One of the key shortcomings of BIRDS, unlike the other LCA tools mentioned previously, is that its results are pre-processed based on pre-defined building prototypes and does not allow for sustainability analysis of customized building designs. Architects and designers have interest in their own unique building designs, which will vary (likely significantly) from any prototype building that is selected, whether it's a house or a high-rise office building. A tool that implements the BIRDS framework, including access to the underlying source data, while offering greater flexibility for building designers would benefit the construction industry in meeting ever increasing sustainability goals. Based on discussions with stakeholders and review of other current and planned tool development, it was determined that such a tool must provide maximum flexibility in building characteristics and designs through interoperability with and ability to be executed from highly supported, regularly updated, and freely available building modeling software.

To accelerate a proof of concept and development of such a tool, the most simplistic and impactful capabilities were identified for the initial version. First, the calculations would focus solely on environmental performance using LCA instead of taking a hybrid approach. The two reasons for focusing on environmental impacts are: (1) it is unlikely that users will have access to LCA data and/or technical knowledge of LCA development, and (2) users are likely to have access to cost data that is more accurate for their specific building design than the cost databases that are available to NIST to develop LCC estimates. Second, the calculation engine will limit users to evaluating single-family dwellings. The two reasons for focusing on single-family dwellings are: (1) houses are relatively simple buildings for which to develop LCA estimates, and (2) NIST already has detailed LCA data for a wide range of building components in residential buildings. These two constraints could be relaxed in the future as the tool's capabilities can be expanded.

Based on these characteristics and limited scope, NIST has developed the BIRDS Neutral Environment Software Tool (NEST), which is an application programming interface (API) designed to exchange information with the National Renewable Energy Laboratory (NREL) OpenStudio (OS) software (NREL 2017) to complete LCA estimates for single-family residential buildings. OS allows a user to design a custom building, run whole building energy simulations using EnergyPlus (E+) (DOE 2015), and using its "Measure" capabilities send and receive information on the building's design, operation, and performance as well as display results. OS is free to the public and updated on a 6-month cycle in conjunction with E+. By leveraging the significant capabilities of OS, BIRDS NEST could be designed as a calculation engine without a user interface, allowing for efficient future allocation of resources for maintenance and improvements to the API's capabilities.

After developing a proof of concept for BIRDS NEST, NIST is currently collaborating with ASMI to provide a more robust whole building LCA estimate. BIRDS NEST is being redesigned to pass the necessary information to ASMI's new IE4B web API to calculate the LCA results for the building structure and envelope. BIRDS NEST calculates the LCA results for the building systems and operational energy consumption, aggregates the LCA results for the whole building, and returns the data to OS for reporting. The interoperability between OS, BIRDS NEST, and IE4B is accomplished through standardization of a set of building specification enumerations based on NREL's HPXML format for residential buildings and a common set of impact categories and life-cycle stages based on Standard EN 15978 [78]. The flow diagram in Fig. 9.10 provides the information transfer between OpenStudio, BIRDS NEST, and IE4B. Assuming successful completion of this tool, future expansion could occur in the area of multifamily residential and commercial buildings.

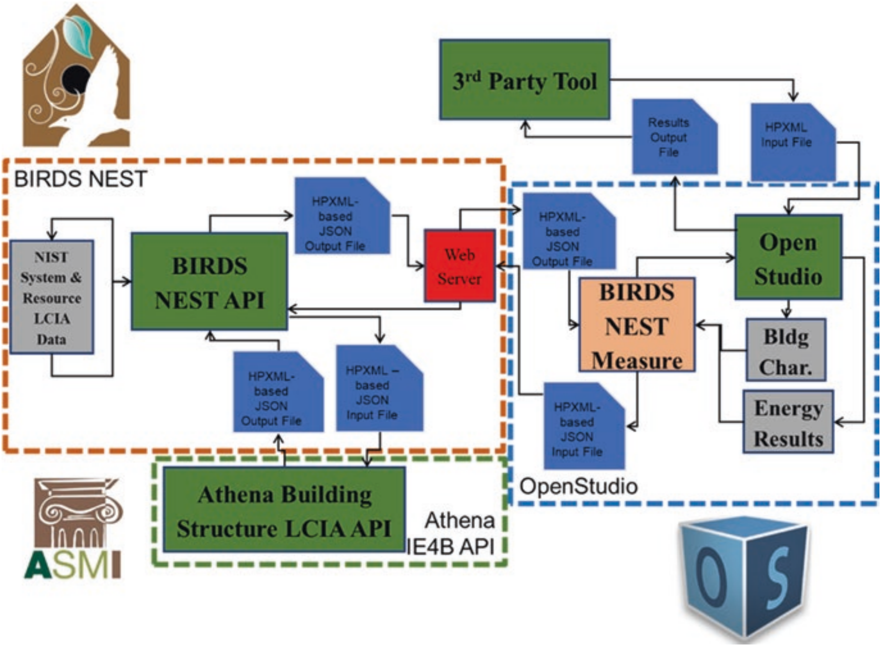

Fig. 9.10 BIRDS NEST flow diagram

BIRDS NEST provides an example of how interoperable software focused on different evaluation criteria – in this case building sustainability – can help decision-makers evaluate the trade-offs in their options.

9.7.2 Fire-LCA

In a conventional LCA the risk for accidents and associated environmental impact of these risks should they be actuated, are not included. This can be exemplified by the evaluation of different fire safety solutions for products or buildings. In a traditional LCA the cost of the fire protection method (e.g. the use of flame retardants or the incorporation of additional material to protect a metal frame) is negative from an LCA standpoint. The Fire-LCA model provides a framework to take into account the environmental benefit of reducing the size and number of fires by choosing a high level of fire safety [75].

In the case of the evaluation of normal household fires the fire process can be treated as a commonly occurring activity in the society. The frequency of fire occurrences is relatively high (i.e. high enough for statistical treatment) and statistics can be found in most countries. This implies that it is possible to calculate the different environmental effects of a fire if emission factors are available. Statistical fire models can be set up for other types of fires but the uncertainty in the statistical fire model will increase as the statistical data is more limited.

The fundamental function of a better fire performance is to prevent a fire from occurring or to slow down the fire development. Improving a product's fire performance will thus change the occurrence of fires and the fire behavior. By evaluating the fire statistics available with and without different types of fire performance improvements the environmental effects can be calculated. The benefits of a higher fire performance must be weighed against the "price" society has to pay for the production and handling of possible additives and/or other ways of production. The LCA methodology will be used to evaluate the application of higher fire performance in society. In this way a system perspective is applied.

The Fire-LCA model is illustrated in Fig. 9.11. The left-hand side of the figure shows a traditional LCA while the right-hand side illustrates the incorporation of accidental fires into the model. A Fire-LCA study follows the same criteria as a traditional P-LCA concerning the parameters to be considered in the analysis, i.e. energy use, resource use, emissions and waste. For the left-hand side of the flow

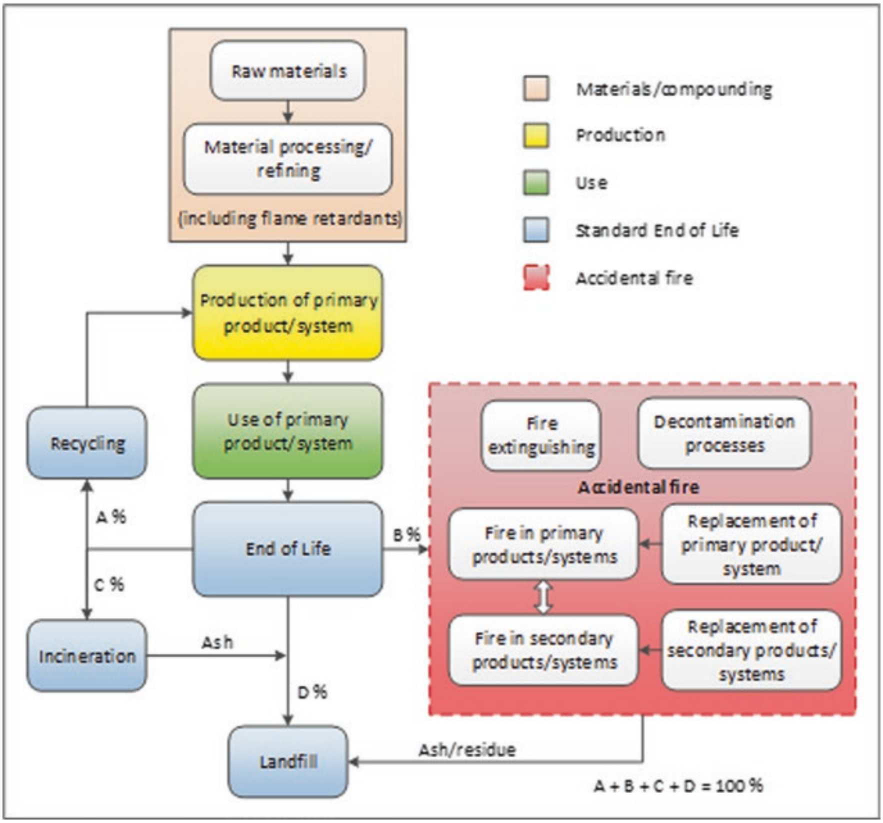

Fig. 9.11 Fire-LCA flow diagram

chart, the methodology outlined in ISO 14040 [61] is adopted. In the case of the fire modules, fire emissions are of greatest interest together with vehicles used in the response and the need to replace burned material.

In the case of fire emissions, a wide variety of species are potentially produced when organic material is combusted. In Sect. 9.2 of this chapter, the variety of emissions that might be considered has been outlined. Due to the low combustion efficiency of a fire, it produces significantly higher yields of eco-toxic products than, e.g. energy production through the combustion of fossil fuels. Therefore, in the fire, depending on the specific fire scenario, large amounts of large organic species, e.g. polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), particulates, dioxins and furans might be expected. Exactly which species should be considered will depend on the materials involved in the product or service under evaluation, and on the fire scenarios being considered. As an example, a product containing a halogenated flame retardant (chlorine or bromine) would be expected to produce dioxins and furans but these would not be expected in large quantities from products without these halogen species in their chemical makeup.

In the Fire-LCA model, the terms “primary fires” and “secondary fires” have special meaning that may differ from the terminology used elsewhere. Thus, they are defined as follows:

- *Primary fires* are fires starting in the primary product, i.e. the functional unit. These fires can spread to also involve the entire room or the entire building
- *Secondary fires* are fires starting in some item other than the functional unit which spread and ultimately involve the functional unit.

The primary fires are typically divided into four categories, i.e.:

- Small fire in product only, results in no emissions, i.e., only replacement of the product,
- Larger fire involving the product only, results in product replacement and inclusion of fire emissions from the burning product,
- Fire involving entire room, results in fire emissions from the room (including the product) and replacement of both the product and room contents, and
- Fire involving the entire dwelling or building, results in emissions from burning the entire dwelling or building and replacement of the entire dwelling or building.

This grouping is probably appropriate for most fires in building contents, but changes may need to be made if building materials, industrial fires, etc. are evaluated. There is only one category of secondary fires. Emissions from burning the product and the replacement of the product should be included for the secondary fires. All other material involved in secondary fires is not included in the environmental load of this occurrence. The emissions in this case are the emissions from the product alone, in many cases burning in a flashed over room.

A full Fire-LCA should also include the environmental cost of the fire extinguishing activities and decontamination processes. These can be a significant part of the environmental cost of a fire should the response require multiple units or take place over an extended period of time.

9.7.3 SiteWise™

Another example of an LCA-based approach that has been developed for specific applications is SiteWise™. SiteWise™ has been developed by Battelle, US Navy and US Army Corps jointly to calculate the environmental footprint of remedial activities generally used by these organization and provide support in deciding which of the different potential remedial activities is best from the point of view of environmental impact [79]. The tool itself is comprised of a series of excel sheets and provides a detailed baseline assessment of several sustainability metrics including:

- Greenhouse gas (GHG) emissions
- Energy use (total energy use and electricity from renewable and non-renewable sources)
- Air emissions of criteria pollutants (total emissions and onsite emissions) including nitrogen (NOx), sulfur oxide (SOx), and particulate matter (PM)
- Water consumption
- Resource consumption (landfill space and top soil consumption)
- Worker safety (risk of fatality, injury and lost hours).

As in a traditional LCA, the inputs which need to be considered are [79]:

- Production of material required by the activity
- Transportation of the required materials, equipment and personnel to and from the site
- All on-site activities to be performed (e.g., equipment operation)
- Management of the waste produced by the activity.

The model breaks down the process or activity into blocks over which it can identify these metrics. Each block is first broken down into modules that can be used to represent components of each alternative remedial action or to mimic each remedial phase present in most remedial actions. These phases include remedial investigations (RIs), remedial action constructions (RACs), remedial action operation (RAO), and long term monitoring (LTM). The footprint of each module is calculated separately and combined into the blocks. These blocks are then summed together in the final analysis allowing the model to eliminate double counting of environmental factors when identified correctly in the excel framework. The final sum provides an estimate of the overall footprint of the remedial alternatives. Using this approach, the SiteWise™ tool can be applied at the remedy selection, design, or implementation stage. The building block approach of the tool makes it flexible enough to be used at the remedy optimization stage as well.

9.7.4 Wildfires

Environmental impacts from wildfires result in economic losses from reduced air and water quality, vegetation and soil loss, loss of wildlife habitat, and the loss of carbon sequestration from trees. To our knowledge, there are no custom LCA or LCC-based models which have been developed specifically with wildland fires in mind. Traditional methods can relatively easily be modified to include relevant impacts from the wildland fire context through a combination of risk-based LCA approaches (e.g. Fire-LCA and SiteWise) and traditional LCA methods.

Wildland fire specific impacts can induce remediation costs, increase risk of other hazards (e.g., mudslides), and result in the loss of amenity value (e.g., recreation). Other impacts include the loss of ecosystem services, which are the stream of benefits provided by wildlife and the environment that have anthropogenic value (see for example [80]).

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Chapter 10
Mitigation Strategies for Buildings

Brian J. Meacham

10.1 Introduction

With respect to specific building fire safety/protection mitigation strategies, there are many fire protection systems and features that can be implemented. These can be largely grouped into means to prevent fire ignition, means to manage the development and spread of fire and fire effluents, and means to manage occupant safety. These fundamental tenets of fire safety design are reflected well in the Fire Safety Concepts Tree (FSCT) published by the National Fire Protection Association in the USA [1].

The FSCT follows a basic decision-tree type relational structure, in which components pertinent to achieving the fire safety objective(s) are linked by logic gates. The logic gates are 'AND' gates, which mean the connected components are each required to fulfill the objective (i.e., X *AND* Y are both required), and 'OR' gates, which mean any of the connected components could be effective on its own (i.e., A *OR* B *OR* C would work). The FSCT has several levels of related components leading back to the fire safety objective.

At the fundamental level, the FSCT illustrates that to achieve a stated fire safety objective(s), one can either 'prevent fire ignition' *OR* 'manage fire impact' [1]. To manage the fire impact, the FSCT indicates that one can manage the fire *OR* manage the exposed. While the 'manage exposed' branch is intended to apply to anything being protected, it is often used for consideration of occupant life safety. As used in the context of environmental impacts, it is suggested that the 'manage exposed' be modified to 'manage exposure', since the environment cannot be moved as occupants can.

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As such, a few modifications to the FSCT are provided here. The resulting tree is called the Environmental Impact of Fires Management Tree (EIFMT). In this realization, the objective is 'manage environmental impact of fire.' The main pathways to achieve this remain 'prevent fire ignition' *OR* 'manage fire impact' as in the FSCT, but the 'manage fire impact' branch is modified to 'manage exposed' *AND* 'manage exposure' (Fig. 10.1).

Each of the management options, prevent fire ignition, manage the fire, and manage exposure, can be further detailed with additional considerations. These are presented in Figs. 10.2, 10.3 and 10.4 and in the sections that follow.

The 'prevent fire ignition' branches as shown in Fig. 10.2 follow directly from the FSCT [1] where the focus is on means to keep potential sources of ignition away from combustible materials by controlling for one or more interactions.

The 'manage fire' branches are shown in Fig. 10.3. This also follows from the FSCT with a few modifications, such as suggesting the use of environmentally friendly suppressants. The 'control combustion process' path is focused on fuels and the environment within which the fuels are located. The 'suppress fire' path is focused on controlling the further development of the fire, or extinguishing the fire, using some type of applied agent such as water or other agent (as in some fire extinguishers). Automatically suppress fire is typical via fixed systems, such as fire sprinkler systems or gaseous systems. Manually fire suppression can be by building occupants, local fire brigades, or the fire service. The 'control of the fire by construction' path includes strategies such as fire- and smoke-rated barriers, fire resistive ratings of structural systems, fire and smoke dampers, and fire and smoke venting/exhaust measures.

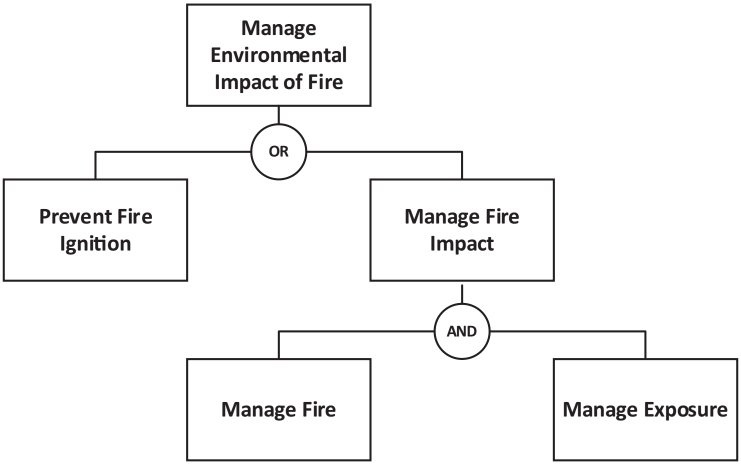

Fig. 10.1 Top branch of EIFMT. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

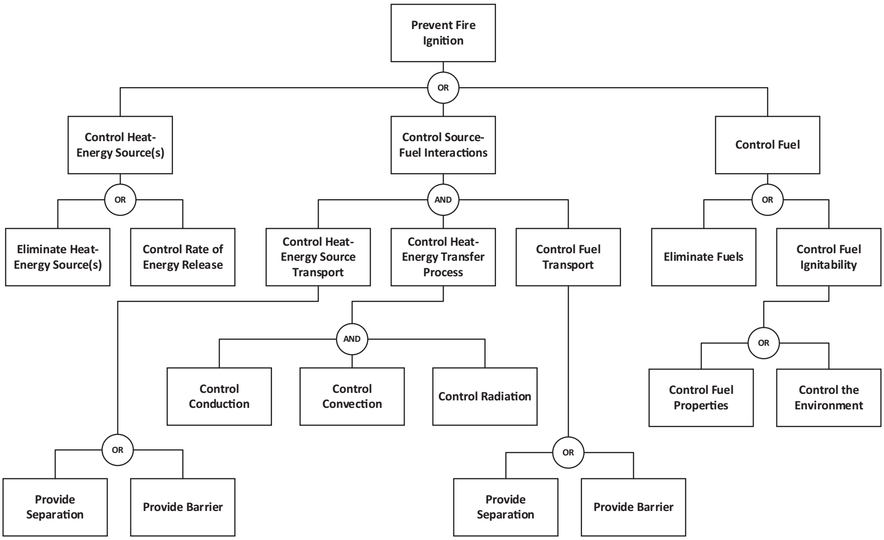

Fig. 10.2 Prevent fire ignition. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

The reference to ‘environmentally friendly agent’ (suppressant) is intended to keep use of nontoxic suppressant materials in the forefront. This includes water with no additives, nontoxic water additives (e.g., surfactants), and nontoxic and non-greenhouse gaseous agents. Oxygen reduction (hypoxic) systems are considered under the ‘control chemical composition of environment’ box of the ‘control combustion process’ branch.

The ‘manage exposure’ branches are shown in Fig. 10.4. This is a unique branch to the EIFMT, in essence replacing the ‘manage exposed’ branch of the FSCT. The reason for the new conceptualization is to keep a focus on environmental impacts as the issue being managed, as compared to life safety or property protection, as envisioned in the FSCT. The decision pathways in this branch reflect management of airborne, waterborne and soil impacts. It includes a linkage back to the ‘manage fire’ branches, as that is one exposure management measure.

In the following sections, each branch is discussed in more detail.

10.2 Environmental Impact of Fire Concept Tree Branches

As outlined in Sect. 10.1, to achieve the objective of managing environmental impact of fire in buildings, one can either prevent fire from occurring or manage the impacts, which can be accomplished by managing the fire or its exposure to the

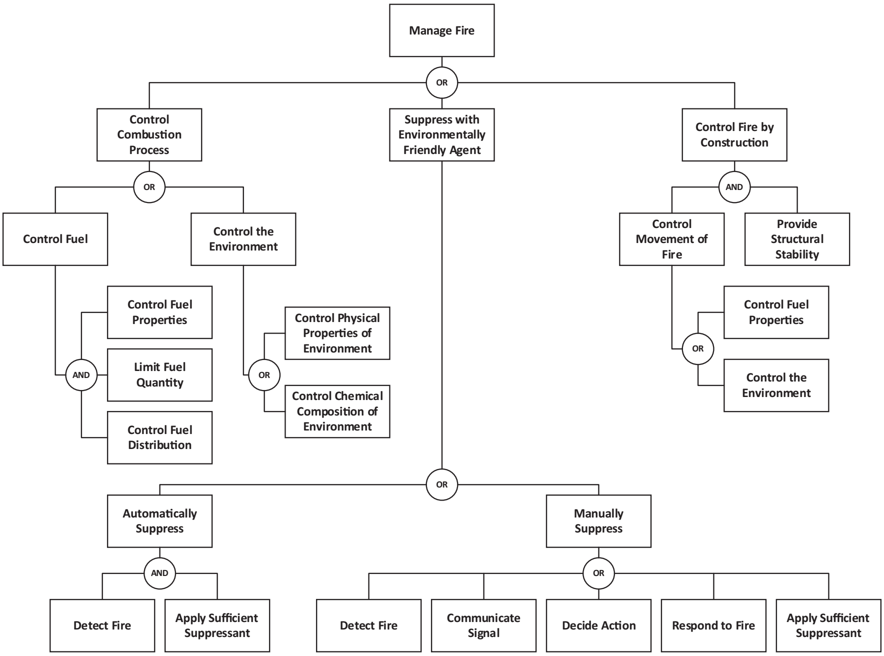

Fig. 10.3 Manage fire branches. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

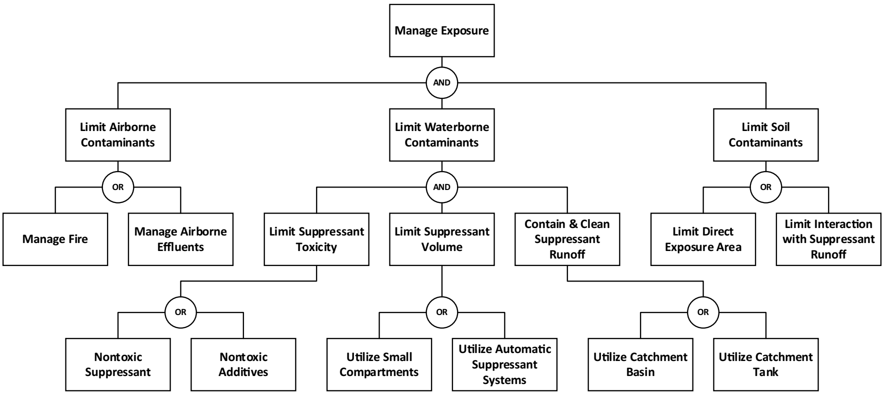

Fig. 10.4 Manage exposures branches. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

environment. The relationships are illustrated in the EIFMT. The top level is shown in Fig. 10.5. In the following sections, each branch of the EIFMT is discussed.

10.2.1 Prevent Ignition

To prevent a fire from occurring one can think of the fire triangle: control for potential ignition sources, control the fuel, or limit the oxygen availability (see Chap. 3). This is reflected in Fig. 10.6 as control heat-energy source(s), control source-fuel interactions, or control fuel.

Control Heat-Energy Source(s)

Controlling for the heat-energy interaction is about minimizing competent ignition sources, that is, sources of potential ignition with sufficient strength to cause ignition of a fuel (see Chap. 3). This can be accomplished by eliminating potential ignition sources altogether, such as open flames, electrical arcs, and the like. If this not possible, it is often feasible to limit the rate of energy release from an energy source through material selection (Fig. 10.7).

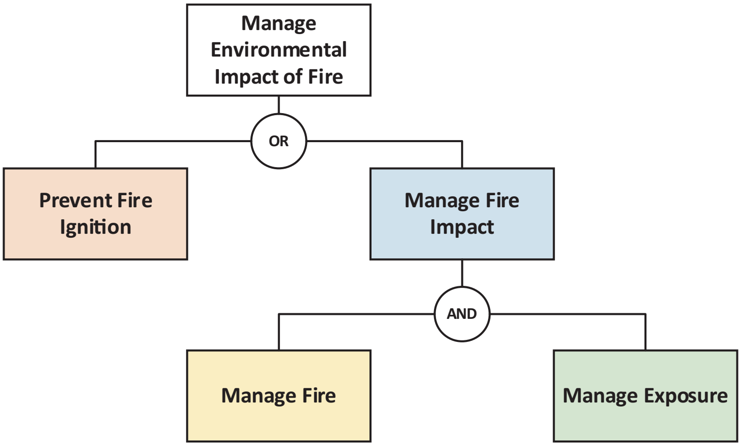

Fig. 10.5 Top branch of EIFMT. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

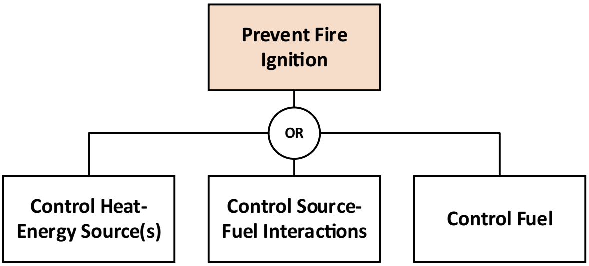

Fig. 10.6 Top level of EIFMT prevent fire ignition branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

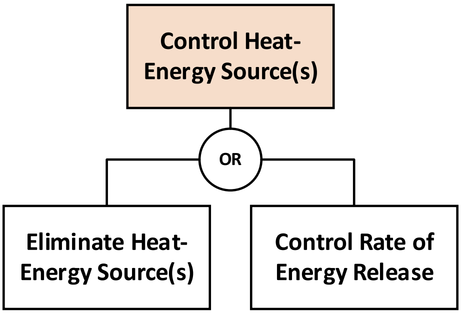

Fig. 10.7 Control heat-energy source(s) branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

Control Source-Fuel Interactions

This branch focuses on keeping a competent ignition source from fuel sources. This is done by stopping an ignition source from moving to a fuel, controlling for the heat transfer process, and controlling the fuel from moving to a source of ignition (see Chap. 3) (Fig. 10.8).

Control Fuel

Fuel control is a very effective, but not always practical approach. In some cases, it may be possible to choose non-combustible material, such as for structural system or thermal insulation. However, it is not practical to prohibit the storage of combustible materials in warehouse, retail, and other such facilities. In some types of

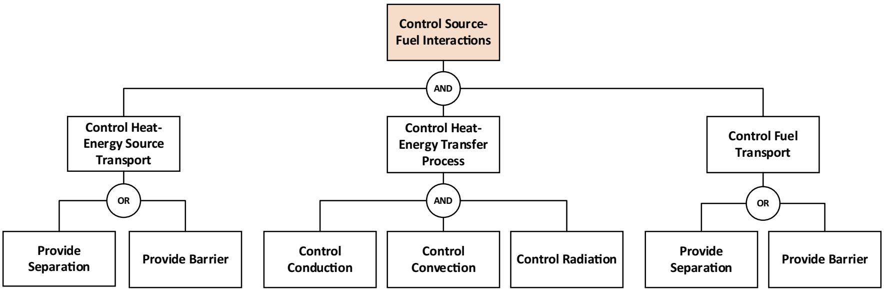

Fig. 10.8 Control source-fuel interactions branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

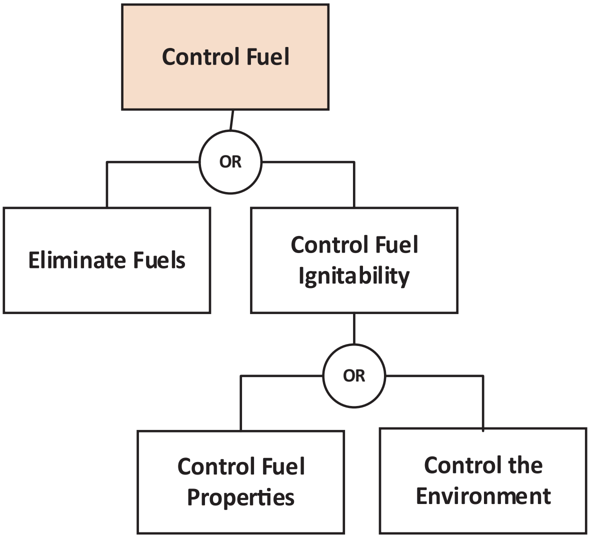

Fig. 10.9 Control fuel branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

occupancies, use of oxygen reduction (hypoxic) system may be feasible for lowering the oxygen concentration and thus inhibiting combustion (Fig. 10.9).

Reference is made to Chap. 5 on emission factors measurements, as well as Chap. 9 on tools for assessment, such as life cycle analysis (LCA), for guidance on environmental impact associated with difference fuels (materials).

10.2.2 Manage Fire

If a fire cannot be prevented from occurring, then one can either manage the fire or manage the exposure. This branch of the EIFMT focuses on managing the fire through control of the combustion process, control through building construction, or by suppression. A major consideration is that the smaller the fire, and the less environmentally-unfriendly materials involved, the less the environmental impact (Fig. 10.10).

Control Combustion Process

Control of the combustion process is framed in terms of the fuels and the environment within which the fuels are located. Control of the fuel is largely the same as described in Sect. 10.2.1.3 above. A difference here is that combustible fuels are expected to be present (not possible to eliminate), so managing the quantity becomes a control option. Likewise, control of the environment can be thought of in terms of reducing the oxygen that is needed to support combustion of many materials (Fig. 10.11).

Suppress with Environmentally Friendly Agent

Suppressing, sometimes also referred to as extinguishing, is focused on application of some material that interrupts the combustion process, including cooling, reducing oxygen or interrupting the chemical reaction. As a difference from the FSCT, a significant consideration here is the selection of environmentally-friendly agents (suppressants, additives) to achieve the function with the minimal environmental impact possible (Fig. 10.12).

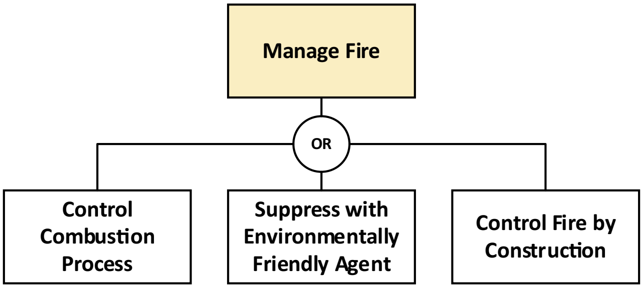

Fig. 10.10 Manage fire branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

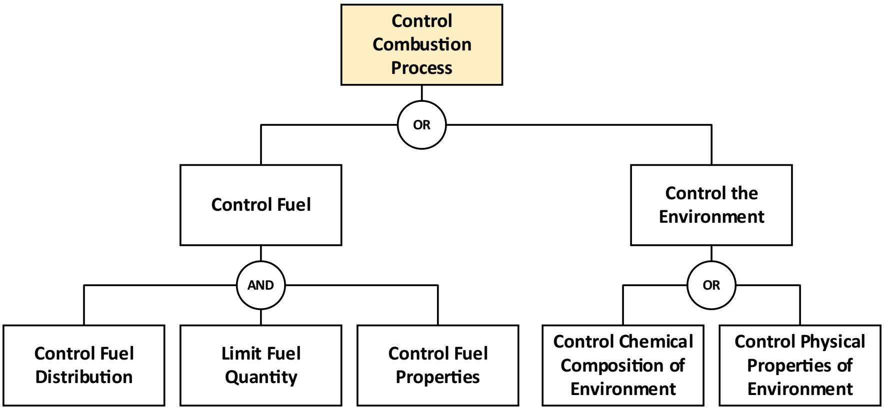

Fig. 10.11 Control combustion branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

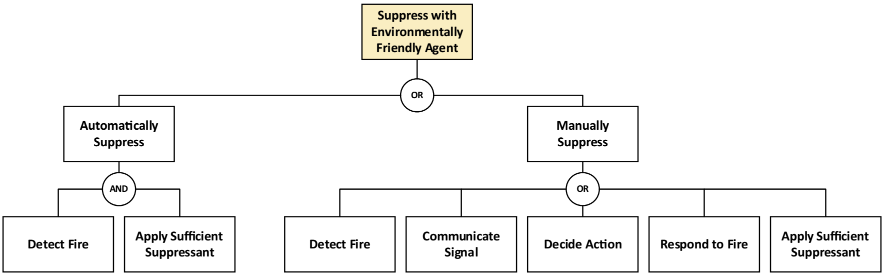

Fig. 10.12 Suppress fire branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

As discussed in Chap. 8, there can be environmental impacts from different suppression agents added to water for fighting wildland fires. Many of these same materials can be used within buildings as well, and the concerns are similar. In addition, some gaseous extinguishing materials may have ozone-depleting components or contribute in some way to greenhouse gas emissions. While there have been regulations to control for these concerns promulgated for many years, there can still be some environmentally impactful materials in use for special hazard situations.

It should also be noted that, even if the suppressant is not inherently impactful to the environment, such as water, the products of combustion associated with the fire can render the runoff from firefighting activities impactful. Control for this is discussed under the ‘manage exposure’ branch of the EIFMT and in subsequent sections.

Control Fire by Construction

The control of a fire by construction is an approach to limit the area and volume of compartments within which a fire may occur. A principal reason why this can be effective is that the smaller the compartment, the less material in the compartment there is to burn and release harmful emissions. In addition, proper compartment barrier construction can limit the spread of fire, which keeps it smaller. Finally, appropriate material and protection decisions for the structure system can resist the possibility of structural failure due to fire, again reducing the potential for fire spread, maximum size and emissions potential (Fig. 10.13).

As used in this context, the control of the environment relates to limiting the oxygen available to support combustion by means of controlling ventilation openings to the compartment (e.g., doors, windows, ducts), and where provided, protecting them appropriately. A simple automatic door closer can be an effective measure in this regard.

10.2.3 Manage Exposure

As a significant component of the EIFMT, the 'manage exposure' branch is aimed at considering options for limiting the impact of fire control measures on the environment. If a fire occurs, there will be emissions. If the size and impact of the fire cannot be limited by managing the fuel or controlling through construction, suppression activities will be needed. Unfortunately, as discussed in Chap. 2,

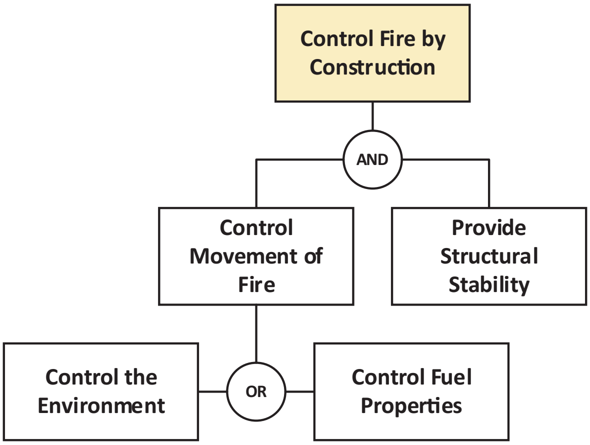

Fig. 10.13 Control by construction branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

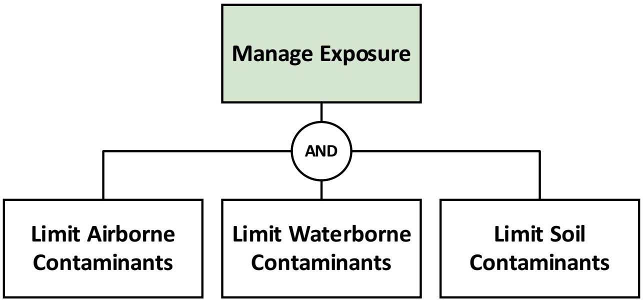

Fig. 10.14 Manage exposure branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

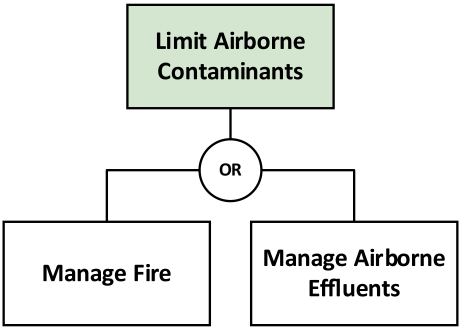

Fig. 10.15 Limit airborne contaminants branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

significant environmental impact can be associated with fire suppression activities, especially if effluents can be spread well beyond the area of fire origin (Fig. 10.14).

As discussed here, the focus is on limiting exposure due to airborne, waterborne and soil contaminants, given that a fire occurs.

Limit Airborne Contaminants

Limiting airborne contaminants is related to management of the fuels involved and the overall size of the fire. In many ways, the larger the fire the bigger the potential impact, assuming the same fuels. This is not just associated with the volume of effluents produced but is also a function of the potential for significant spread of the effluents as the size (power) of the fire increases. As the energy output of fires increase, the plume of hot gases and effluents increases in volume and height.

As plume reach higher into the atmosphere, the effluents can be spread over longer distances (see Chap. 4). Where suppression is not contemplated, this places emphasis on managing construction and contents (Fig. 10.15).

Where building fire suppressant systems are used, such as automatic sprinklers, both airborne and waterborne contaminants can be reduced. In addition, keeping the fire small results in less carbon emission overall, since less rebuild is needed.

Limit Waterborne Contaminants

In many respects, limiting the amount and spread of waterborne contaminants is amongst the most impactful environmental control measures one can take, aside from controlling the size of fire and materials involved in combustion. Water is universally used for suppressing building fires, and once the fire service becomes involved, the volume can become significant, particularly for very large fires. In addition, for some hazards, additives are mixed with the water, to increase their efficacy, some of which may be harmful to the environment. Finally, the material being burned in a fire, or released as a result of the fire, can be toxic and potentially spread with the distribution of firefighting water. As such, limiting release of firefighter water into surface and underground water sources (and soil) is critical in safeguarding the environment.

The magnitude of concern is probably best recognized by the tragic events of the Sandoz Ltd. warehouse fire near Basel, Switzerland, in 1986 [2], which is detailed in Chap. 2. The warehouse contained some 1250 tons of pesticides, solvents, dyes, and various raw and intermediate materials. The 90 m by 50 m warehouse was originally constructed to store machinery, and therefore lacked smoke detection and

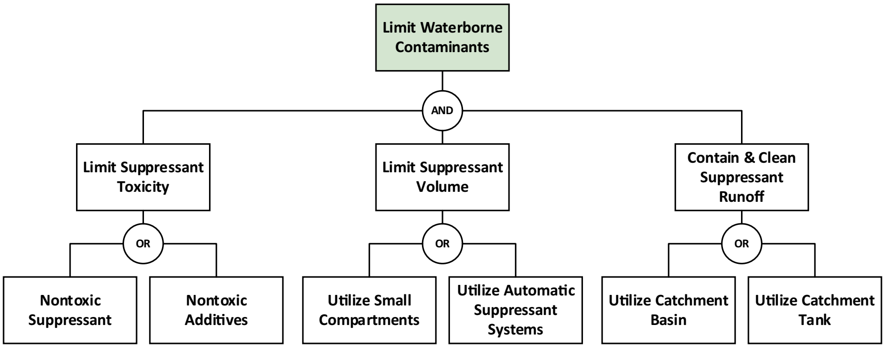

Fig. 10.16 Limit waterborne contaminants branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

sprinkler systems and only contained one dividing wall. Given the amount of stored materials, considerable water was needed to control the fire. While almost all the stored materials were consumed by the fire, large quantities were introduced into the soil and groundwater at the site, and ultimately some 10,000 and 15,000 m^3 of firefighting contaminated runoff water made its way into the Rhine River. The chemicals discharged into the Rhine River by the firefighting runoff resulted in large-scale kills of benthic organisms and fish, particularly eels and salmonids, with impacts observed as far away at the Netherlands.

As reflected in Fig. 10.16, limiting the amount of hazardous material being introduced into waterways can be managed by limiting the toxicity of the suppressant and any additives, limiting the amount of suppressant required, and by containing and cleaning the contaminated firefighting runoff. Benefits of fire sprinkler systems in reducing carbon contributions are discussed further in Chap. 6.

Limit Soil Contaminants

Once contaminants become airborne or waterborne, they can eventually end up in soil. As such, soil contamination can be limited by controlling the fire size and the suppressant approach used for a building. However, fuels can also be located outside of a building, on the property, and combustion of such materials could result in direct exposure to the soil on which they are located via the fire or suppression activity. Such exposures can be managed by limiting storage in direct contact with soil and providing impervious containment systems for firefighting runoff (Fig. 10.17).

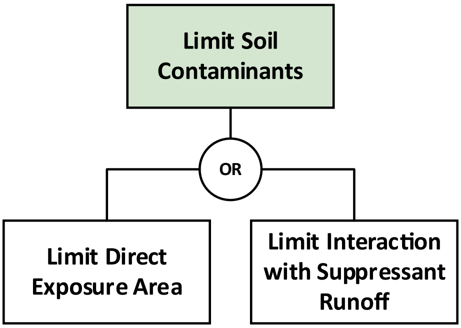

Fig. 10.17 Limit soil contaminants branch. (Adapted from, and reproduced with modification and permission of NFPA, from NFPA 550, Guide to the Fire Safety Concepts Tree, 2017 edition. Copyright ©2016, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org)

10.3 Fire Mitigation and Control Measures Through Building Fire Regulation

Many combinations of the ‘prevent ignition’ and ‘manage fire’ mitigation concepts are considered by building fire safety regulations. Whether function-based, performance-based or prescriptive-based, robust building fire safety regulatory systems often include multiple fire mitigation means, with several having all or nearly all approaches considered. However, this is often not the case for the mitigation concepts listed under the ‘manage exposure’ branch, as fire safety of the environment is typically not a stated objective of building regulations for most building uses.

The extent to which fire safety features are included in building fire safety regulation is often driven by the occupancy or use classifications of the building (e.g., places of public assembly, domestic/residential, places of business, mercantile, industrial, and storage), which are in turn informed by level of hazard present and risk to occupants. The types of fire safety systems and features that may be part of building fire safety regulations include the following, grouped by type of fire safety/protection being afforded.

- Fire prevention (EIFMT prevent fire branch)
  - Controls on heat-energy sources, such as

    Electrical ignition hazards (including static charges)
    Heating appliances
    Hot work (e.g., welding)

  - Controls on source-fuel interaction, such as

    Physical separation to manage heat transfer
    Use of barriers to provide separation

  - Controls on fuels, such as

    Controls on natural gas, propane, fuel oil, Li-ion batteries in building for heating/emergency power
    Limits on interior finish materials
    Limits on type, quantity and arrangement of stored materials

- Means to manage fire spread (EIFMT manage fire branch)
  - Control combustion process (fuels/environment), such as

    Limits on combustible interior finish materials
    Limits on total fuel load
    Provision of oxygen reduction (hypoxic) systems
    Control ventilation

  - Control by construction (passive systems/structural fire protection), such as

    Structural fire resistance requirements (primary and secondary structure)
    Fire resistance of interior walls, including doors, vents, and other openings in walls
    Fire spread limitations on interior walls, ceilings and floors (to limit spread of fire and smoke)
    Fire resistance/fire spread requirements for exterior walls (façade systems, wall systems, …)

  - Control by construction (control environment)

    Smoke control systems
    Smoke exhaust systems
    Smoke venting systems

  - Suppression

    Fire detection
    Building fire alarm and fire service notification
    Automatic fire suppression

    - Fire sprinkler systems
    - Special suppression/extinguishing systems (e.g., water mist, CO_2, etc.)

    Manual suppression systems

    - Fire extinguishers
    - Occupant use firefighting hoses
    - Connections for firefighter apparatus
    - Firefighters standpipes (internal hydrants)

    Water supply/fire department access

    - Mains water connection
    - Local fire water storage tanks
    - Fire pumps
    - Fire department/brigade access requirements (for apparatus, reaching the building, etc.)

- Manage exposure to the environment (EIFMT manage exposures branch)
  - Limit airborne contaminants (see prevent and manage fire branches)
  - Limit waterborne contaminants

    Manage fire by construction
    Manage fire by suppression
    Use environmentally friendly suppressants
    Contain and control firefighting water runoff

  - Limit soil contaminants

    Control firefighting water
    Control direct contact of fuels and soils

The following sections briefly discuss some of the above mitigation strategies in more detail. Impacts on the environment from fires in buildings is discussed in Chap. 6. Tools for assessing the environmental impact of fire in buildings, with and without mitigating strategies, are discussed in Chap. 9.

10.3.1 Non-combustible Construction Materials

Building regulations generally permit a wide range of construction materials as part of the structural framing, interior partitions, interior finish, and exterior insulation and cladding. In some cases, combustible materials are permitted to be used, often with some associated fire protection requirement (e.g., spray-applied fire proofing for steel structural framing), but not always. Should the decision-makers involved in specifying building design and construction look to reduce the potential environmental impacts from fire that may occur in the building, consideration can be given to specifying the use of non-combustible materials.

However, as in any design decision, there may be pros and cons, often dependent upon the overall objectives for the project. For example, timber is often considered more sustainable than process-intensive materials, which can have higher carbon emissions potential, such as concrete and steel. However, timber is combustible, so timber-frame structures may emit more carbon than other materials during a fire event.

There are of course options to mitigate for combustible structural framing, both in terms of passive and active fire protection (see for example Meacham and McNamee [3]) and tools such as Fire Life Cycle Analysis (Fire LCA) can be helpful in assessing such environmental impacts of material options (see Chap. 9, as well as McNamee et al. [4] and Meacham and McNamee [3]).

However, such measures are not always effective for buildings under construction, when fire protection measures and systems may not yet be installed or operational. In some countries, building fire safety codes or standards are available to provide guidance during construction (e.g., NFPA 241, which provides measures for preventing or minimizing fire damage to structures, including those in underground locations, during construction, alteration, or demolition [5]) (Fig. 10.18).

10.3.2 Limiting Compartment Size

As discussed in the IEFCT overview above, smaller compartments within buildings can translate to smaller fires, which means fewer environmental impacts from fire. The approach of limiting compartment size based on risk to occupants, hazards associated with the building use, and materials used for structural framing are included in building regulations.

Fig. 10.18 Fire in timber frame apartment building under construction. (Source: Captain John Bonadio, Waltham Fire Department, as published at https://www.enr.com/articles/42484-what-local-officials-want-to-do-about-wood-frame-building-fires-in-massachusetts (last accessed September 2020), Courtesy of Waltham, Massachusetts Fire Department)

However, as with selection of building materials, there may be objectives for the building which are in conflict with the concept of small compartments, depending on building use. Places of assembly for large numbers of people, transit facilities, warehouses, and industrial facilities are some examples. In cases such as these, where small compartments are not practical in terms of the intended use of the building or spaces in the building, limitations in compartment size may be relaxed, but often only if fire suppression systems or smoke venting features used.

10.3.3 Control of Contents

For many building use categories, building regulations do not include controls on contents. This typically includes residential, commercial (office, business), places of public assembly, institutional buildings (e.g., hospitals, prisons) and education buildings. While some controls may be placed on maximum storage of hazardous or flammable materials (e.g., cleaning supplies), there is typically no control on furniture, personal goods and the like. In some countries this can include little or no control on contents of retail stores as well. Should a building owner or tenant choose to make decisions on contents based on reducing environmental impact, many options exist. One significant decision may be to reduce the use of plastic materials.

Over the past several decades, plastics have replaced cellulosic materials in many products. This creates several challenges.

Plastics, being based on petroleum, can be ignited more readily, burn more rapidly, and in some cases release more energy than many cellulosic materials. For example, a study by Kerber [6] compared sets of representative residential living rooms, where each set had rooms of the same size, laid out in a nearly identical manner, but with one room furnished with 'modern' fuels (high concentration of plastics) and the other with 'legacy' fuels (largely cellulosic). The outcomes reflected a stark difference. In the first set of experiments (experiments 1 and 2), the modern room transitioned to flashover in 3 min and 40 s, whereas the legacy room transitioned to flashover at 29 min and 30 s. In the second set of experiments (experiments 3 and 4), flashover in the modern room occurred at 4 min and 45 s, and at 34 min and 15 s in the legacy room. In the second set of experiments, the heat release rate (HRR) profile was also recorded. The compartment temperature profiles and HRR profiles for the second set of experiments are illustrated in Figs. 10.19 and 10.20 respectively.

Potential implications for environmental impact of the faster time to flashover and higher HRR for the modern fuels include:

- greater impacts due to environmental impact of plastics compared with cellulosic materials (see Chap. 9 regarding tools for assessing environmental impacts of materials),
- greater potential to spread the fire to involve more fuels within the building, and possibly the structure itself, before the fire service can begin suppression activities (greater emissions),

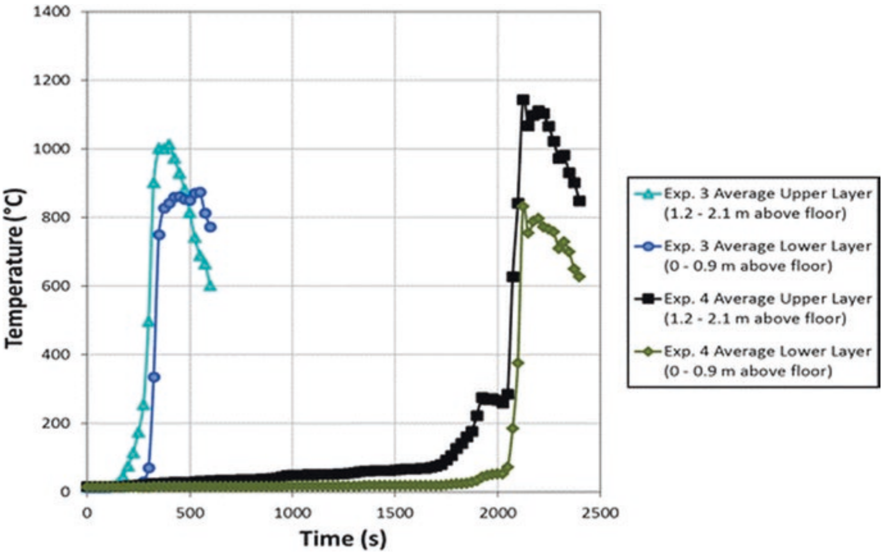

Fig. 10.19 Comparison of upper layer temperatures – 'modern' and 'legacy' furnishings [6]

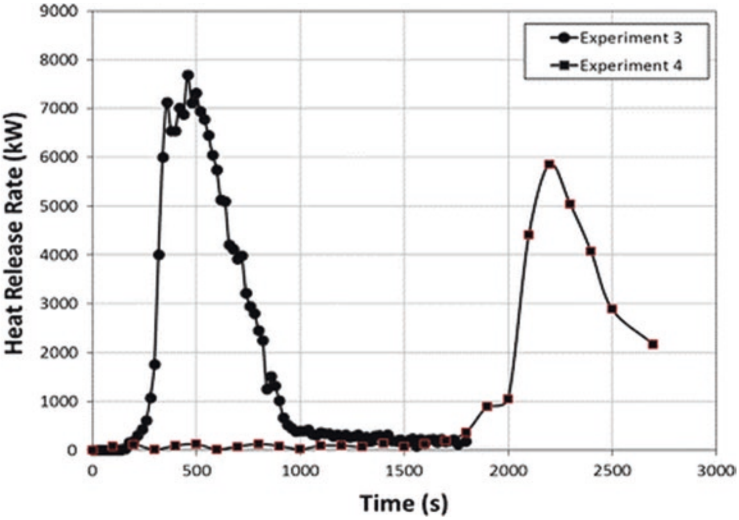

Fig. 10.20 Comparison of HRR profiles – 'modern' and 'legacy' furnishings [6]

- greater amount of firefighting water required, and
- greater potential for significant or complete rebuild (see discussion below on sprinklers, suppression water and carbon emissions).

Where it is necessary to store combustible materials, one can look to options such as storing them in small, well-protected compartments or containers. Some building regulations require this for certain classes of hazardous or toxic materials, but the concept can be extended to more general storage.

If the environmental impact is a consideration at the design stage, installation of an automatic sprinkler system can help significantly. (Sprinkler systems can also be installed after construction, but typically at a higher cost.) Research at FM Global [7] that involved large-scale fire tests of furnished residential living rooms – one sprinkler protected and one not – found that environmental benefits of automatic fire sprinklers were significant, as quantified in terms of total greenhouse gas production, quantity of water required to extinguish the fire, quality of firefighting water runoff, potential impact of firefighting water runoff on groundwater and surface water, and mass of material requiring disposal. It was also found that environmental impacts of sprinkler protection buildings would lower due to reduced embodied carbon associated with less material being required for refurbishment or reconstruction. The benefits of automatic sprinklers are discussed further in Sect. 10.3.4 below.

General Storage/Large Shops

Control of contents can be difficult in general storage (warehouse) buildings, large retail shops, and similar environments. In such spaces, the obvious use is to store, and in some cases display for sale, large quantities of materials, which need to be readily accessed and moved about. This results in an operational need for less compartmentation as compared with other building uses, and often is characterized by storage of materials in high piles, shelves and racks.

In some countries, automatic sprinkler systems are required by regulation for such occupancies and a means to control the potential size and spread of a fire should one occur. In other countries, however, the regulatory approach is use of smoke and heat venting to release hot gasses and fire effluents out of the space, and manual suppression by the fire service. From an environmental impact perspective, the latter approach can result in significantly more emissions to the environment for the following reasons:

- Fire size by the time the fire service responds will almost always be much larger than if automatic sprinklers are present and operate (since actuation occurs for mush smaller fire sizes).
- With larger fire size, much more fuel will be burned, and the quantity of emissions will be higher.
- Given the larger fire size by the time of fire service response, and given that significantly larger quantities of water will be needed by the fire service to suppress the fire (as compared with automatic sprinklers), emissions potential via water pathways and into the soil increase.

Fig. 10.21 Warehouse fire. (Source: by Dorsey Photography licensed with CC BY 2.0)

Much like the FM Global research noted above [7], a study by BRE Global on warehouses [8], which analyzed the environmental impact and cost-benefit ratio of automatic sprinkler systems installed in small (<2000 m^2), medium (2000 m^2–10,000 m^2) and large (> 10,000 m^2) warehouses, found similar benefits. The BRE study found there was an overall net environmental benefit over the lifetimes of the exemplar warehouses as a result of automatic sprinkler protection due to a reduction in CO_2 emissions from fire, reduced fire size, reduced quantities of water required to fire fires, and saving in embodied CO_2 resulting from reduced loss of contents and warehouse reconstruction. The benefits of automatic sprinklers are discussed further in Sect. 10.3.4 below (Fig. 10.21).

In the USA and other countries, large 'warehouse-type' shops, sometimes referred to as 'big box' stores or supercentres (superstores or megastores), have become commonplace. Much like 'traditional' warehouse facilities, these buildings typically contain a wide range of materials stored on high racks, often on pallets. From an environmental impact of fire perspective, they can be considered warehouses, and the same challenges and mitigation options exist. As with warehouses, the fire protection requirements within regulation can vary by country, and automatic sprinklers may not be required.

Aside from building regulatory requirements for these occupancies, insurance companies often have additional requirements. For many insurance companies, this includes requirements for automatic sprinkler systems.

Fig. 10.22 Fire following explosions at West Pharmaceutical Services, Inc., Kinston, NC, USA. (Source: U.S. Chemical Safety Board, 2003)

Use and Storage of Hazardous Materials/Hazardous Processes

Perhaps the building uses with the highest potential to result in significant impact to the environment as a result of fire are facilities the use and/or store large amounts of hazardous or toxic materials. This includes any industrial facility to uses or produces significant amounts of hazardous or toxic materials, from solvents used in manufacturing, to raw and finished materials involved in material production, to bulk storage of raw and finished such materials. A representative range of fires and explosions in such facilities is presented in Chap. 2.

A challenge in many of these facilities is that fire ignition can come from many sources, including static charges and electrical arcing. In processes and storage involving fine combustible dusts and highly flammable liquids, this can pose significant challenges, which may not always be adequately addressed by building regulation or electrical installation requirements. Fig. 10.22 shows the aftermath of a dust explosion at West Pharmaceutical Services, Inc., Kinston, NC, USA [9], and Fig. 10.23 shows a fireball and effluent plume which resulted from a fire in the packaging area involving a 300-gallon portable steel tank being filled with ethyl acetate, a flammable solvent, at the Barton Solvents chemical distribution facility in Des Moines, IA, USA [10].

Fig. 10.23 Fire plume, Barton Solvents, Des Moines, IA, USA. (Source: U.S. Chemical Safety Board, 2008)

In addition, if fire-rated compartmentation is not in place or inadequate, and automatic suppression systems are not in use, the initial event can readily involve additional fuel, which given the nature of the facilities, is often toxic to the environment. Furthermore, there is also the potential, particularly in the event of an explosion, that if proper over-pressure venting is not provided, passive and active fire protection systems and be damaged and rendered inoperable or ineffective by the initiating event.

Petroleum Processing and Storage Facilities

One of the most significant sources of potential impact to the environment outside of wildland fire is petroleum processing (refineries) and storage facilities. This is largely due to the amount of fuel available to burn should a fire occur and the flammability of the materials involved. While much of the processing and storage is outside of traditional 'buildings,' this is an important hazard potential to address, and fires and explosions do sometimes occur within processing facilities themselves.

For many such facilities, mitigation strategies include control on static and electrical sources of ignition, flame arrestors in piping systems and tank vents, rapid (flame) detection, fire resistive coatings, fixed water suppression systems, foam suppression systems, and dikes or berms to contain spills of flammable liquids. There are also many sensors and controls on system components, such as valves, piping

Fig. 10.24 Refinery Fire, El Segundo. (Photo credit: Sodai Gomi, licensed with CC BY 2.0)

Fig. 10.25 Fire at Caribbean Petroleum Corporation Tank Terminal, Bayamon, Puerto Rico, USA. (Source: U.S. Chemical Safety Board, 2015, courtesy U.S. Customs and Border Protection, Caribbean Air and Maritime Branch)

and storage, which aim to shut down flows of materials if large leaks occur, pressures rise or fall unacceptably, or systems become overfilled (Fig. 10.24).

As a specialized hazard, there are many industry-developed and industry-focused guidelines and standards that provide details on fire and explosion mitigation approaches and technologies. A few examples of organizations which produce such resources include the American Petroleum Institute (API), the Center for Chemical Process Safety (CCPS), the Institution of Chemical Engineers (IChemE), and the Technical Research Institute of the Netherlands (TNO). Some representative guidelines and standards from these are other organizations are provided in Sect. 10.5 (Fig. 10.25).

For many of these types of facilities, emissions into the air can be significant, which is why considerable efforts are placed on preventing fire occurrence. Emissions into the water and soil are mitigated through the use of containment areas around storage tanks, in particular.

However, additives are often mixed with fire suppression water for fighting hydrocarbon fires to form a foam which can help suppression through reducing oxygen near the fuel surface and smothering the flame, and by cooling the fuel surface. About 30–40 years ago it was found that some of these additives can have harmful impacts on people and the environment, in particular perfluorinated chemicals (PFCs), including perfluorooctane sulfonate (PFOS), polyfluoroalkyl substances (PFAS) and perfluorooctanoic acid (PFOA), which were utilized in some formulations of Aqueous Film Forming Foam (AFFF) for some decades (e.g., [11–16]).

Concerns with firefighting foams were not limited to the USA. In 2014, for example, Germany and Norway submitted a proposal to the European Commission for a restriction of the manufacture or sale of PFOA in the European Union [14, 16]. Also, in 2014, the state of Queensland, Australia, published as environmental management of firefighting foam policy [17, 18], applicable to foams used for structure fires as well as in wildland fires. See further discussion on firefighting foams in Sect. 10.3.4 below and in Chap. 8.

Airports, Mission Critical and Firefighter Training Facilities

While airports and some mission critical facilities, such as defense facilities, do not experience as many fires as other types of facilities, they can present environmental impact concerns based on the amount of live fire training that is undertaken, coupled with the fact that firefighting foams are often used given their effectiveness in fighting hydrocarbon fires. For airport terminals and other ancillary buildings on site, the general building fire safety measures outlined above would apply. For aircraft hangars and firefighting operations involving aircraft and aircraft fuel, the use of firefighting foams can be an additional concern (Fig. 10.26).

In the 1970s, the US Department of Defense (DoD), began using Aqueous Film Forming Foam (AFFF) that contained PFOS and, in some formulations, PFOA, at several airfields and other mission critical facilities. Given that AFFF was demonstrated to be so effective for fighting petroleum-based fires, the US Federal Aviation Administration (FAA) required its use at airports nationwide as well.

However, in the 1990s, health concerns with PFCs had started to emerge (e.g., [11, 12]). In 2009, the US Environmental Protection Agency (US EPA) Office of

Fig. 10.26 Aircraft firefighting training exercise. (Source: “190,816-F-ZB472–1134” by U.S. Department of Defense Current Photos is marked under CC PDM 1.0)

Water established a provisional short-term health advisory for PFOS and PFOA under the Safe Drinking Water Act (SDWA), and in 2016, the US EPA issued a SDWA lifetime health advisory (LHA) recommending individual or combined levels of PFOS and PFOA concentrations in drinking water be below 70 parts per trillion [15].

Given the low levels that would be acceptable in the environment, the DoD issued a policy requiring sampling and testing of drinking water systems where DoD was the water purveyor, and to take action where the EPA LHA was exceeded. In addition, the DoD followed a comprehensive approach to identify installations where DoD used AFFF containing PFOS or PFOA, since releases of PFOS and PFOA on DoD installations are primarily associated with firefighting training areas, hangars, fire suppression systems, and aircraft crash sites. Since then, actions to reduce the use of firefighting foams with PFOS or PFOA at airports and government mission critical facilities has ensued. Similar actions have been taken in other countries as well (e.g., [14, 16–18]).

10.3.4 Suppress with Environmentally Friendly Agent

In this section, various suppression system types are presented as part of the suppression component of the ‘manage fire’ branch of the EIFMT. The discussion is general in nature, with a focus on environmental impact issues. Representative analysis and design standards, guidelines and handbooks are noted in Sect. 10.5.

Water-Based Suppression Systems

Water is the most widely used substance for fire suppression. It is used in both automatic fire sprinkler and fine water mist systems installed in buildings, and in manual suppression systems used by the fire service via internal connections (e.g., firefighting standpipe or hydrant systems) or external connections (e.g., to external fire hydrants or other water sources). It is used mostly without additives, but substances that can increase suppression effectiveness are sometimes added (see Sect. 10.3.4.2).

Automatic Fire Sprinkler Systems

Automatic fire sprinkler systems have been in use since the late nineteenth Century. In the USA, early adopters of automatic sprinkler systems were mill owners in the Northeast part of the USA who were looking for solutions to control the growth and spread of fire in large open floor-plan mills which were constructed of heavy timber framing [19].

In brief, automatic fire sprinkler systems are comprised of a water supply, a network of pipes within a building, and sprinkler heads (sprinklers) located throughout the protected space, which connect to the water supply through the network of pipes. In most applications, sprinkler heads are located high in the protected space, at or in the ceiling, just below the ceiling or its supporting structure, or in the walls. In storage and similar facilities, particularly those featuring high-rack storage of goods, sprinklers are often also located within the racks. Sprinkler systems can have water in the piping all the time (wet systems) or be filled with air or an inert gas, such as Nitrogen, until a fire is detected, at which point a valve opens to allow water to flow into the pipes (dry system). Most sprinkler systems feature individually operated, heat activated sprinkler heads, which actuate when a specific temperature is reached at the head. Only those sprinkler heads which actuate flow water. Flow rates will depend on the type of head, size of the orifice, the water pressure in the system, and deflector design, but can be as low as about 60 l/min at 48 kPa. Water supply requirements are determined based on number of heads in the designated design area, flow requirements per head, and a specific amount of time, such as 30 min (time is often specified in design standards). In many cases, only a small number of heads need to actuate and flow water to control or suppress a fire. In some specific applications, the sprinkler heads may all be normally open, and when a fire is detected, water flows through all the heads in the defined design area. This is known as a deluge system. These are design to flow much more water and are used when the hazard is significant (Fig. 10.27).

Building and fire regulations in many countries now require automatic fire sprinklers to be installed in buildings in which the risks or hazards are high, from high-rise residential buildings to hazardous materials storage facilities. As noted above, automatic fire sprinklers can provide a significant benefit in reducing the environmental impact of fire, since in most cases the fire will be controlled at a small size,

Fig. 10.27 Fire sprinkler ceiling mount side view. (Source: Brandon Leon, licensed with CC BY-SA 2.0)

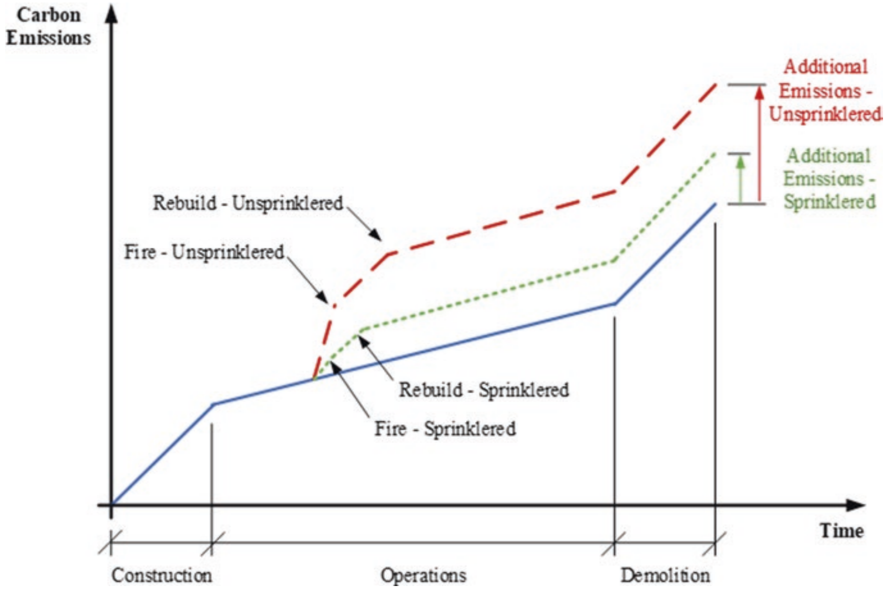

Fig. 10.28 Qualitative reflection of carbon emissions of a building with and without fire occurrence. (Source: Wierczorek et al. [7] ©2010 FM Global. All rights reserved)

which will reduce emissions due to fire, the extent of impact from firefighting water, and will reduce extent of repair, refurbishment or rebuild.

This can be illustrated well by considering Fig. 10.28 (adapted from [7]), which shows environmental impact of a building, reflected in terms of carbon emissions, with and without a fire during its lifetime. In Fig. 10.28, the bottom curve (solid blue line) qualitatively reflects embodied carbon associated with building materials and building construction, the carbon emissions through the life of the building (e.g., from heating, cooling, lighting), and end of life emissions associated with demolition. Assuming a fire occurs at some point in the operating life of the building (dotted lines), there will be emissions associated with the fire, as well as emissions associated with the rebuild (materials and construction). If the building is sprinklered (green dotted line), the overall additional carbon emissions will be much less than if unsprinklered (red dashed line) due to lower fire and rebuild emission contributions (Fig. 10.28).

In Fig. 10.28, the relative magnitude of the increased carbon emissions due to fire depend significantly on the type (material) and amount of contents and structure consumed by the fire. Methods to estimate the emissions are provided in Chap. 5.

In addition to reducing carbon emissions over the lifetime of the building, use of automatic sprinklers can significantly reduce the amount of water that is needed to suppress the fire. Not only does this save water, but it results in lower quantities of firefighting water runoff, which can also be impactful to the environment (see Sect. 10.4). With respect to facility design, this reduce the overall capacity of any

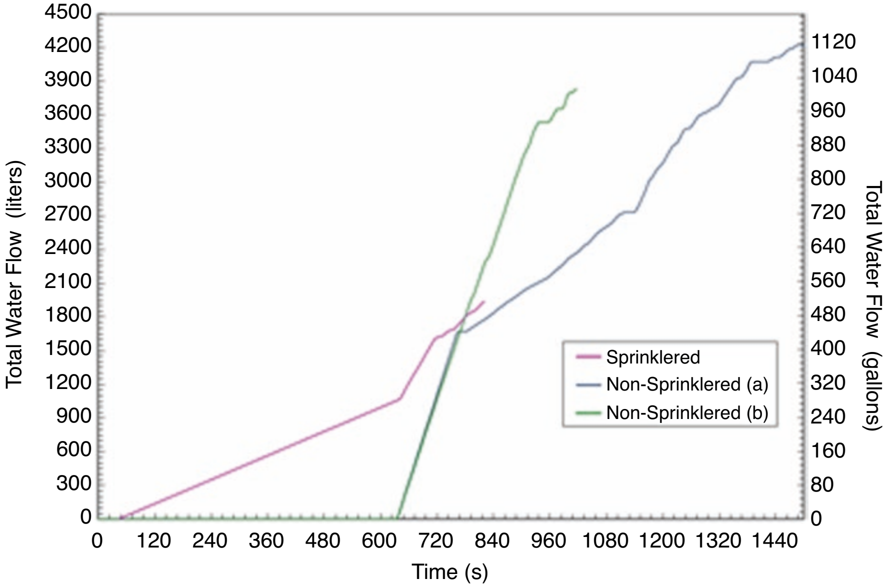

Fig. 10.29 Total water flow required to suppress test fires in sprinklered and non-sprinklered living room fire tests. (Source: Wierczorek, et al., 2010 [7] ©2010 FM Global. All rights reserved)

firefighting water catchment tanks or areas that may be required by legislation or otherwise desired as an environmental protection feature.

An example of the order of magnitude of water savings can be seen in Fig. 10.29 [7]. In Fig. 10.29, the pink line reflects the total water flow requirement in an experiment in which sprinklers were present, and the green line and the blue line reflect experiments in which no sprinklers were present, and water from a hose stream was required to suppress the fire. In these experiments, the room size and contents were the same for all tests. In the absence of sprinklers, as much as twice the amount of water was needed to suppress a fire in a single, small compartment. As the size of fire and compartment increase, the manual fire suppression water requirements increase even more substantially (Fig. 10.29).

In BRE's assessment of the costs and benefits of sprinklers in reducing the environmental impact of fire in warehouses [8], estimates of CO_2 released during a fire, CO_2 embodied in rebuilding and replacing contents, and water usage (sprinkler and manual) were made, based on the estimated area of fire involvement (sprinklered and unsprinklered). In this study, the average estimated environmental impacts of fires over an assumed 45-year lifetime of a sprinkler system yielded outcomes as reflected in Table 10.1.

As in any such assessment, there are many assumptions regarding structural materials, contents, area involved in the fire, number of fires over expected lifetime and more, and the reader is directed to the full report for details [8]. However, much

Table 10.1 Average estimated environmental impacts of fires in a warehouse over assumed 45-year lifetime of sprinkler system

Environmental impact	Unsprinklered	Sprinklered
Tonnes CO_2 release by burning contents	1014	3
Tonnes CO_2 equivalent embodied in replacement contents	2693	6
Tonnes CO_2 equivalent in rebuilding	246	1
Tonnes CO_2 equivalent for water usage	13	1
Total tonnes CO_2 equivalent	**3966**	**11**
m^3 of water used in firefighting	**12,340**	**627**

Recreated and adapted from [8], Table 2

like the FM Global evaluation of environmental impact of residential fires, the BRE assessment illustrates the considerable reduction in environmental impacts from fire in sprinkler protected warehouses as comparison to warehouses without sprinkler systems.

Fine Water Mist Systems

Fine water mists systems can be considered a variation of an automatic fire sprinkler system, but where typically the water supply is under higher pressures and the heads (nozzles) are designed to produce much smaller water droplets. Whereas traditional sprinklers deliver water droplets that wet and cool surfaces, the fire suppression mechanisms of fine water mist systems include dilution of the oxygen supply in the zone of burning as a result of steam produced from evaporation of water droplets in the heated area surrounding the fire, along with cooling effects of the water [20]. With the high pressure and small droplets, the water mist can envelop items in a space and can fill the space.

An environmental benefit of fine water mist systems is that they require even less water than a traditional fire sprinkler system to suppress a fire. They can also operate more quickly, when the fire is smaller, which reduces emissions from the fire and keeps contents replacement and rebuild impacts lower. However, water mist systems are not as effective as sprinklers for some types of fires and environments, particularly where the mist cannot penetrate to the seat of the fire, as might be experienced in large fires in large volume spaces.

Manual Fire Suppression

Manual fire suppression using water may be undertaken by occupants of a building, particularly if occupant-use hoses are installed, by an on-site fire brigade, or by the fire service. As noted in the above sections, water is an effective fire suppressant, but by the time manual response to a fire occurs, the amount of water required can

Fig. 10.30 Structural fire fighter training. (Photo Credit: US NPS, Riley Caton, 2010)

become significant. This poses both an environmental impact in terms of use of a scarce resource, as well as the potential for introducing hazardous or toxic materials into the environment through firefighting water runoff.

Whereas the water supply for an automatic sprinkler system could be as low as 60 l/min at 48 kPa per head, and the design area as small as 1–2 heads (small compartment), the required amount of water for suppression, given a 30-min flow time estimate, could be as low as 1800 l. This can be seen from the FM Global test outcomes illustrated in Fig. 10.29 above [7]. By contrast, in the same figure, up to 4200 l of water was required to manually suppress a fire in an equivalently furnished room: about 2.3 times as much (Fig. 10.29).

Looking to the BRE study [8], estimates of average quantities of firefighting water needed for fires in warehouses of different size groupings of warehouses (small, medium and large) also indicate that up to 2.3 times as much firefighting water may be required for situations involving only manual fire suppression activities. This is reflected in Table 10.2 for medium size warehouses. Note that the estimated amount of firefighting water required for sprinklered fires in warehouses is higher than in the FM Global residential fire experiments in part because it can be expected that several sprinklers will operate in a warehouse environment, whereas only one sprinkler actuated in the residential living room experiment.

In addition, based on data used in the BRE study which suggests that more fires occur in unsprinklered warehouses than sprinklered ones [8], the total estimated

Table 10.2 Representative firefighter water requirements and other impacts for representative warehouse size ranges per event

	Small (<2000m^2)		Medium (2–10,000 m^2)		Large (>10,000 m^2)	
Quantity	US	S	US	S	US	S
Area burnt (m^2)	70	7	923.5	7	923	7
Area damaged (m^2)	123.5	124	1632	121	3097	125.5
CO_2 from fire (tonnes)	21	2	280.5	2	280	2
CO_2 embodied (tonnes)	56.5	5	745.5	5.5	745	5.5
FF water used (m^3)	**2986**	**2149**	**4986**	**2130**	**3373**	**2142**

Recreated and adapted from [8]
Note: *US* unsprinklered, *S* sprinklered

firefighting water requirements over the lifetime of the warehouse is much higher for manual suppression alone than when sprinkler protection is provided, as reflected in Table 10.1. In this case, the firefighting water requirement for the unsprinklered warehouse was 12,340 m^3 (12,340,000 l), as compared with 627 m^3 (627,000 l) for a sprinklered warehouse.

It should be noted that in the BRE analysis, estimates of firefighting water requirements were based on assumptions about the number of firefighting vehicles responding and previously determined correlation between area of burning and amount of suppression water required [21]. Bureau Veritas assumed that on average six apparatus would respond to an unsprinklered fire and that on average 3391 m^3 of water would be used. Based on the data provided, and assuming that each responding apparatus would on average pump 565 m^3 of water per fire, a correlation between the area of the fire (A_{fire} (m^2)) and the volume of water required (V (m^3)) was derived:

$$V = 1403\left(A_{fire}\right)^{0.24} \tag{10.1}$$

While different data could be expected to change the estimates of total firefighting water requirements, both the FM Global and BRE studies show a similar ratio between sprinklered and unsprinklered fires in residential and storage facilities. As a first order estimate, it could be assumed a similar ratio applies to other building uses as well.

Finally, it should be noted that the BRE study also points out that the length of time required for firefighting operations can have a significant impact on water usage as well. For example, a case study about a Sony warehouse fire in London was presented, where it was estimated that some 13,030 m^3 of firefighting water was required for a single fire event [8]. The amount of water needed for this fire was attributed to the fact that 6 h of intensive firefighting operations were required to bring the fire in the 23,964 m^2 facility under control, and that some level of firefighting continued over a total of 14 days until the fire was completely extinguished.

Water-Based Suppression Systems with Additives

As noted in Sects. 10.3.3.3 and 10.3.3.4, as well as in Chap. 8, additives can be mixed with water to increase the suppression efficiency for certain types of fuels and fires. As reflected in the EIFMT, the aim is to use environmentally friendly suppressants. Many of the additives available currently for enhancing fire suppression effectiveness are friendly to the environment; however, as noted in Sect. 10.3.3.4, some additives used over the past several decades have been shown to cause human and environmental impacts, in particular perfluorinated chemicals (PFCs), including perfluorooctane sulfonate (PFOS), polyfluoroalkyl substances (PFAS) and perfluorooctanoic acid (PFOA), which were utilized in some formulations of Aqueous Film Forming Foam (AFFF).

As noted in Sect. 10.3.3.4 and in Chap. 8, there have been several studies into the human and environmental impacts of firefighting water additives, more commonly referred to as firefighting foams (FFF), both from wildland fire and facility fire perspectives (e.g., [11, 12, 14–17, 22, 23]). A useful study was conducted for the New Zealand Fire Service to evaluate the environmental impact of FFF used in New Zealand [23]. The study provides a good overview of FFF classification, chemical composition, and environmental impact potential for specific FFFs.

In general, there are several categories of FFFs, the chemical composition of which determines the application to which it is best suited. The types include [23, 24]:

- Protein Foam
- Fluoroprotein Foam (FP)
- Film Forming Fluoroprotein Foam (FFFP)
- Alcohol-resistant Film Forming Fluoroprotein Foam (AR-FFFP)
- Aqueous Film-forming Foam (AFFF)
- Alcohol-resistant Aqueous Film-forming Foam (AR-AFFF)
- Synthetic Detergent Foam
- Class A Foam
- Fluorine-Free Foam (F3)

Foam is generated by proportioning foam concentrate (additives) with water via fixed or portable proportioning devices, and the foam is discharged through nozzles, foam monitors, or sprinklers depending on the application [24].

FFF can be categorized as Class A or Class B. Class A foams act to reduce the surface tension of water used in firefighting through addition of a surfactant, which increases the ability of the water to penetrate into materials, thus allowing for improved wetting and more rapid and complete end to combustion. Class B foams are used on fires involving flammable liquids, being formulated to develop a thermally stable cap or seal over the surface of flammable liquids, which excludes oxygen and prevents the release of flammable vapor which could ignite if a suitable fuel loading ratio is achieved [23] (Fig. 10.31).

Fig. 10.31 Firefighter Training with FFF. (Photo Credit: “131,205-Z-NI803–107” by Matt Hecht is marked under CC PDM 1.0)

With respect to FFF in the environment, the persistence of the foam (chemicals) and their ability to degrade are critical parameters. The following overview is extracted from the New Zealand study [23] unless otherwise noted. Introduction of relatively large volumes/masses of readily biodegradable compound into the environment may cause significant degradation in a short period of time. This degradation will be due to the use of oxygen as microorganisms metabolize the compound that has been introduced. If the increased biological demand for oxygen exceeds the environmental natural ability to replenish, oxygen levels become depleted or exhausted. In aqueous environments the visible signs of this are seen as large-scale fish death, and death of other animals such as invertebrates. For a specific compound or mixture of compounds the biological oxygen demand (BOD) value will be proportional to concentration; meaning the greater the dilution the lower the BOD: this is an important factor to consider when assessing the impact releases of such compounds may have on a receiving environment.

Class A foams are predominantly mixtures of surfactants and emulsifiers in aqueous suspension. Class A foams may also contain a mixture other functional compounds, such as fire retardants, that suit specific fire-fighting needs, these compounds vary from product to product. Class A foams are inducted into fire-fighting water at a rate of 0.1–1% by volume, this is relatively low when compared to induction rates of 3–6% for many Class B foams. The short-term impact of the surfactant, emulsifier and retardant compounds in Class A foam has been recognized internationally, but is generally considered to be less than that posed by Class B foams, specifically those containing fluorinated compounds.

Class B firefighting foams produced over the last 50–60 years have contained perfluoroalkyl and polyfluoroalkyl substances (PFAS) or mixtures of these compounds as these provide excellent thermal and chemical stability. The composition of such fluorosurfactants in the foam concentrates are rarely clearly identified in material data sheets as it is considered a proprietary secret by manufacturers. Up until the mid-2000's the predominant compounds used for foam manufacturing were perfluorooctane sulphonates (PFOS). These were withdrawn from manufacturing by the 3 M Company due to environmental/ecological concerns regarding their persistence, bioaccumulative capacity and toxicity characteristics (collectively known as PBT). PFOS have been replaced with a number of other fluoro-compounds and more recently some fluorine-free foam compounds.

The NZFS study discusses the environmental impacts in some detail. As part of the effort, a framework was created to provide a systematic approach to ranking the potential long-term environmental impact of a FFF product to allow end-users to factor the environmental impact aspect of FFF performance into their considerations. The study identified specific products and ranks them with respect to their potential impact to the environment [23]. This can be a helpful resource for those looking to identify FFF with low environmental impact potential.

Gaseous Extinguishing (Suppression) Systems

As an alternative to water-based systems, gaseous extinguishing (suppression) systems can be used for some applications. While some gaseous agents provide cooling, many interrupt the combustion process either through chemical reaction or reducing the amount of oxygen available. Gaseous agents are often used in areas involving electrical equipment, machinery and materials for which interaction with water is inappropriate or dangerous.

One of the longest used gaseous agents is carbon dioxide (CO_2). The primary mechanism by which CO_2 extinguishes fire is oxygen reduction (smothering), but the cooling effect does make some contribution to fire extinguishment, particularly when CO_2 is applied directly to the burning material [25]. CO_2 can be found in handheld fire extinguishers and as part of 'total flooding' systems, in which the gas is released into a container or compartment (room). There are life safety concerns with CO_2, in total flooding applications, since oxygen is reduced to unsafe levels. While CO_2 is a greenhouse gas, the amount released in fire suppression activities is not a significant environmental concern.

Total flooding clean agents and systems were developed in response to the regulation of Halon 1301 under the Montreal Protocol and its amendments, which culminated in the phase-out of production of halons in the developed countries at the end of 1993. Clean agents include halogenated and inert gas fire suppressants and are generally defined as electrically nonconducting fire extinguishants that vaporize readily and leave no residue [26]. Like some CO_2 systems, clean agent systems are typically used as 'total flooding' fire extinguishing systems, but unlike CO_2, do not result in lethal conditions for any occupants of a protected space inadequately exposed when properly designed and installed.

Table 10.3 Environmental factors for halocarbon clean agents and inert gases

Designation	ODP	GWP (100 years)	Atmospheric lifetime (years)
Halon 1301	12,000	7030	65
HFC-227ea	0	2900	34.2
HFC-23	0	14,310	270
HFC-125	0	3450	29
FK-5-1-12	0	1	0.038
Inert gas	0	0	NA

Recreated and adapted from [26]

Clean agent halon replacements fall into two broad categories [26]: (1) halocarbon compounds and (2) inert gases and mixtures. Halocarbon clean agents include compounds containing carbon, hydrogen, bromine, chlorine, fluorine, and iodine. They are grouped into five categories: (1) hydrobromofluorocarbons (HBFC), (2) hydrofluorocarbons (HFC), (3) hydrochlorofluorocarbons (HCFC), (4) perfluorocarbons (FC or PFC), and (5) fluoroiodocarbons (FIC) and Fluoroketones (FK). The recent introduction of Fluoroketones has enabled the use of halocarbon agents with near zero global warming potential in normally occupied areas. Inert gas clean agents include nitrogen and argon and blends of these. One inert gas replacement has a small fraction of carbon dioxide.

Two main environmental impacts that need to be considered with respect to halocarbon extinguishing agents are (1) ozone depletion potential (ODP) and (2) global warming potential (GWP). Another environmental factor, atmospheric lifetime, is also typically considered. Table 10.3 [26] summarizes environmental impact data for halocarbon agents (FC and HFC compounds have zero ODP) and inert gases.

10.4 Manage Fire Exposure to the Environment

A focus of the EIFMT 'manage exposure' branch is aimed at considering options for limiting the impact of fire on the environment, taking into account the extent to which measures have been taken to prevent or manage the fire itself. If a fire occurs, there will be emissions, and little can be done to manage the environmental exposure via airborne pathways. Insight into the development and spread of fire effluents as associated with buildings can be obtained from Chaps. 3, 4 and 6. Control of fire ignition and managing of fire spread in buildings is outlined above.

If fire suppressing activities are needed, there will be the potential for waterborne impacts. Section 10.3 above speaks to the benefits of automatic fire sprinklers in reducing airborne emissions and total suppressant volume needs. However, even when sprinklers are used, some level of manual fire suppression is generally needed. When there are no sprinklers, firefighting water needs can be significant. Much of this section focuses on managing the firefighting runoff in order to minimize the potential for Sandoz-like events.

For some building and facility uses, storage of raw or finished materials may be outside of buildings. In such cases, direct contamination of soil may result from a fire. This can be exacerbated by firefighting water runoff, if not contained.

10.4.1 Control of Fire-Fighting Water Quantity and Runoff

Regardless of best intentions and measures to control against the ignition and control of fire spread, many buildings' fire defense systems can become overwhelmed, requiring the intervention of the fire service to undertake manual fire suppression activities, even when fire sprinklers are in place. As discussed in Sect. 10.3, the amount of firefighting water produced can be significant, depending on the size and intensity of the fire, especially when manual fire suppression is the only suppression approach employed. The firefighting water can be damaging to the environment if there are significant quantities of toxic effluents resulting from the fire, and even more so if toxic firefighting additives are in use. Control of firefighting runoff water therefore becomes an important means of reducing the environmental impact of fire.

The catastrophic industrial accident in the Italian town of Seveso in 1976 prompted the European Commission (EC) to promulgate the Seveso Directive (see EC, 2020, as well as discuss in Sect. 10.5), which included the implementation of the EC Major Accident Reporting System (MARS). From a European perspective, this was a key event in turning public and political attention to the human and environmental impacts of industrial accidents. Subsequently, when the 1986 Sandoz event occurred, the need to consider the contribution of firefighting water runoff and its impacts on the environment became more focused. This was further enforced with the 2001 *OECD Environmental Outlook for the Chemicals Industry*, wherein it was noted that more than 300 major chemical related accidents had been reported to the EC MARS between 1985 and 1997, and that "in the EU, chemical accidents that cause ecological harm often involve water pollution (and this pollution is frequently the result of firewater runoff)" [27].

Events and concerns such as these led the International Organisation for Standardisation's (ISO) Technical Committee (TC) 92 (Fire safety), Subcommittee (SC) 3, *Fire threat to people and environment*, to draft a technical report on *Environmental damage limitation from fire-fighting water run-off* [28]. This Technical Report reviewed the best practices at the time, discusses emission pathways associated with firefighting runoff water, risk-reduction and firefighting tactics to limit environmental damage, and guidance on characteristics and approaches to designing firefighting water runoff basins. While this Technical Report provided good guidance, it did not provide specific calculation methodologies for estimating retention needs. However, it provided some representative incidents, and reflected a risk-based approach for sizing retention based on guidance from Australia [29].

Interest in controlling firefighting runoff remained high, and on the 25th anniversary of the Sandoz fire and release of toxic firefighting runoff water into the Rhine River, the United Nations Economic Commission for Europe (UNECE) held a seminar “to reflect on the work carried out and progress achieved in the area of prevention of accidental water pollution in the UNECE region” and “to examine existing deficits in the prevention of water pollution by chemical substances, and formulate the way forward to address these deficiencies” [30]. The seminar illustrated that while much progress had been made to reduce impacts from firefighting water runoff, significant challenges remained in several countries with respect to firefighting in hazardous facilities and the containment of firefighting water, and it was recommended that guidance be developed. The result was development of *Safety guidelines and good practices for the management and retention of firefighting water*, published by the UNECE in 2019.

Key recommendations embodied in the UNECE guidelines are as follows [30].

“(a) Firefighting water is hazardous to waters irrespective of the material burned. This means that, for example even burned packaging material and combustion products from building materials can contaminate firefighting water by turning it into a water-endangering agent. The development of huge amounts of firefighting water should therefore be avoided in the first instance. Firefighting water must be retained completely and disposed of adequately in order to prevent the contamination of water and soil, both within and across countries;

(b) Governments should provide leadership and create suitable administrative and legal frameworks to introduce mandatory requirements for firefighting water management and retention in case of emergencies at all hazardous activities (i.e., not only at storage facilities) (Fig. 10.32);

Fig. 10.32 Structural firefighter training. (Photo Credit: US NPS, Riley Caton, 2010)

(c) Retention capacities for firefighting water should be established at all hazardous facilities. They should be subdivided into fire compartment areas that are as small as possible. As an example for determining the retention capacities for firefighting water, the German VdS 2557 guideline [31] or the Swiss inter-cantonal guidelines [32] can be used in industrialized countries. For less industrialized countries, a quick, rough estimation based on a direct proportionality of the firefighting water retention volume needed compared with the largest fire-compartment area can be undertaken. Even a complete burn-down should be taken into account, if there is not sufficient retention capacity for firefighting water;

(d) These guidelines focus on water-based extinguishing strategies; however, differing firefighting strategies should also be considered. In general, the retention volume for firefighting water can be drastically reduced by implementing efficient measures to prevent fires from spreading, by using automated fire detection in combination with automatic extinguishing systems (sprinklers, deluge systems, high expansion foams and extinguishing gases) and by applying efficient firefighting techniques;

(e) These safety guidelines and good practices are intended to support governments, competent authorities and operators in applying measures and improving existing practices to prevent accidental pollution of soil and water, including pollution that could cause transboundary effects. Joint bodies, international organizations and other relevant actors could support this work by raising awareness about these guidelines and assisting competent authorities and operators in their implementation. The use of these safety guidelines will help develop a common safety level across the UNECE region. It will also support the implementation of the 2030 Agenda for Sustainable Development (notably the achievement of Sustainable Development Goal 6 on ensuring the availability and sustainable management of water and sanitation for all) and the four priorities of the Sendai Framework for Disaster Risk Reduction 2015–2030."

The *Safety guidelines and good practices for the management and retention of firefighting water* [30] are available free for download and the details are not repeated here. The guidelines include a range of methods of estimating capacity of firefighting water retention areas, case studies regarding release events, and guidance for governments and policy makers regarding implementation of recommended measures.

With respect to estimating retention capacity, the Joint Expert Group on Water and Industrial Accidents of the UNECE proposed a simple model that is easy to use and conservative in terms of firefighting water that may be required [30]. Quite simply, the model estimates that 1 m^3 of water retention volume (R) will be required per square metre of the protected object surface or its biggest fire compartment (A_f).

$$R\left(\mathrm{m}^3\right) = A_f\left(\mathrm{m}^2\right) \tag{10.2}$$

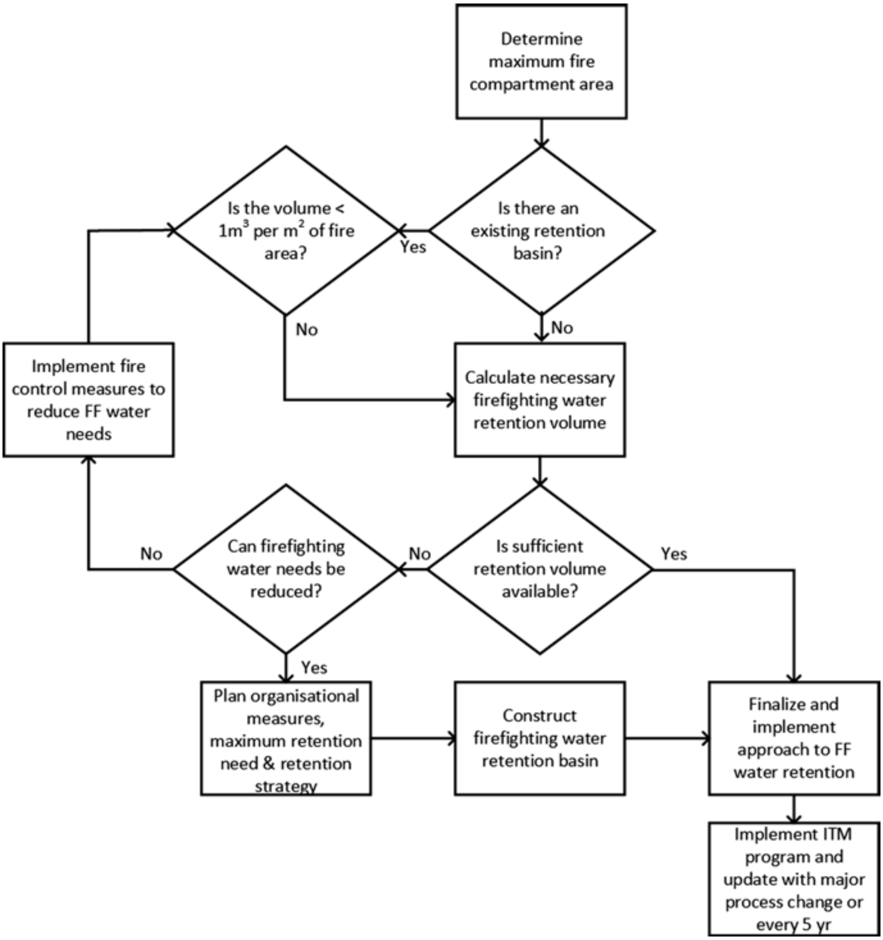

Fig. 10.33 Decision process for assessing firefighting water retention needs. (Adapted from Fig. 2 in [30])

A general decision process that can be used in assessing and sizing firefighting water retention needs, based on this simple approach, is shown in Fig. 10.33 (adapted from Fig. 2 in [30]).

When using the simplified approach, it is suggested that the calculated retention volume can be reduced to 10% of the calculated volume if a constantly operating facility fire service (brigade) is available at the site. Also, the guidelines present the German VdS and Swiss KVU relationships, cited above, as well as some derived from other publications (e.g., [33–35]) and government entities (e.g., [36, 37]).

From an operational perspective, if adequate firefighting water runoff retention is not possible, the ECE guidelines suggest consideration be given to complete burn-down of the site. However, this would result in tradeoffs between effluents delivered through the air versus a combination of through the air and via potential runoff water. Guidance in Chaps. 3, 4, 6, 8 and 9 can be helpful in assessing overall potential emissions and pathways of exposures as support for planning and operational decision-making.

10.4.2 Control of Fire Effluents Directly into the Soil

Aside from fire effluents being distributed through the air or water before being deposited into the soil, exterior storage of raw or finished materials at a facility site, or external equipment (e.g., electrical transformer) may provide a pathway for direct contamination of soil in the case of fire. This can be exacerbated by firefighting water runoff, if not contained.

Perhaps the most straightforward way to address this concern is by implementation of impermeable barriers and containment, sized to contain the stored material and any required firefighting water (in addition to storm water). This approach is used for large-scale petroleum product storage, for example, with tanks being stored within protected berms or dikes. This can effectively allow for capture and containment, as well as providing separation of fuel sources to aid in the control of fire spread from one fuel package to another, as well as in fire suppression (e.g., installation of fixed firefighting foam monitors). This approach could be used for solid or gaseous materials stored in tanks or vessels as well.

In situations where storage may involve solid materials in piles or racks, use of impermeable layer between the storage and soil, grading to manage water flows, and capture of the runoff water can be used. Even though such storage or equipment is outside of a building, fire control measures as outlined in Sect. 10.3 may be possible, including fire walls to provide shielding of radiant energy reaching another fuel source, and fixed water spray or other suppression systems, which focus on the fuel source of concern (e.g., electrical transformer).

10.5 Regulations, Standards, Guidelines and Related Resources

In most countries, the first place to look for fire protection requirements for buildings and facilities are the building and fire regulations (codes). These may be:

- Developed and promulgated by government, either nationally (e.g., England, New Zealand), regionally or both (e.g., the federal system in Germany);
- Developed by quasi-governmental organizations and adopted into law and promulgated by government (e.g., Australia, where model code is developed by the Australian Building Codes Board, Austria, where the model regulation is developed by the Austrian Institute for Building Construction (OIB) and adopted and promulgated in each province, and Canada, Austria, where the model code is

developed by the National Research Council (NRC) and adopted and promulgated in each province); or

- Developed by private sector organizations and adopted into law and promulgated by government (e.g., the USA, where model codes are developed by the International Code Council (ICC) and the National Fire Protection Association (NFPA) and adopted and promulgated at the state and/or local level).

Building and fire regulations typically reference applicable consensus standards (sometimes called reference standards) that are developed across a wide range of groups, from broadly representative standards development organizations (SDOs), which exist at national (e.g., the American Society of Testing and Materials (ASTM) in USA or British Standards Institution (BSI) in the UK), regional (e.g., European Organization for Standardisation (CEN) in Europe) or internationally (e.g., International Organisation for Standardisation (ISO)), to industry-specific (e.g., American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE)) or sector-specific groups (e.g., the National Fire Protection Association (NFPA)), to insurance entities (e.g., FM Global).

Many consensus (reference) standards and design codes focus on specific requirements associated with testing, design, installation and maintenance of materials and systems. These consensus standards and design codes may be cited by reference in building regulation, which makes them legally enforceable, or are available as voluntary guidance. There can be many hundreds of applicable reference standards and design codes which underpin a comprehensive building regulatory framework. These technical documents, which make up part of the overall regulatory infrastructure, are often supported by handbooks, textbooks and related technical resources.

The interconnection between entities, documents and sector participants can be illustrated by considering the relationships between the State Building Code in the USA and model regulations, reference (consensus) standards, and market entities, and sector participants as reflected in Fig. 10.34.

The State Building Code would be developed the Building Code Commission or equivalent in a state. It most often is based on a set of model codes developed by the International Code Council (ICC), a private sector code development organization. The ICC publishes model Building, Fire, Energy, Mechanical and other codes, which together contain the ‘top level’ regulatory provisions for buildings, which when adopted into law at a state or local level (State Building Code), becomes the legally enforceable building code (regulation).

Within each model code are references to numerous reference (consensus) standards, developed by standards-development organizations (SDOs), insurance industry, professional associations and more, which address all types of material, system, and product performance, quality, design, installation, test and maintenance features. There is also within model codes and consensus standards reference to guidelines and codes of practice from professional societies, insurance entities, testing laboratories and more. All of the documents are supported by research, academia, building owners, code officials and more, who participate in the document development processes, and by related sources of technical data and information.

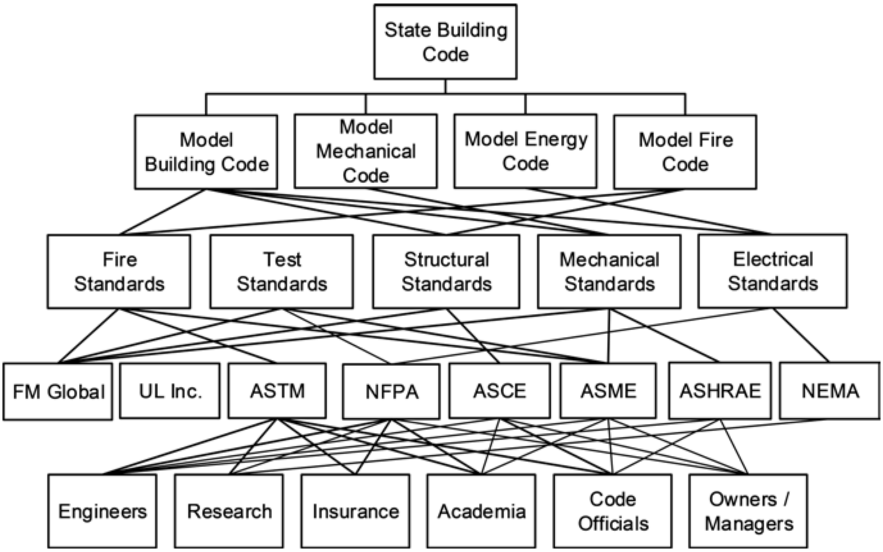

Fig. 10.34 Interrelationship between regulations, standards, and market in USA [38]

Finally, in addition to the building regulatory systems, other areas of regulation can have bearing. For example, workplace safety is often regulated by occupational health and safety agencies, which typically exist at the national level (e.g., UK Health and Safety Executive (HSE), US Occupational Safety and Health Administration (OSHA)), and several of their regulations and guidance apply to workplaces. These too may have components that apply to specific industries or processes. Environmental or resource protection departments or agencies also play a significant role, especially in the area of environmental protection from fire.

This section presents a high-level overview of the types of regulatory and private-sector entities that develop applicable material, along with exemplar requirements and resources that are available and representative examples of the content addressed. Due to the extensive amount of material in this area, this overview is neither comprehensive nor exhaustive. Exploration of applicable legislation and regulation, and availability of applicable resources, should be undertaken at the time of analysis or design for the specific facility location.

10.5.1 Building and Fire Regulation

Most countries have some manner of formal building regulation which govern the fire safety design of buildings and facilities. These may be called building regulations (e.g., Building Regulations, England), building laws (e.g., Building Standard Law, Japan), building codes (e.g., Building Code of Australia), or building standards (e.g., Building Standards, Scotland). For simplicity, these are referred to hereafter as building regulations.

As a general observation, most building regulations do not have a specific focus on protection of the environment from fire: their primary fire-related focus is life safety, and to some extent property protection, which is often limited to controlling fire spread to adjacent properties. However, in providing for protection of life and property against fire, they provide fundamental components of the EIFMT within the ‘prevent fire’ and ‘manage fire spread’ branches.

In addition to building regulations, many countries have separate fire (prevention) regulations (codes, laws) as well. Here also, the focus is typically on protection of life and property against fire, focusing on fundamental components of the EIFMT within the ‘prevent fire’ and ‘manage fire spread’ branches. Fire regulations often address limitations on hazardous materials, and where permitted, the associated fire protection requirements. In some cases, control of firefighting runoff water is a consideration.

The types of mitigation strategies typically considered by building and regulations are overviewed in Sect. 10.3 above and will not be further explored here. Discussion on different structures and compositions of building regulations and regulatory systems, and means to assess the adequacy of those systems, can be found in the literature (e.g., [39–43]), including with focus on fire safety (e.g., [44–48]).

10.5.2 Consensus (Reference) Standards

Most building and fire regulations cite consensus standards which cover a wide range of topics. Review of the building and fire regulations in a jurisdiction will often lead to applicable consensus standards.

As noted above, consensus standards are developed be recognized standards development organisations (SDOs). Countries may have more than one SDO, with many countries also using regional (e.g., CEN) or international (e.g., ISO) standards. These SDOs develop a range of standards associated with test, design, installation and maintenance of materials and systems for electrical and fire safety in the built environment. They do this through the formation of standards development committees formulated by topic (e.g., electrical safety, fire resistance testing, sprinkler system design and installation requirements), which are composed of subject matter experts, as well as representatives if manufacturers, government, insurers, users of the standards and others.

Following are a very few examples of SDOs which develop consensus standards that are important to preventing ignition and managing fire impact:

- American Society for Testing and Materials (ASTM), USA
- Association Française de Normalisation (AFNOR), France
- British Standards Institution (BSI), England

- Deutsches Institut für Normung (DIN), Germany
- European Committee for Electrotechnical Standardization (CENELEC), Belgium
- European Committee for Standardisation (CEN), Belgium
- International Electrotechnical Commission (IEC), Switzerland
- International Organization for Standardisation (ISO), Switzerland
- National Fire Protection Association (NFPA), USA
- Standards Australia (SA), Australia
- Standards New Zealand (NZS), New Zealand
- Verband Deutscher Elektrotechniker (VDE), Germany

In some cases, SDOs also produce standards focused particularly on fire impact to the environment. ISO is one of these. The ISO Technical Committee on Fire Safety (ISO TC92) has a sub-committee (SC3) which focusses on developing a standardised methodology to assess the environmental impact of fires. To date they have published a series of documents compiling important definitions and instructions concerning assessing the environmental impact of fires and represent an important starting point for the development of a methodology to assess the cost of the environmental impact of fires.

- ISO 26367 *Guidelines for assessing the adverse environmental impact of fire effluents*
- ISO 26367-1 Part 1: *General* [49]
- ISO 26367-2 Part 2: *Compilation of environmentally significant emissions from fires* [50]
- ISO 26367-3 Part 3: *Sampling and analysis* (working draft)
- ISO 26367-4 Part 4: *Incorporating Fires into Models of Environmental Impact* (internal committee document)
- ISO 26368 *Environmental damage limitation from fire-fighting water run-off* [28]
- ISO 19677 *Guidelines for assessing the adverse impact of wildland fires on the environment and to people through environmental exposure* [51]

10.5.3 Industry and Professional Organizations Standards and Guidelines

In addition to SDOs, many standards, codes of practice and technical guidelines are developed by research institutions, industry and professional organizations. In some cases, these organizations can obtain accreditation as a SDO, so that their standards can be reference by building regulations, while in other cases the documents remain extra-regulatory, but can be critical to fire hazard and risk management, particularly in high-hazard industries and environments. A representative sampling of such organizations, and the types of documents that they produce, are provided below.

- American Institute of Chemical Engineers (AIChE), Center for Chemical Process Safety (CCPS), USA

  - *Guidelines for Chemical Process Quantitative Risk Assessment* (2000), AIChE, New York, NY, USA
  - *Guidelines for Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities* (2003), AIChE, New York, NY, USA
  - *Guidelines of Determining the Probability of Ignition of a Released Flammable Mass* (2014), AIChE, New York, NY, USA
  - *Guidelines for Combustible Dust Hazard Analysis* (2017), AIChE, New York, NY, USA

- American Petroleum Institute (API)
  - *RP 2001 (2019): Fire Protection in Refineries*, API, Washington, DC.
  - *RP 2028 (2002): Flame Arresters in Piping Systems*, API, Washington, DC.
  - *RP 2030 (2014): Application of Fixed Water Spray Systems for Fire Protection in the Petroleum and Petrochemical Industries*, API, Washington, DC.
  - *RP 2218 (2013): Fireproofing Practices in Petroleum and Petrochemical Processing Plants*, API, Washington, DC.

- American Society of Civil Engineers (ASCE), USA
  - *Standard 29-5: Standard Calculation Methods for Structural Fire Protection* (with SFPE) (2007), ASCE, Reston, VA, USA

- Building Research Establishment (BRE), UK
  - *External fire spread: building separation and boundary distances* (BR 187, 2nd Edition) (2014), BRE, Watford, Herts, England
  - *Fire performance of external thermal insulation for walls of multistorey buildings* (BR 135, 3rd edition) (2013), BRE, Watford, Herts, England

- BRANZ, New Zealand
  - *Guide to passive fire protection in buildings* (2017), BRANZ, Judgeford, Porirua, New Zealand
  - *TR13: Method for determining safe separation distances between buildings in the event of fire* (1996), BRANZ, Judgeford, Porirua, New Zealand

- Chartered Institution of Building Services Engineers (CIBSE), England
  - *Guide E: Fire Safety Engineering* (2019), CIBSE, London, England.

- Research Institute of Sweden (RISE), Sweden
  - *SP Method 2369: Protection System for Storage of Inflammable Goods in Retail Environments – Fire Safety Cabinets*, RISE, Borås, Sweden
  - *SP REPORT 2004:43: Fire-LCA Guidelines*, RISE, Borås, Sweden
  - *RISE Report 2018:44: Engineering methods for structural fire design of wood buildings: Structural integrity during a full natural fire,* RISE, Borås, Sweden

- Society of Fire Protection Engineers (SFPE), USA
  - *SFPE Engineering Guide: Performance-Based Design for Fire (2007),* SFPE, Gaithersburg, MD, USA

  - *SFPE Standard S.02, Calculation Methods to Predict the Thermal Performance of Structural and Fire Resistive Assemblies* (2007), SFPE, Gaithersburg, MD, USA
  - *SFPE Engineering Guide: Guidelines for Substantiating a Fire model for a Given Application* (2011), SFPE, Gaithersburg, MD, USA

- Technical Research Organization of the Netherlands (TNO), Netherlands
  - *Methods for the calculation of physical effects: Due to releases of hazardous materials (liquids and gases)* ("Yellow Book") (2005), VROM, The Hague, Netherlands
  - *Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials* ("Green Book") (1992), Directorate General of Labour of the Ministry of Social Affairs and Employment, The Hague, Netherlands

- UNECE, Geneva, Switzerland
  - *Globally Harmonized System of Classification and Labelling of Chemicals (GHS)*, 8th edition, United Nations Economic Commission for Europe, Geneva, Switzerland (2019)

10.5.4 Insurance Industry

The insurance industry is also a source of standards and guidelines related to fire and explosion protection of buildings and facilities, as well as for standards associated with the testing, certification and approval of materials, products and systems. In some countries, test, certification and approval standards may be referenced by building regulations or consensus standards. Guidelines are often not referenced by regulation, but may be required by the insurance organisation's insured (client). Some insurance industry guidelines are available for use, regardless of regulatory requirement. Below is a small sample of the types of standards and guidelines that are produced by insurance entities with respect to preventing ignition and managing fire impact.

- FM Global, USA
  - Approval Standards (https://www.fmapprovals.com/standards-development/new-and-updated-standards, last accessed December 2020)

    FM 3232. Video Image Fire Smoke Detectors for Automatic Fire Alarm Signaling, FM Approvals LLC, Norwood, MA, USA
    FM 3610. Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II & III, Division 1, Hazardous (Classified) Locations, FM Approvals LLC, Norwood, MA, USA
    FM 4430. Heat and Smoke Vents, FM Approvals LLC, Norwood, MA, USA

ANSI FM 4880. American National Standard for Evaluating the Fire Performance of Insulated Building Panel Assemblies and Interior Finish Materials, FM Approvals LLC, Norwood, MA, USA

- Design Guidance (FM Data Sheets, https://www.fmglobal.com/research-and-resources/fm-global-data-sheets, last accessed December 2020)

  FMDS 1-1 (2020). Firesafe Building Construction Materials, FM Global, Norwood, MA, USA.
  FMDS 1-21 (2012). Fire Resistance of Building Materials, FM Global, Norwood, MA, USA.
  FMDS 2-0 (2020). Installation Guidelines for Automatic Sprinklers, FM Global, Norwood, MA, USA.
  FMDS 5-10 (2011). Protective Grounding for Electric Power Systems and Equipment, FM Global, Norwood, MA, USA.
  FMDS 7-14 (2019). Fire Protection for Chemical Plants, FM Global, Norwood, MA, USA.
  FMDS 8-9 (2020). Storage of Class 1, 2, 3, 4 and Plastic Commodities, FM Global, Norwood, MA, USA.

- Underwriters Laboratories Inc. (UL), USA
  - *UL 9450A (2018). Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*, Underwriters Laboratories, Inc., Northbrook, IL, 2018.
  - *UL 263 (2014). Fire Tests of Building Construction and Materials*. Underwriters Laboratories Inc. Northbrook, IL.
  - *UL (2018) 1699B Standard for Photovoltaic (PV) DC Arc-Fault Circuit Protection*, Underwriters Laboratories, Inc., Northbrook, IL, 2018.

10.5.5 Occupational Health and Safety Regulation

In some countries, legislation and regulation aimed at safeguarding worker health and safety includes requirement or guidance related to fire safety and exposure to toxic or hazardous materials in the workplace. While focused human health and safety, measures to safeguard people can often help safeguard the environment as well. A small sample of this type of guidance is as follows.

- Health and Safety Executive (HSE), UK
  - *The Dangerous Substances and Explosive Atmospheres Regulations 2002*
  - *HSE L138 (2013), Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and guidance*, UK HSE, Crown Copyright, London, England

  - *Controlling fire and explosion risks in the workplace: A brief guide to the Dangerous Substances and Explosive Atmospheres Regulations* (2013), UK HSE, Crown Copyright, London, England
  - *The control of fire-water run-off from CIMAH sites to prevent environmental damage*, Guidance Note EH70 (1995), UK HSE, Crown Copyright, London, England

- Occupational Health and Safety Administration (OSHA), USA
  - *29 Code of Federal Regulations 1910, Subpart H - Hazardous Materials.*
  - *29 Code of Federal Regulations 1910, 1910 Subpart L - Fire Protection*
  - *29 Code of Federal Regulations 1910 Subpart N - Materials Handling and Storage*
  - *29 Code of Federal Regulations 1910 Subpart R - Special Industries*

10.5.6 Environmental Regulation

In some countries, there are environmental or natural resource legislation and regulation which have bearing on recording and or helping to minimize fire impacts on the environment. Much of the relevant legislation and regulation relates to limiting the release of hazardous or toxic materials into the environment as a result of fire. This is controlled for primarily in limits on storage of hazardous materials and requirements related to firefighting water. However, tracking quantities of hazardous material, and emissions into the air from fire, may also occur. Following are exemplar areas of environmental regulation. As with the building regulation discussion above, review of local and national requirements is needed.

US Environmental Protection Agency (USEPA)

Following industrial accidents like Bhopal [52], Section 112(r) of the Clean Air Act Amendments was modified to require the USEPA to publish regulations and guidance for chemical accident prevention at facilities that use certain hazardous substances [53]. These regulations and guidance are contained in the Risk Management Plan (RMP) rule: Section 40, U.S. Code of Federal Regulations (CFR), Part 68, Chemical Accident Prevention Provision, Risk Management Program. The RMP Rule requires facilities that use USEPA-regulated toxic or flammable substances, above threshold quantities, to develop an RMP which:

- identifies the potential effects of a chemical accident,
- identifies steps the facility is taking to prevent an accident, and
- spells out emergency response procedures should an accident occur.

The intent of the RMPs is to provide valuable information to local fire, police, and emergency response personnel to prepare for and respond to chemical emergencies in their community and to foster communication and awareness to improve accident prevention and emergency response practices at the local level. The plans are required to be revised and resubmitted to EPA every 5 years. Each facility's RMP should address three areas:

- Hazard assessment that details the potential effects of an accidental release, an accident history of the last 5 years, and an evaluation of worst-case and alternative accidental releases;
- Prevention program that includes safety precautions and maintenance, monitoring, and employee training measures; and
- Emergency response program that spells out emergency health care, employee training measures and procedures for informing the public and response agencies (e.g., the fire department) should an accident occur.

The rule includes a List of Regulated Substances under section 112(r) of the Clean Air Act, including their synonyms and threshold quantities (in pounds) to help assess if a process is subject to the RMP rule. These regulated substances are also subject to the requirements of the general duty clause. Where the Clean Air Act Section 112(r) program has been delegated to a state, that state may have additional requirements for the federally listed chemicals, and/or additional listed chemicals.

To assist with assessment of impacts, the USEPA published *Risk Management Program Guidance for Offsite Consequence Analysis* [54] on how to conduct the offsite consequence analyses for RMPs. As part of the RMP, regulated entities are required to provide information to the state, local, and federal governments and the public about the potential consequences of an accidental chemical release based on analysis which consists of two elements: a worst-case release scenario and alternative release scenarios.

To simplify the analysis and ensure comparability, EPA defined the worst-case scenario as "the release of the largest quantity of a regulated substance from a single vessel or process line failure that results in the greatest distance to an endpoint," where the distance to the endpoint is the distance a toxic vapor cloud, heat from a fire, or blast waves from an explosion will travel before dissipating to the point that serious injuries from short term exposures will no longer occur. Alternative release scenarios are scenarios that are more likely to occur than the worst-case scenario, and that will reach an endpoint offsite. The current guidance provides more detail than the 1993 *Guiding Principles for Chemical Accident Prevention, Preparedness and Response* [55], which was the OECD [56] document of the same name.

Another area in which environmental regulation plays a role is in firefighting runoff water, in particular, water in which PFAS additives are used. The US EPA has developed a Per- and Polyfluoroalkyl Substances (PFAS) Action Plan [57] which describes the EPA's approach to identifying and understanding PFAS, approaches to addressing current PFAS contamination, preventing future contamination, and effectively communicating with the public about PFAS. Four key actions are:

- Initiating steps to evaluate the need for a maximum contaminant level (MCL) for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS);
- Beginning the necessary steps to propose designating PFOA and PFOS as "hazardous substances" through one of the available federal statutory mechanisms;
- Developing groundwater cleanup recommendations for PFOA and PFOS at contaminated sites; and
- Developing toxicity values or oral reference doses (RfDs) for GenX chemicals and perfluorobutane sulfonic acid (PFBS).

In addition to these significant actions, the EPA's PFAS Action Plan identifies more short-term and long-term actions that are currently being implemented to understand and address PFAS. Short-term actions include:

- Developing new analytical methods and tools for understanding and managing PFAS risk;
- Promulgating 'Significant New Use Rules' that require EPA notification before chemicals are used in new ways that may create human health and ecological concerns; and
- Using enforcement actions to help manage PFAS risk, where appropriate.

Short-term actions are generally taking place or expected to be completed within 2 years. The Action Plan also sets out long-term regulatory and research approaches the EPA will pursue to reduce exposures and to understand the potential human health and environmental risks associated with PFAS.

With respect to emissions to the air, while the RMP guidance is meant to limit impact, it is not possible to eliminate emissions to the air once a fire occurs. However, the US EPA requires that fire emissions be tracked as part of overall emissions inventories. This includes structure fires, vehicle fires and wildland fires. As outlined in EPA's *Emissions Inventory Guidance for Implementation of Ozone and Particulate Matter National Ambient Air Quality Standards (NAAQS) and Regional Haze Regulations* [58], fires are not regulated, but are considered 'events' for which data can be collected. The methodology for collecting emissions data for structure fires can be found in [59].

Europe: The Seveso Directive

Much like the Chemical Accident Prevention Provision, Risk Management Program of the US EPA [53], the Seveso Directive (Directive 82/501/EEC) was established following the catastrophic accident in the Italian town of Seveso in 1976, and subsequently amended following later accidents such as Bhopal, Toulouse and Enschede (Directive 96/82/EC) and again in 2012 (Directive 2012/18/EU) [60]. The driving force was the concern that major accidents involving dangerous chemicals pose a significant threat to humans and the environment, as well as considerable economic losses. Recognizing that the use of large amounts of dangerous chemicals is unavoidable in some industry sectors, it was deemed necessary that measures be implemented to prevent major accidents and to ensure appropriate preparedness and response should such accidents occur.

The Seveso Directive applies to more than 12,000 industrial establishments in the European Union where dangerous substances are used or stored in quantities exceeding certain thresholds, mainly in the chemical and petrochemical industry, as well as in fuel wholesale and storage (incl. LPG and LNG) sectors. Depending on the amount of dangerous substances present, establishments are categorised in lower and upper tiers, with more stringent requirements applicable to the upper tier.

The Seveso Directive obliges operators of facilities with dangerous materials to take 'all necessary measures to prevent major accidents and to limit their consequences for human health and the environment' [61]. The requirements include:

- Notification of all concerned establishments (Article 7);
- Deploying a major accident prevention policy (Article 8);
- Producing a safety report for upper-tier establishments (Article 10);
- Producing internal emergency plans for upper tier establishments (Article 12);
- Providing information in case of accidents (Article 16).
- Main obligations for Member State authorities

Member States may maintain or adopt stricter measures than those contained in the Directive, but need to ensure that a number of requirements are fulfilled:

- Producing external emergency plans for upper tier establishments (Article 12);
- Deploying land-use planning for the siting of establishments (Article 13);
- Making relevant information publicly available (Article 14);
- Ensuring that any necessary action is taken after an accident including emergency measures, actions to ensure that the operator takes any necessary remedial measures and informing the persons likely to the affected (Article 17);
- Reporting accidents to the Commission (Article 18);
- Prohibiting the unlawful use or operation of establishments (Article 19);
- Conducting inspections (Article 20).

Like the Risk Management Program (RMP) required by the US EPA, the Seveso Directive requires that Member States require facility operators their major-accident prevention policy (MAPP), and for those facilities in the upper-tier, to produce a safety report for the purposes of [62]:

(a) demonstrating that a MAPP and a safety management system for implementing it have been put into effect in accordance with the information set out in Annex III;
(b) demonstrating that major-accident hazards and possible major-accident scenarios have been identified and that the necessary measures have been taken to prevent such accidents and to limit their consequences for human health and the environment;
(c) demonstrating that adequate safety and reliability have been taken into account in the design, construction, operation and maintenance of any installation, stor-

age facility, equipment and infrastructure connected with its operation which are linked to major-accident hazards inside the establishment;

(d) demonstrating that internal emergency plans have been drawn up and supplying information to enable the external emergency plan to be drawn up;

(e) providing sufficient information to the competent authority to enable decisions to be made regarding the siting of new activities or developments around existing establishments.

Implementation of the Seveso Directive is handled by each Member State, and national requirements should be investigated in the country of concern. For example, in the UK, compliance with the Seveso Directives is via the Control of Major Accident Hazards (COMAH) Regulations [63].

The HSE Guide to the COMAH Regulations [64], in addressing the issue of the safety report, point to fire detection systems, fire and explosion protection systems and fire suppression systems on the prevention side (Paragraph 459), as well as a description of the equipment installed in the plant to limit the consequences of major accidents for human health and the environment, including for example detection/protection systems, technical devices for limiting the size of accidental releases, including water spray; vapour screens; emergency catch pots or collection vessels; shut-off valves; inerting systems; and fire water retention (Paragraph 459).

Queensland Government: Firefighting Foam

As discussed in Sect. 10.4, control of firefighting runoff water is a concern in many countries, in particular when firefighting foams having environmental impacts are used. The regulations vary by jurisdiction. One example is the *Environmental Management of Firefighting Foams Policy* promulgated by the government of the state of Queensland, Australia [17]. The policy was implemented in response to significant evidence regarding the potential for all types of firefighting foams to have immediate and long-term detrimental effects on environmental and other values during operational incidents, training, maintenance activities and waste disposal when handled improperly and resulting in releases of foam to the environment to bodies of water, soils and groundwater. This policy requires that:

“When choosing and procuring firefighting foam, assessing its suitability for a particular application, assessing its potential to cause undesirable adverse effects, and determining the necessary management measures, the user must take into account in their risk assessment and contingency planning the following issues (including consideration of any relevant performance standards):

- the composition of the foam and appropriate effectiveness for the intended application
- the types and quantities of concentrate to be held on site
- the potential volume of firewater that could be generated during an incident
- the ability to manage and contain spills and firewater on site

- the measures to prevent release of contaminants to soils, groundwater, waterways and air
- the facility location and proximity to environmentally sensitive areas
- the circumstances under which an intended or unintended release might occur
- the pathways for foam and other incident contaminants to be released to the environment
- the potential for PBT and BOD impacts on the local and wider environmental values
- on-site and off-site treatment and disposal of wastewater and contaminated materials
- potential remediation of contaminated soils, waterways and groundwater
- any training, maintenance and testing needs and requirements.

The Policy also recognises that a prime consideration when choosing and procuring firefighting foam is the effectiveness of the foam for the intended application in providing adequate levels of firefighting performance, safety and property protection. The alternatives available that meet the appropriate independently verified performance standards and approvals must then be compared in terms of a net environmental benefit analysis to select the optimal combination that also best addresses the relevant environmental protection standards and overall best practice.

All firefighting foams must be assessed for their potential to cause environmental harm prior to use or disposal. The need for management, containment as well as protective measures and procedures must be assessed in terms of the foam's properties relative to:

- Environmental persistence of the compounds in their formulation and any breakdown products.
- Biopersistence, bioaccumulation, bioconcentration and biomagnification potential.
- Toxicity (both acute and chronic effects).
- Biochemical oxygen demand and biodegradability."

The explanatory notes accompanying this policy [18] provides significant information regarding the environmental impacts of firefighting foams and how to undertake the required environmental impact assessments.

Irish Environmental Protection Agency: Firefighting Water Runoff

With concerns for hazardous runoff of firefighting water, the Environmental Protection Agency (EPA) in Ireland has developed guidance on firewater retention for firewater run-off [57]. The term 'firewater' as used in this guidance document "specifically relates to the liquid that arises from water, foam, rainwater or other substances that have been used for firefighting purposes, and are therefore likely to contain polluting matter, particularly arising from them having come into contact with combustion products." The concern is that firewater arising from a fire incident typically contains high concentrations of substances which are harmful to the aquatic environment, and if it is allowed to enter into soil, drains or watercourses in an uncontrolled manner, has the potential to cause significant environmental damage. The guidance is primarily written for sites licenced by the EPA (Ireland), regulated under the Environmental Protection Agency Act, 1992 (as amended), and the Waste Management Act 1996 (as amended), but is sufficiently broad in scope to accommodate other industrial facilities who may wish to use this guidance document for reference. The guidelines provide information on the following topics:

- Firewater retention qualifying criteria (hazardous substance storage thresholds, environmental receptor criteria)
- Firewater risk assessment (FWRA)
- Retention capacity calculation
- Design of firewater retention facilities
- Firefighting strategies
- Treatment and disposal
- Firewater risk assessment report

The firewater risk assessment (FWRA) discussion begins with a discussion of site measures that can be taken with respect to prevention of significant fire events. The Guide is consistent with the branches of the EIFMT, noting that compartmentation can be used to restrict the spread of fire within buildings and between closely-spaced building by utilising walls built with fire resisting materials, spacing fuel packages and buildings suitably far apart, and suitably designed and installed sprinkler systems can also assist in limiting the spread of fire.

The FWRA methodology assessed the risk (R) of firewater run-off to the environment based on the significance (S) of a fire event that could generate substantial quantities of firewater, and a potential environmental hazard (H), due to the generation of firewater run-off. The Guidelines include details on the FWRA methodology, several options for estimating retention needs, and several worked examples. The FWRA process is reflected in Fig. 10.35 below.

10.5.7 Handbooks, Textbooks, Research Reports and Related Resources

Aside from the regulations, standards and guidelines noted above, there is a vast resource of technical information available in the form of handbooks, textbooks, research reports, university thesis and similar resources. Such documents contain details for assessing and designing mitigation systems and strategies for all parts of the EIFMT. Below are just a few such resources that one might consider.

Professional associations and societies

- American Society of Air-conditioning, Heating, and Refrigeration Engineers (ASHRAE), USA
  - *Handbook of Smoke Control Engineering*

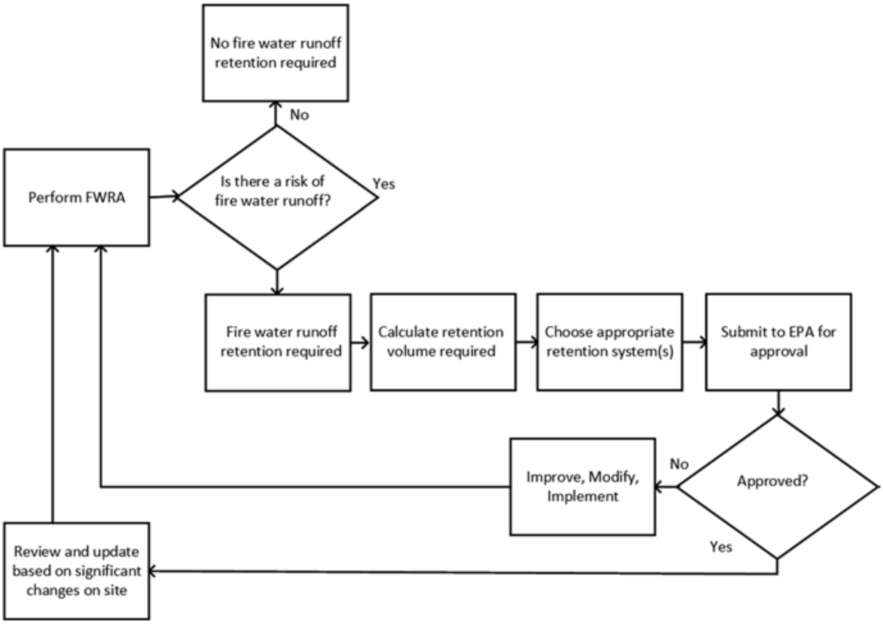

Fig. 10.35 FWRA process flowchart. (Adapted from [57])

- Confederation of Fire Protection Associations Europe, Denmark
  - *CFPA E Guideline No 18 2013 F, Fire protection on chemical manufacturing sites, CFPA Europe*, c/o DBI, Jernholmen 12, 2650 Hvidovre, Denmark
  - *CFPA E Guideline No 35: 2017 F, Fire safety in warehouses*, c/o DBI, Jernholmen 12, 2650 Hvidovre, Denmark
  - *CFPA E Guideline No 37: 2018 F, Photovoltaic systems: Recommendations on loss prevention*, c/o DBI, Jernholmen 12, 2650 Hvidovre, Denmark
- Fire Protection Association, UK
  - *Building Protection: Guide to Fire Doors (2015)*, Fire Protection Association, Moreton-in-Marsh, Gloucestershire, England
  - *Fire Risk Management in Industrial Premises (2007)*, Fire Protection Association, Moreton-in-Marsh, Gloucestershire, England
  - *Fire Safety Management in Warehouses (2014)*, Fire Protection Association, Moreton-in-Marsh, Gloucestershire, England
- National Fire Protection Association, USA
  - *Fire Protection Handbook (2022)*, National Fire Protection Association, Quincy, MA, USA.

- Society of Fire Protection Engineers, USA
  - *SFPE Handbook of Fire Protection Engineering (2016)*, Springer. New York, NY, USA

Research institutions

- BRANZ, New Zealand (https://www.branz.co.nz/pubs/)
  - Wade, C. and Frank, K. (2019). *Fire resistance requirements in single-storey industrial and warehouse buildings*, SR417
  - Wade, C., Gerlich, J.T. and Abu, A. (2014). *The relationship between fire severity and time-equivalence*, SR314
  - Frank, K., Park, HJ, Baker, G. and Wade, C. (2018). *Vertical external fire spread from flames extending out of an opening*, SR360
- BRE, UK (https://www.bregroup.com/)
  - Fraser-Mitchell, J., Abbe, O. and Williams, C. (2013). *An Environmental Impact and Cost Benefit Analysis for Fire Sprinklers in Warehouse Buildings – Final Report*. BRE Global, Watford, Herts, England.
- FM Global, USA (https://www.fmglobal.com/research-and-resources/research-and-testing/research-technical-reports)
  - Chatterjee, P. (2018). *Sprinkler Performance under Sloped and Obstructed Ceilings*
  - Ditch, B. (2016). *Development of Protection Recommendations for Li-ion Battery Bulk Storage: Sprinklered Fire Test*
  - Ditch, B. and de Vries, J. (2013). *Flammability Characterization of Lithium-ion Batteries in Bulk Storage Research Technical Report*
  - Wieczorek, C.J., Ditch, B and Bill Jr., R.G. (2010). *Environmental Impact of Automatic Fire Sprinklers Research Technical Report*
- National Fire Protection Association (NFPA), USA (https://www.nfpa.org/News-and-Research/Data-research-and-tools)
  - Jordan, S.J. and Ryder, N.L. (2020). *Protection of Storage Under Sloped Ceilings Phase III: Large Scale Testing Summary and Guidance*, Fire Protection Research Foundation
  - Nazneen, N. and Wang, Q. (2019). *Evaluation of fire and explosion hazard of nanoparticles*, Fire Protection Research Foundation
  - McNamee, M., Marlair, G., Truchot, B. and Meacham, B. (2020). *Research Roadmap: Environmental Impact of Fires in the Built Environment*, Fire Protection Research Foundation
- National Institute of Standards and Technology (NIST), USA (https://www.nist.gov/publications)
  - Sauca, A., Zhang, C., Grosshandler, W.L., Bundy, M.F. and Choe, L.Y. (2019). *Development of a Standard Fire Condition for a Large Compartment Floor Assembly,* Technical Note (NIST TN) 2070

  - Hoehler, M.S. and Smith, C.M. (2016). *Influence of Fire on the Lateral Load Capacity of Steel-sheathed Cold-Formed Steel Shear Walls - Report of Test,* NIST Interagency/Internal Report (NISTIR) 8160
  - Phan, L.T., Gross, J.L. and McAllister, T.P. (2010). *Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings,* Technical Note (NIST TN) 1681

- Research Institution of Sweden (RISE), Sweden (https://www.ri.se/en)

  - Andersson, P., Blomqvist, P., Lorén, A. and Larsson, F. (2013). *Investigation of fire emissions from Li-ion batteries,* SP Report 2013:15
  - Brandon, D. (2018). *Engineering methods for structural fire design of wood buildings– structural integrity during a full natural fire*, RISE Rapport 2018:44
  - Just, A. and Brandon, D. (2017). *Fire Stops in Buildings,* SP Report 2017:10

Textbooks

- Buchanan, A.H. and Abu, A.K. (2017). *Structural Design for Fire Safety*, Wiley, Chichester, UK.
- Drysdale, D. (1999), *Fire Dynamics*, 2nd Edition, Wiley, Chichester, UK.
- Fitzgerald, R.W. and Meacham, B.J. (2017). *Fire Performance Analysis for Buildings*, 2nd Edition, Wiley, Chichester, UK.
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10.6 Summary

Mitigating fire impacts to the environment from building fires can be accomplished by preventing fire ignition, managing the development and spread of fire and fire effluents, and managing exposure to the environment of fire effluents and products associated with fire suppression. The fundamental options have been presented in the form of the Environmental Impact of Fire Management Tree (EIFMT). For each branch of the EIFMT, representative mitigation measures have been overviewed, and reference has been made to exemplar resources for assessment and mitigation design. In addition, context has been provided with respect to the extent to which EIF issues are addressed by regulation, and when it may be necessary to seek extra-regulatory solutions. Representative examples of technical resources, in the form of standards, guidelines, research reports, handbooks and textbooks has also been provided.

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4. McNamee M, Truchot B, Marlair G, Meacham BJ (2020) Research roadmap: environmental impact of fires in the built environment. Final Report. FPRF Research Report. Fire Protection Research Foundation, online (https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/US-Fire-Problem/RFRoadmapEnvironmentalImpactFires.pdf)
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Chapter 11
Mitigation Strategies for Waste Fires

Ragni Fjellgaard Mikalsen and Karolina Storesund

11.1 Introduction

In this chapter, mitigation strategies for avoiding environmental impacts from fires in waste will be presented. Waste fires can ignite spontaneously, may be very long-lasting and difficult to extinguish, with potentially large emissions of smoke and water runoff. Large storage volumes, combined with a wide range of chemical components present, makes waste fires a potential environmental disaster. There are reports of landfill fires burning for days, months and even years [1, 2]. Two example fires are shown in Figs. 11.1 and 11.2.

The main reason for extinguishing difficulties is that even though flaming fires on the surface of the waste may be mitigated, there may still be deep-seated, perpetual smoldering fires below the surface, which may cause the fire to reappear. Mitigating waste fires could therefore have significant environmental benefits, and the mitigation strategies which will be covered in this chapter include:

- Preventive measures to prevent ignition of waste fires, and to prevent small fires from escalating
- Active measures in case of a larger waste fire to subdue the fire or obtain complete extinguishment: choice of equipment, water additives, methods and tactics during extinguishing efforts, and to handle water run-off and smoke emissions

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https://doi.org/10.1007/978-3-030-94356-1_11

Fig. 11.1 Waste fires in a landfill in Zgierz, Poland in 2018. (*Source: Photo by Zorro2212, licensed CC BY-SA 4.0*)

Fig. 11.2 Waste fires at a waste facility in Oslo, Norway in 2018. Smoke emissions and runoff of extinguishing water during these long-lasting fires are environmental challenges. (*Photos: Oslo Fire and Rescue Service (OBRE), used with permission*)

11.2 Type of Waste Storage and Types of Waste

Waste is produced and collected in our households, by businesses, in schools etc. and transported for large-scale, industrial waste handling and storage. The focus here will be on this large-scale waste handling and storage, focusing on four types of waste storage (Fig. 11.3).

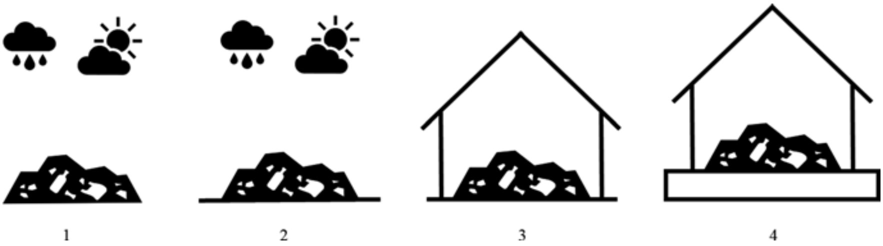

Fig. 11.3 Four forms of waste storage: Outdoor waste deposits or landfills without solid cover under the waste (1), and more controlled forms of waste storage at waste facilities, here illustrated by outdoor storage with solid cover under the waste (2), and indoor storage without (3) and with (4) collection of run-off water. (*Figure based on* [5], *used with permission*)

Historically, waste deposits in the form of large, outdoor piles of waste without access- or volume control, also known as landfills, have been the most widespread. According to the Waste Industry Safety and Health Forum (WISH), some of the largest and most long-lasting waste fires with the largest risks for the environment and for public health have occurred in outdoor waste deposits [3]. Today, landfills are still common in some regions of the world - in particular in developing countries. A well-known problem in landfills is self-heating ignition, which initially starts by natural decomposition of organic material in the pile, leading to a deep-seated smoldering fire near the insulated centre of the pile, which in turn accelerate the self-heating processes, and the smoldering fire can eventually migrate to the surface and transition to a flaming fire [4]. Mitigating environmental emissions from waste fires in uncontrolled landfills is a near-impossible task, since the pile size makes self-heating ignition inevitable, and the enormous quantities of waste makes extinguishing efforts near-impossible. From a fire safety and environmental perspective, the best mitigation strategy for fires in landfills, is to avoid making landfills containing any form of organic material. Unfortunately, in many regions where landfills are common, fire safety and environmental concerns related to the landfills are not sufficiently addressed.

While landfills dominate some regions of the world, in other regions, waste handling and storage are now industrialized processes at waste facilities. The transition is motivated by the economic benefits of utilizing waste for material and energy recycling, as well as environmental benefits for nearby communities, facilities and nature resources. At waste facilities, the handling and storage may occur indoor or outdoor. The waste can be placed on a tilted, solid cover (such as asphalt) to control runoff from rainwater or extinguishing water. In indoor facilities, waste is shielded from weather, and a more complete collection of all runoff is possible. The use of indoor storage is motivated by consideration for the environment and neighbours, but it can be in conflict with fire safety, due to more restricted access for fire fighters during extinguishing efforts, and a higher heat stress to load-bearing structures of the building housing the waste. Mitigation strategies for such facilities are discussed at the end of this chapter.

In waste facilities, waste is separated into different waste fractions, which are handled separately. Examples of waste fractions are organic waste, paper and cardboard, metal, plastics, hazardous waste, residual waste etc. There are several classification systems for waste, such as the European List of Waste or European Waste Catalogue code [6], and miscellaneous national standards. The different classification systems for different areas makes it difficult to obtain a unified, global overview of which specific waste fractions contribute to the largest environmental impacts. A recent evaluation of fire risk at Scandinavian waste facilities suggests that the waste types with the highest ignition frequency, combined with large storage volumes, give the largest potential environmental impacts [5, 7]. High-risk waste types were found to be general, residual waste, batteries (especially batteries not correctly sorted), electrical and electronic (EE) waste, as well as paper, paperboard and cardboard.

11.3 Emissions from Waste Fires: Case Examples and Studies

Any major waste fire, regardless of the type of waste burned, could potentially lead to the release of pollutants into the air, water or soil. The smoke composition and smoke spread from a waste fire depends on the type of fuel burning, if the fire is a flaming or smoldering fire, the oxygen supply, the local weather conditions, terrain and more, as is the case for smoke emissions from other types of fires, as discussed in Chap. 4. Depending on whether it is a surface or subsurface fire, the smoke production rate will vary, but smoke emissions will continue until the fire is completely extinguished. In the case of extinguishing efforts, the environmental impact of water runoff from the fire depends on the amount of extinguishing water used, the type and amount of additives used, and whether or not the runoff water is collected. If extinguishing foams are used, this can reduce the consumption of extinguishing water, but the foam itself can contribute to contamination if discharged into water. Once emitted to the water reservoirs, the contaminants may have acute or long-term consequences for maritime life, as discussed in Chap 8.

To assess the environmental impact from waste fires, it is central to know which materials have burned. For the majority of waste fires, it is difficult to assess precisely which materials have burned, for two reasons. Firstly, waste fractions often contain unintended small quantities from other waste fractions, for example batteries or hazardous waste in the general waste, plastics with some food residues, electronic waste mixed with the paper waste etc. Secondly, due to the large scale and complexity of waste sorting systems at waste facilities, the fires and firefighting efforts are often equally complex, which makes it difficult to know which materials have been involved in a fire. Some example fires at waste facilities are presented below to give insight into the complexity and scale of such fires.

During a fire in 1.3 million shredded tires at a landfill in Iowa, USA in 2012, Downard et al. [1] measured and characterized the smoke emissions 4.2 km downwind from the fire. They reported elevated concentrations of CO, CO_2, SO_2, polycyclic aromatic hydrocarbons (PAH), fine particulates (PM2.5), elemental carbon, as well as an increase in number of particles. They did not detect elevated concentrations of metals used in tire manufacturing (such as zinc, iron and lead) in the plume. The firefighting efforts to smother the fire with dirt lasted for 8 days. The study point out that the use of tires as landfill liners should be subjected to a cost-benefit risk assessment, which also should keep the potential environmental consequences in mind.

In May–September 2014, a smoldering fire occurred in a 5500 m^2 landfill in Iqaluit, Canada [8]. Since waste separation was not practiced at the time in the area, the materials burning were a wide range of wastes, including plastic, rubber, wood, paper, and metal waste. Air pollution was monitored at four locations situated 1.2–3.8 km from the landfill. The study showed that during active burning, the measured median daily dioxin/furan concentrations were 66 times higher than after the fire was extinguished, while for the other monitored pollutants (PM2.5, O_3, NO_2, polycyclic aromatic hydrocarbons, and volatile organic compounds), the concentrations changes were less dramatic. The landfill was up to 12 m deep, and the firefighting efforts in September 2014 spanned a two week period, followed by one month of post-fire monitoring.

In the Re municipality in Norway, 2014, a fire at a waste facility was believed to start by self-ignition in a pile containing 1,230,000 kg of environmentally treated electrical and electronics waste. During a 36 h extinguishing effort, the fire service used both water and foam, and much of the extinguishing water was discharged via the sewer system of the facility and into a small stream nearby. 1560 kg dead fish was removed from the stream, caused by a combination of oxygen depletion in the stream from the foam discharge, and metal contaminants (in particular copper and cadmium) above acute toxic levels for aquatic animals. Nearby farmers had parts of their crop destroyed by contaminated water [5, 9].

In Sweden, 2016, a small fire in a free-standing container at a waste facility spread to one third of a 2700 m^2 large pile of plastics from construction work and households. The fire developed rapidly, and due to the large total site of the storage area of 11,300 m^2, the tactics of the firefighters was to limit the spread (similar to that used in wildfires). The operation lasted for four days, involved 2000 persons, and the 6,000,000 kg waste was covered by 7,000,000 kg sand and 1,000,000 kg gypsum to obtain extinguishment [5, 10].

Data from analysis of extinguishing water from six fires in three waste facilities in Sweden are presented by [10]. The materials burning in the fires were reported to be a wide range of wastes, including plastics and residual waste from households and from industry. The study showed the following; Relatively neutral pH levels in the water, most likely due to diluted extinguishing water; High nitrogen concentrations; High metal concentrations; High conductivity, most likely due to high chloride content; High concentrations of organic components (aliphatic hydrocarbos, fenols, toluene, polycyclic aromatic hydrocarbons (PAH); Elevated concentrations of chloric dioxines; Elevated concentrations of brominated diphenyl ethers (2,2′, 4,4′ -Tetra BDE and 2,2′, 4,4, 5 -Penta BDE), linked to the use of flame retardants in furniture and mattresses which was found in the material burning (such use of Penta-BDE is now prohibited by the EU); PFAS content was also found, which is used in some types of extinguishing foams, the result showed high concentration of fluorotelomer sulfonate (6:2 TFS, which is used as a replacement for PFOS and PFOA), and significant content of PFOS and PFOA. Lönnermark et al. point out that there was a large variation of the extent of the analysis carried out after these fires, and that there is a need for clear guidelines for waste fire water analysis and criteria to evaluate the water quality.

Emissions and environmental consequences in connection with firefighting in general, including firefighting of waste fires, are areas in which there is a need for more knowledge and expertise. For waste fires specifically, there is a need for increased focus on environmental surveillance during and post-fire (and publication of findings thereof), and a need for laboratory studies of pollutant composition of smoke and water emissions.

11.4 Fire Mitigation Strategies at Waste Facilities

Fires in waste can start for a number of reasons, in essence initiated by either the waste handling process itself (self-heating ignition, heat of friction from machines, introduced ignition sources such as batteries, etc.) or human activities (arson, smoking, hot works, etc.). By training staff and raising their awareness of fire risk as well as by securing the facility by for example preventing unauthorized access to the site, the facility can be protected and fires caused directly by human activities can be minimized. However, as self-heating ignition is a considerable cause of waste fires, and that these have the potential to grow very large, measures handling this particular risk are required [5].

Measures that are particularly important to put in place in order to limit the risk of large size fires and of fires spreading include routines for limiting the quantities of stored waste as well as for separating the different types of waste, routines for monitoring the condition of the stored waste, order and tidiness, and access to sufficient equipment for initial extinguishing efforts.

Fire detection by use of technical equipment as well as manual observation are key preventive measures for fires in waste facilities. Fire incident statistics indicate that fires are detected to a greater extent by observations made by employees at the plant than by automatic detection [5]. If visual observation is the only detection, for example, a fire that starts by self-ignition inside a waste pile, it will not be detected until well into the course of the fire. On a general basis, a detection system for waste facilities should be adapted to the local conditions and what is to be detected. There are different types of detection technologies ranging from smoke detection (point detection and aspiration measurements) to different forms of heat detection, thermal imaging and flame detection, as well as ordinary camera surveillance. Different types will be optimal for uncovering different types of fire. The system must also be well documented with regard to its suitability for the intended use. For waste facilities, this means that the type of waste, the quantity and storage conditions, possible sources of ignition and environmental conditions such as dust and dirt should be taken into account when choosing detection solutions.

Equipment at the facility to deal with contaminated extinguishing water should be ensured and it should also be ensured that the extinguishing water capacity is sufficient. The incident in Re in Norway, mentioned above, was estimated to have required 12 m^3 of foam fluid mixed to 3%, as well as 1800 m^3 of water [5]. Hence, a waste fire can require large amounts of water and water access is key for the outcome of the fire.

Due to the dependence on observations and early detection, the first efforts on site performed by waste facility personnel or the industrial protection play an important role while responding to any fire incidents. Therefore, it is important to ensure the competence and awareness of both employees and management at waste facilities, as well as of the fire department with regard to fire prevention and risk management. Exercises together with the fire service and the facilities can be an important tool for learning, exchange of experience and identification of improvement potential.

There are several different extinguishing systems and technologies, e.g. fixed, automatic sprinkler or gas systems, manually operated hand extinguishers and extinguishers that can be controlled manually or automatically. These can be adapted to different types of fires; e.g. special hand extinguishers for fire in lithium batteries, various extinguishing foams for fire in solids and liquids, etc. It is important to have properly sized fire extinguishment equipment available, but there have been several examples demonstrating that it can be challenging to find sufficient and relevant documentation of the functionality of different solutions.

One way to deal with a waste fire from the fire service's point of view is to isolate the fire by moving combustible material and letting it burn out under surveillance. By this method, the consumption of extinguishing water will be reduced, which will be positive with regard to runoff and pollution of water bodies. At the same time, this will increase emissions to air and consequently exposure of toxic fire smoke to everyone in relatively close proximity to the fire. This strategy can also cause a prolonged production shutdown.

Extinguishing water that does not evaporate during the extinguishment of the fire will remain in the proximities of where the fire occurred or drain into surrounding areas. The degree of contamination in the residual extinguishing water will vary [11] and the composition of pollutants in the extinguishing water during and after a fire will be dependent on the amounts of water used during the extinguishing operation. Extinguishing water used to cool down nearby structures threatened by the fire will only contain substances that are already present on the site or that have been washed out of the structures. Contaminants can also originate from additives to the extinguishing water, such as foaming agents. Water used for extinguishing the fire itself or for cleaning the site will to a large extent be characterized by residual products from the fire [12].

The main route for leakage of pollutants from the waste facility to the environment is via the plant's surface water drainage system. This would occur either directly or via street inlets, via drainage systems and sewers, or directly to water bodies and soil and consequently posing a hazard of polluting the groundwater [13].

In the event of a major extinguishing operation in a waste facility, there is a need to collect contaminated extinguishing water so that it will not flow uncontrollably into water bodies. A system for collecting water should preferably be automatic so that minimum manual control is required. The system should be designed so as not to limit the fire department's extinguishing work and should not contribute to increased spread of the fire.

Extinguishing water collecting systems may be stationary or mobile. In a situation where the established collecting systems are undersized, reserve systems can be used to ensure minimal environmental impact. Examples of established and reserve collecting systems for polluted fire water are given in Guidelines [5, 11, 14].

Stationary collecting systems can be established in the form of:

- Permanent surface with controlled runoff
- Collection pools
- Storage tanks
- Shut-off valves for pipelines
- Oil separators
- Pumping trucks
- Relieves
- Closed overwater system, possibly connected to public facilities

Reserve collecting systems for emergency situations can include:

- Areas that can be sacrificed for allowing surface water to penetrate into the ground.
- Building barriers with, for example, sandbags.
- Pits and ditches
- Portable tanks, cylinders and tank trucks
- Absorbents

If the collected extinguishing water is sufficiently free of debris and particles, reuse of the extinguishing water may be considered. This will reduce the total volume of extinguishing water needed and can be a means of simplifying the handling of the extinguishing water.

It will always be beneficial to gather pollutants in a limited area at A fire site. If it is not practical to collect extinguishing water, the distribution should be limited or the water can be directed to strategic areas, for example by sealing street inlets. Inlets can for example be covered with rubber cloths or lids. Distribution of contaminated water can also be prevented by using suitable absorbents.

The composition of the components in the extinguishing water that has been collected is often complex and the degree of contamination may vary based on the fuel and extinguishing techniques used. There are a number of different methods for purifying extinguishing water which must be combined to deal with the various contaminants that the water may contain (debris, particles, metals, organic matter, foam liquid, etc.). Composition and concentrations of pollutants in the extinguishing water, the required degree of purification, cost and available resources and the level of acuteness of the situation will all determine the methods to use for purification.

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Chapter 12
Mitigation Strategies for Wildfires

Kate Parkins, Jane Cawson, Bianca Pickering, and Trent Penman

12.1 Introduction

Fire management agencies around the world invest significant resources to reduce the likelihood and impact of future fires and increase the success of fire suppression [1, 2]. Strategies are largely focused on fuel management – the purposeful manipulation of fuel structure, composition and load to alter future fire behaviour [3–5]. Fuel management is the primary means for land and fire managers to reduce the occurrence, size and severity of future fires [6–9]. There are multiple fuel management strategies used, with varying levels of effectiveness. Common strategies include fire-based fuel treatments (e.g. prescribed fire), mechanical fuel treatments (fuel modification by machinery), biological treatments (e.g. grazing and herbivory) and landscaping [10, 11]. The choice of treatment type varies depending on environmental and social context [11]. All fuel management approaches have advantages and drawbacks and involve a diverse and complex set of challenges that need to be considered when evaluating the most appropriate method to apply. Fire and land management agencies must quantify the extent to which their fuel management actions reduce wildfire risk across multiple values in the most cost-effective manner [12, 13].

In this chapter, we discuss mitigation strategies for wildfire in the context of fuel management, with a primary focus on reducing the impacts to people and property. We provide a review of the efficacy of fuel management strategies for Australian ecosystems, drawing on international examples where appropriate. We consider a range of different fuel management strategies, including prescribed fire, mechanical treatments, grazing and landscaping. First, we describe each fuel management

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strategy and outline their objectives, temporal longevity and the scale at which the strategy is commonly applied. We then provide an overview of the known evidence-base for the efficacy of each strategy in terms of their influence on three key elements of wildfire risk:

I. The likelihood of ignition
II. Spread to the Wildland-Urban Interface, and
III. Impacts at the Wildland-Urban Interface.

Finally, we discuss fire risk mitigation strategies under a changing climate.

12.2 Fuel Management for Wildfire Mitigation

12.2.1 Fuel Traits and Flammability

The components of vegetation (fuels) that have the potential to burn include surface litter (e.g. leaves and twigs), living and dead plants, bark and tree canopies [14]. The ability of these fuels to burn is broadly described in terms of flammability [15, 16]. The concept of flammability has four metrics: ignitability (ability for fuel to ignite), combustibility (how rapidly the fuel burns), sustainability (duration of combustion) and consumability (the proportion of fuel consumed) [17, 18]. The scale at which this flammability definition is applied is an important consideration. For instance, flammability measurements can be conducted on individual parts of plants (leaves and branchlets), the whole plant, or multiple plants within a vegetation community. As the concept of flammability is scaled up to a landscape level, so does the complexity of fuel dynamics and our understanding of flammability. The primary objective of fuel treatments is to reduce flammability at the plant, community and landscape scale. Therefore, knowledge of the effect of fuel properties on metrics of flammability is important for understanding the rationale for fuel treatment strategies.

At the leaf scale, variation in fuel flammability is driven by structural and chemical traits. Those shown to negatively influence flammability (ignitability and combustibility) include fuel moisture content, ash content and leaf thickness [19]. Traits shown to positively influence flammability include volatile oil content, specific leaf area, leaf surface area and surface area to volume ratio [19]. When moving beyond the leaf scale, the vertical and horizontal arrangement of fuels become increasingly important [16, 20]. Research into litter beds has shown packing ratio, bulk density and litter depth to be important structural characteristics impacting flammability and that individual leaf traits impact these assemblages [21]. For instance, large curly leaves create a more aerated litter bed (low packing ratio) that is associated with greater combustibility and consumability compared to densely packed litter beds [22, 23].

At larger spatial scales (i.e., community and landscape), important fuel-complex attributes include plant architecture, the presence and quantity of dead materials, the connectivity of fuels from the ground to the canopy, species composition and overall fuel biomass. Outdoor experiments and fire modelling allow for these attributes to be tested and are often measured in terms of fire behaviour characteristics such as rates of fire spread (ignitability), fire intensity (combustibility) and burnout time (sustainability) [15, 16, 24]. For instance, rate of spread and fire intensity will increase as fuels become more spatially connected and as the quantity of dead material increases [20, 25].

A holistic understanding of how the characteristics and arrangement of fuels impact flammability can allow for targeted fuel management practices. For instance, the most common forms of fuel management rely on the modification, reduction or removal of vegetation [26, 27]. The aim is to reduce the biomass and/or the connectivity of fuels within and between the different fuel strata, thereby moderating the intensity and rate of spread of wildfires [28]. Other management options include the ranking of species by their comparative flammability [29] to guide landscaping at strategic locations (e.g. around buildings) or the purposeful alteration of fire regimes. Alternatively, management that excludes disturbances, such as low-intensity fire and grazing, may increase stand flammability through changes to plant composition and structure. For example, in California, USA, long term fire exclusion policies led to the composition and structural conversion of some fuel-limited forest ecosystems [30]. The loss of traditional frequent low-severity fire events (i.e. low consumability) has led to an increase in the density of fire-sensitive and shade-tolerant species which has increased the severity of fires when they occur (i.e. high consumability) [31]. The reintroduction of historic patterns of fire into these ecosystems aims to convert these vegetation communities to their original “low flammability” state [32, 30].

Fuel management strategies can be used as standalone treatments, or as part of a suite of different strategies. However, it is important to note that fire behaviour is complex and at the landscape level is highly dependent on weather and topography [33–35]. While fuel management may help reduce risk in the landscape, it will not prevent large scale wildfires from occurring [5, 36].

12.2.2 Prescribed Burning

Prescribed burning is the overarching term used to describe different types of fire-based treatments, including hazard reduction burning (also called controlled or planned burning), ecological burning (burning to achieve an ecological objective), and cultural burning (burning practices developed by indigenous people, to enhance the well-being of the land and its people). In this chapter, we will use the term ‘prescribed burning’ to refer to the planned use of fire with the primary aim of fuel reduction for wildfire mitigation.

Prescribed burning is a pre-emptive fire management strategy, defined as the deliberate and controlled application of fire into a landscape under mild weather conditions to reduce fuel biomass and connectivity [3, 9, 37]. The primary goal of prescribed burning is to reduce the intensity and rate of spread of future unplanned fires, and to increase the likelihood of successful suppression [3, 38, 39]. Prescribed burning typically occurs outside of the wildfire season under conditions that facilitate burning at low intensities with slow rates of spread [40–42]. Prescribed burning may differ slightly in the way it is implemented in different fire-prone regions, though the objectives which drive its use are largely universal. These objectives are: to reduce future fire impacts on people, property and assets; increase containment likelihood; and reduce ignition likelihood.

The use of prescribed fire as a wildfire mitigation strategy continues to provoke considerable public and scientific debate. The primary concerns are related to environmental or ecological impacts, risk of escape, smoke hazard and reduced air quality, decreased aesthetics, financial responsibility and the longevity of treatments [3, 9, 28, 43, 44]. One school of thought is that considerably more prescribed burning is required to reduce the economic and ecological impact of major wildfires [45–49]. An opposing view is that fire should be avoided at all costs, with burnt landscapes perceived as ecologically destroyed [50–52], and with increased health and wellbeing costs resulting from reduced air quality from smoke [53–55].

One of the desirable features of prescribed burning is its ability to be applied at fine spatial scales as well as more broadly across the landscape. Prescribed burning is commonly implemented at the wildland-urban interface, WUI (interface burns), or more broadly across the landscape (landscape burns). Interface burns are applied in proximity to residential areas and important assets to reduce the impacts of future unplanned fires to areas with high densities of people and/or assets. In contrast, landscape burns are undertaken in strategic areas that are commonly away from residential areas in contiguous forest, to reduce the rate of spread and intensity of a future wildfire. Both approaches are designed to increase the likelihood of safe and effective suppression and consequent protection of human life and property.

Prescribed burning can reduce future fire severity, though the effect is generally short-lived (less than 5 years) and dependent on fire weather conditions and site productivity. The assumption that the risk of high severity fires continually increases with time since previous fire is an oversimplification. Fire weather is the dominant driver of fire severity, with time since fire and topography being of secondary importance [35, 56]. Recently burnt areas (less than five years since fire) are more likely to have lower severity fire than long unburnt areas [33, 35, 57, 58], however these affects are reduced or disappear as fire weather increases [58, 59]. As the climate changes, the window for safely undertaking fire-based fuel treatments is changing [60, 61].

12.2.3 Mechanical Treatments

Mechanical fuel treatments involve the use of machinery to alter vegetation structure for the purpose of reducing fuel hazard. Mechanical treatments include mastication (or mulching), slashing (or mowing), and thinning. Mechanical treatments such as ploughing and chain rolling are also used, but their application is less common due to their environmental impact. Mechanical approaches can be applied independently or as a precursor to other treatments such as prescribed burning. Mechanical fuel treatments can be applied in patches across the landscape or in strategic locations as part of a fuel break network (commonly at the WUI). The WUI is the zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels [62]. Mechanical fuel treatments offer some advantages over fire treatments. They are not subject to a narrow range of weather conditions; can be designed to target individual plants; do not produce smoke; and can be applied to fuel types that are difficult to safely burn in a controlled manner. Furthermore, some studies show that mechanical treatments are preferred over prescribed burning by community groups, especially closer to towns [63]. One of their disadvantages is that they can be more costly to implement than prescribed burns. For example, in a U.S. study thinning was seven times more expensive than prescribed burning on average, but some of those costs could be recovered by selling the harvested timber [64].

Mastication

Mastication (also termed mulching) involves the modification of fuel structure through mulching, chipping, shredding or mowing of shrubs and intermediate trees, which can act as a ladder fuel and facilitate fire spread between the surface and tree canopy [4]. The masticated vegetation is generally retained as surface fuel, with the fuel load being relocated within the fuel profile rather than reduced (Fig. 12.1). Masticated fuel beds are distinct from natural fuel beds as they contain a compact mix of small and large woody particles [65]. Mastication can be done in isolation, after forest thinning or before prescribed burning. Mastication is often used within fuel breaks or in WUI areas where prescribed burning cannot be conducted safely.

The main objective of mastication is to reduce the intensity and rate of fire spread by relocating elevated and ladder fuel to the forest floor. In doing so, this better enables fire suppression, ultimately reducing the wildfire risk to people and property. Mastication may also be used for biodiversity conservation. For example, in shrub-encroached eucalypt woodlands and forests where the shrubs have become very dense [66], an objective of mastication is to return the vegetation structure to a more ‘natural’ condition for biodiversity conservation. In forests, mastication can be used to reduce the likelihood of crown fire, thus improving the resilience of the forest to fire.

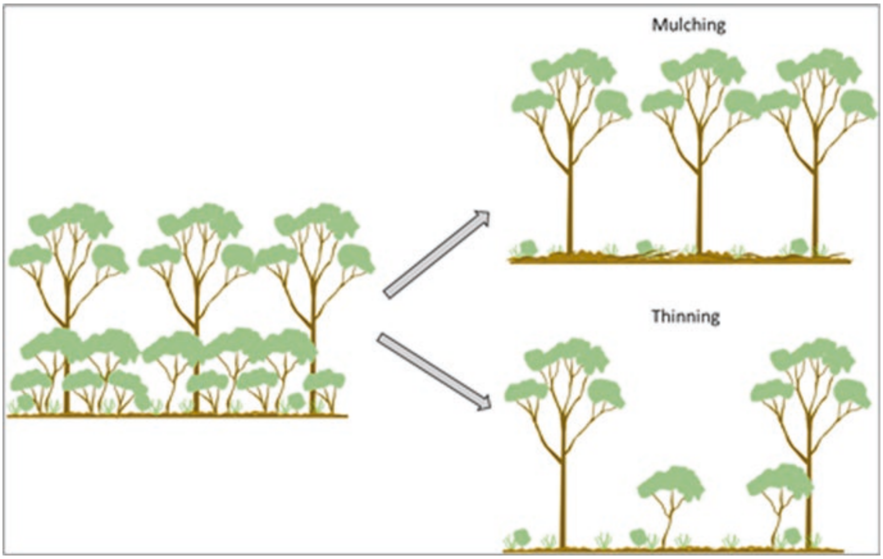

Fig. 12.1 Mechanical fuel treatments typically remove only surface fuel (preserving larger, older trees), and any treated material is generally not removed from site, therefore changing fuel structure but not fuel load. In comparison, thinning involves the complete removal of some stems from a site, thereby changing fuel structure and load

Forest Thinning

Forest thinning is a silvicultural practice that involves removing a subset of trees or branches to enhance the health and growth rate of the remaining trees [67, 68]. Pruning involves removing lower branches of a tree to enhance wood quality [69]. The main objective of forest thinning and pruning in the context of fuel modification, is to alter forest structure to favour low intensity surface fires over high intensity crown fires [6]. Ladder fuel (i.e. fuel that can carry the fire into the tree crown) is removed to increase the height to live crown by pruning branches and cutting small and intermediate trees. This prevents the initiation of a *passive* crown fire (torching). Crown bulk density is reduced by removing small and intermediate trees. This reduces the spread of fire between tree canopies (*active* crown fire). Ultimately, thinning improves the resistance of the trees to fire by reducing the likelihood of crown fire, and helps protect people and property by reducing fire intensity. Thinning may also be used as a precursor to safely returning low-intensity prescribed burning into forests subjected to long periods of fire exclusion or disturbance (e.g. logging) which have caused a build-up of elevated fuel hazard [e.g. in *Pinus ponderosa* forests; 70, 71].

Fuel Removal/Fuel Breaks

Fuel breaks are created using a combination of mechanical fuel treatments – thinning to reduce canopy density and mastication to remove shrub and ladder fuels. The treated fuel may be removed from site or burnt in heaps. An ongoing program of slashing and herbicide spraying is needed to maintain the break. In some situations, the overstorey is retained or thinned. In other areas there may be complete removal of vegetation for all strata. Fuel breaks are implemented at multiple spatial scales, with fuel reduction in strategic breaks occurring broadly in landscapes with contiguous vegetation (i.e. horizontal and/or vertical gaps in fuel for increased access/egress and for suppression advantage), at the WUI (i.e. horizontal gaps between vegetation and properties), and also at the individual homeowner scale (i.e. for defensible space around an asset).

The objective of a fuel break is to give suppression forces a higher probability of successfully attacking a fire [72]. A fuel break can change the behaviour of a fire entering the fuel-altered zone, or it can be a safe point from which firefighters can conduct indirect fire suppression activities (like back burning) during a wildfire. The effectiveness of a fuel break depends on many factors including its design, the behaviour of the fire entering the break and the presence and level of fire suppression resources [73, 74]. Ongoing maintenance of fuel breaks is necessary for continued effectiveness [74].

Grazing

Biological fuel treatments primarily involve the use of large grazing animals to alter vegetation structure for the purpose of reducing wildfire fuel hazard. Biological fuel treatments like grazing are often used in ecosystems where herbaceous vegetation is the primary fuel type driving fire occurrence, such as native grasslands, woodlands and agricultural settings. The main objective for grazing as a means of fuel reduction is that grazing by large animals will reduce plant biomass and therefore fuel hazard. A reduction in biomass through grazing may also reduce fire intensity [75], thus aiding suppression and reducing wildfire risk. Grasslands that are heavily grazed (i.e. eaten out) will substantially slow the rate at which fires spread and increase the likelihood that a fire self-extinguishes [75]. Grazing can be used to reduce fuel loads at fine-scales (e.g. roadside verges), or at broad scales (e.g. landscape-scale grazing). Grazing is often used as a precursor to or instead of prescribed burning. Similar to mechanical treatments, grazing for fuel reduction is not subject to a narrow range of weather conditions like prescribed burning, and can occur regardless of season (although it is more common in spring, summer and autumn months).

Grazing is a complex and dynamic tool when used for fuel reduction. It commonly involves many different plant and animal species, with varying levels of effectiveness. In order to meet the objective of reducing fuel load and altering structure, several important variables need to be carefully considered. These include: the species of herbivore used (e.g. cattle, sheep, goats, donkeys, elephants or a combination); the animals previous grazing experience which may affect their preference for certain plants; the time of year and plant physiology, as animal consumption is driven by seasonal nutrient content; stocking density or animal concentrations; and grazing durations [76–78]. The degree to which grazing can alter fuel structure and load will also be driven by the rate of food intake and plant regeneration rates [79]. Cattle, for example, are more effective at consuming grasses compared to sheep who consume more leafy vegetation and forbs [76].

Targeted grazing in cheatgrass (*Bromus tectorum*) dominated rangelands was found to reduce flame length and fire spread following cattle grazing [80]. However, in some environments grazing may not always be beneficial as a fuel management treatment. In the Australian Alpine region, in locations where the bulk of the vegetation was unpalatable, grazers were found to have little impact on fuel loads and the fire risk was therefore higher [79], with livestock avoiding tussocks and promoting the growth of flammable grasses. Furthermore, grazing by herbivores rarely results in any change to bark or elevated fuels, which contribute significantly to overall fuel hazard levels in many fire prone ecosystems. Because herbivores selectively graze palatable vegetation (live biomass) and vegetation that they can reach (surface, near surface and some elevated fuels), there may be large amounts of flammable dead, bark and canopy fuels remaining after grazing [76]. Despite the increased interest in grazing as a fuel management approach, there remains a limited evidence-base for its use in many parts of the world. This approach remains controversial and part of an ongoing scientific, social, ecological and political debate regarding the benefits and/or deleterious ecological effects associated with its ongoing use in some locations [81].

Landscaping

House loss during a wildfire can occur as a result of ember attack, radiant heat or direct flame contact [82]. Landscaping surrounding a house can substantially reduce the likelihood of house loss during a fire [83]. Many local fire authorities, government and other organizations have developed guidelines around property layout and choice of plant species to increase the likelihood of house survival during wildfire (e.g. [84, 85]). These guidelines typically focus on three considerations that are related to fuels when designing and landscaping a property: creating defensible space; incorporating fuel breaks, and; choosing fire retardant or fire-resistant plants.

Defensible space refers to an area immediately adjacent to structures where vegetation is modified and/or intensively managed in order to reduce the impact of radiant heat and the likelihood of direct flame contact [83]. The size of defensible space will vary depending on a range of factors (e.g. building type, wildfire risk), though typically it will be in the order of tens of meters (e.g. 10–30 m) [86]. Within the defensible space zone, vegetation and landscape features are arranged and managed to impede fire spread, reduce fire intensity and decrease ember attack [87]. Incorporation of fuel breaks into the defensible space zone is recommended to reduce fire spread. Effective fuel breaks can include non-flammable landscape features (e.g. ponds and streams, paths, rock retaining walls), arrangement of plants to minimise the vertical and horizontal connectivity of crowns and ensuring that shrubs and trees are planted away from buildings.

Selecting appropriate plant species is also important when designing defensible space [88]. Although all plants can burn under the right conditions, some species possess traits that make them more resistant to combustion [16, 20]. As described above, a range of traits will influence plant flammability, including the properties of foliage (e.g. leaf size and thickness, volatile compounds, moisture content), crown architecture (e.g. arrangement of branches and foliage) and retention of dead material [16]. Examples of desirable traits for reducing flammability include thick leaves with high moisture content and low volatile compound concentration, low canopy bulk density and low retention of dead material [16]. Grasses and short statured shrubs are desirable close to structures, whereas trees are should be located way from buildings (e.g. 1.5× their mature height). However, trees may be beneficial in terms of reducing wind speed and filtering embers, provided they are carefully selected and maintained.

12.3 Fuel Management at Different Spatial Scales

Fuel management is commonly broken down into three distinct but overlapping spatial scales. These are: landscape treatments (i.e. broadscale fuel treatments); interface treatments (i.e. finer scale fuel treatments, predominantly undertaken at the WUI); or home-owner/community scale actions (i.e. localised defendable space around individual properties, see Fig. 12.2). Decisions around fuel treatment options and the scale at which they are applied is complex. Careful consideration of the costs of implementation, impacts on values (positive or negative), and the risk reduction of each approach is important. There is no doubt that fuel management at any scale will result in altered fuel and modified fire behaviour, however this does not necessarily result in a meaningful reduction in fire risk. Currently, there is little consensus over where, when, how, how frequently and at what scale fuel management should be undertaken to effectively reduce the risk of future fires, and as such, the application of fuel treatment options is frequently argued by scientists, managers, the media and the general public. A better understanding of the principles and known evidence-base for fuel and related land management at different scales will be critical for assessing the effectiveness of different approaches and informing future risk mitigation actions.

The goal of landscape fuel treatment is primarily to reduce the occurrence and extent of future wildfires, by slowing or impeding fire spread or moderating fire behaviour to gain a suppression advantage in a strategic location [5, 74]. Landscape-scale fuel management relies on fuel treatments which can be logistically and economically implemented over large spatial scales. One of the most commonly used treatment types for broad-scale fuel management is prescribed burning, however

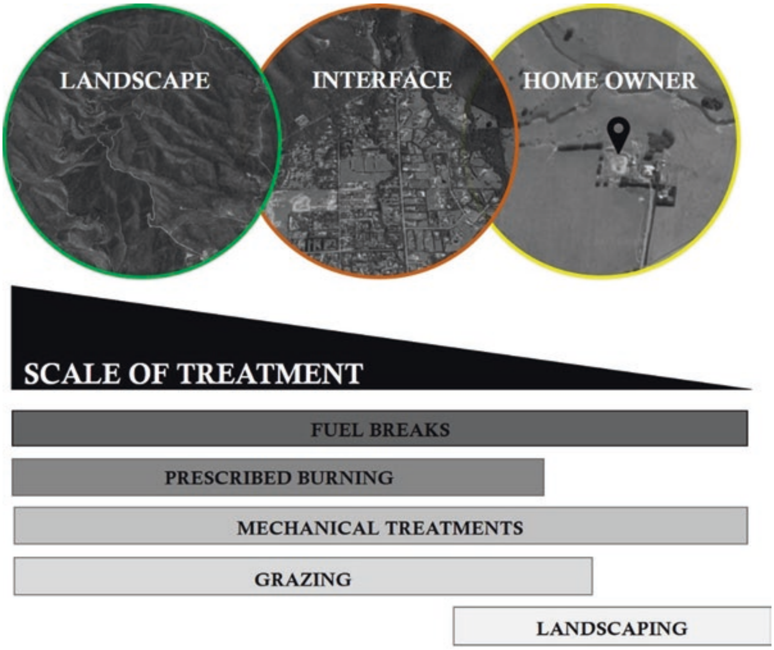

Fig. 12.2 Fuel treatments are commonly applied across three distinct but overlapping spatial scales: the landscape scale; the interface between urban areas and wildland; and the individual home-owner scale

grazing and cropping for fuel management in agricultural settings are also used at the landscape scale (Fig. 12.2). In some environments, the use of strategic fuel breaks across very large areas [e.g. southern California; 89] may also be effective. Mechanical treatments are also used at the landscape scale, however this technique may be more difficult to implement at broad scales due to challenges associated with access (i.e. getting large machinery into remote areas of continuous forest), treatment time and cost. Mechanical treatments may be significantly more expensive than prescribed burning treatments [64].

Prescribed burning and grazing are the more commonly implemented fuel treatments for large spatial scales (Table 12.1), driven primarily by the relatively lower costs associated with their use (compared to mechanical treatments, for example). Prescribed burning can be undertaken over very large scales especially in contiguous forest with little or no human assets (i.e. houses, people, infrastructure). It can also be undertaken fairly quickly, with many thousands of hectares able to be treated over several days, compared to mechanical or grazing treatments which may take several months to cover similar spatial scales. However, broadscale application of prescribed burning is restricted by favourable weather conditions, with burning only able to go ahead when conditions are suitable during and after the burn. Prescribed burning is also inherently patchy, and while very large areas may be considered ‘treated’, some of these areas will remain unburnt [42, 90].

Table 12.1 Fuel treatment scenarios differ in their objectives and effect on fire behavior. They are also implemented at differing spatial scales and their effect on reducing or modifying fuels (i.e. longevity of treatment) will also differ

Fuel treatment	Objective	Effect on fire behaviour	Scale	Treatment longevity
Prescribed burning	Reduce fine fuel biomass and connectivity in shrublands, woodlands and forests	Reduced rates of spread and fire intensity; reduced likelihood of ignitions becoming spreading wildfires	<1–>10,000 ha	Short-lived (e.g. Australia, Mediterranean Europe; <5 years)
Mechanical	Reduce fuel biomass and connectivity in shrublands, woodlands and forests	Reduced rates of spread and fire intensity; reduced likelihood of ignitions becoming spreading wildfires	Mastication <1–100 ha Thinning <1 ha–>1000	Variable (e.g. USA, Australia; 2–>10 years)
Grazing	Reduce surface and near surface biomass in grasslands and woodlands	Reduced rates of spread and fire intensity; reduced likelihood of ignitions becoming spreading wildfires	<1–>10,000 ha	On-going if grazing is maintained. Short-lived following the removal of livestock (e.g. 1–2 years);
Landscaping	Creation of defensible space and/or a reduction in flammable materials.	Reduce the risk of structures igniting during a wildfire and providing a safe space for fire crews or residents to attempt to protect the property.	<1–100 ha	Ongoing if defensible space is maintained and flammable materials are managed effectively.

Fuel break construction is undertaken across all three spatial scales (Fig. 12.2). At the WUI or home-owner scale fuel breaks are implemented in an attempt to prevent fire from spreading into urbanised areas, however this often comes with unrealistic expectations that these locations are ‘fire-proofed’. The primary role of fuel breaks at the home-owner or WUI level is to provide access and a safe zone for suppression crews. Strategies involving fuel removal in the form of fuel breaks are generally ineffective in controlling or stopping fires in the absence of suppression [74]. However, under extreme fire weather conditions fuel breaks will have little impact on suppressibility and in many cases conditions will be too dangerous for fire crews to utilise these zones. The creation and maintenance of fuel breaks can also be more costly than other treatments and can result in substantial ecological impacts, including erosion, fragmentation of key habitat and exotic species expansion [74]. These zones also require long-term maintenance to ensure fuel loads remain low.

The WUI presents a special challenge to fuel treatment programs because it often contains a variety of ownerships (both public and private) and multiple objectives.

Management of fuels within the interface often attempt to reduce potential property loss through decreasing fire intensity, reducing ember attack and increasing suppression advantage [12, 91]. Prescribed burning is frequently used in the WUI, however there has been a greater emphasis on mechanical fuel reduction treatments in these areas (Fig. 12.2), largely due to the increased risk associated with the purposeful application of fire into areas often characterised by dense biomass in close proximity to houses and other human assets.

Management of the home and property is purely a private ownership issue. A range of strategies can be undertaken on a property, some of which involve the management of fuels. Fuel related strategies at fine-spatial scales are mostly associated with landscaping (Fig. 12.2), commonly involving the creation of defensible space and a reduction in flammable materials in close proximity of houses. All of these strategies have the goal of reducing the risk of structures igniting during a wildfire and providing a safe space for fire crews or residents to attempt to protect properties and assets.

Fuel breaks and mechanical treatments are commonly applied across all three spatial scales, whereas prescribed burning and grazing tend to be used more at the broader scale, and less so by individual home-owners. Landscaping in the form of discontinuous fuel, non-flammable components such as creeks, ponds, or less flammable vegetation species are undertaken at finer spatial scales and are driven by individual property owners.

12.4 Measures of Effectiveness

There are many ways to measure the effectiveness of fuel treatments. Here we outline the known evidence-base for the efficacy of fuel management strategies in terms of reducing: i) the likelihood of ignition; ii) spread to the Wildland-Urban Interface, and iii) impacts at the Wildland-Urban Interface.

12.4.1 Ignition and Initial Growth

Fuel treatments are not implemented to alter the rate of unplanned ignitions, rather they are used to lower fuel loads in high ignition risk areas. Ignitions that do occur in these areas are then expected to spread more slowly, be lower intensity and potentially more likely to self-extinguish or be more easily suppressed near the point of ignition [92–96]. The theory is that fuel treatments may lower the likelihood of ignitions becoming established as spreading wildfires. In practice, prescribed burning and grazing will have some utility in reducing the likelihood of ignitions becoming established fires, as these treatments reduce surface and near-surface fuels required for surface fire spread [34, 97]. There are a number of other ignition management strategies that exist, such as total fire bans, electricity management (e.g.

installation of spacers, burying powerlines, blackouts during high wind events), community education, closing of national parks and monitoring of arsonists. These are based on social behaviours or infrastructure design and are not considered fuel management.

Few studies have attempted to quantify the effect of prescribed burning on the likelihood of ignition and growth to a spreading fire. Analysis of empirical and experimental data generally shows that ignition likelihood increases with time since fire, though treatment effects are short lived (e.g. <5 years) and the magnitude of the effect decreases as fire weather worsens [98–100]. Simulation modelling for eucalypt forests of southern Australia has found that high rates of prescribed burning (10% annual treatment rates) can decrease the likelihood of fires being contained below five hectares compared to scenarios of no prescribed burning, though these effect sizes were considerably smaller than that of fire weather [99, 101]. It should be noted that characterising the effect of fuel treatments on ignition rates is challenging as other landscape or human factors have dominant effects [93–95, 100, 102–105, 106].

Masticated fuels were found to have a reduced density of elevated fuels but an increase in surface fuel loads [107]. Other studies have shown meaningful reductions in flame length in masticated fuels (when compared to untreated fuel) which may increase the likelihood of fire suppression [108]. However flaming and smouldering duration has been shown to increase in masticated fuels [109–112]. While masticated fuel treatments may not directly impact on ignition likelihood, they may contribute to slower rates of spread which may increase the likelihood of suppression. However, long combustion times may make the task of blacking out more challenging.

The effectiveness of all fuel treatments for reducing the transition from an ignition to a spreading wildfire will be contingent on early detection of ignitions and availability of resources for fire suppression [99].

12.4.2 Landscape Fire Spread

Fuel amount, structure and complexity influence fire behaviour at a fundamental level but are also important at landscape scales [9]. While complete removal of fuel would prevent combustion and hence the spread of wildfires, fuel treatments do not remove all fuel within a designated area. It is also unrealistic to expect that any fuel management strategy will prevent the occurrence or spread of all unplanned fires [113, 114]. Measuring the efficacy (i.e. longevity of fuel/hazard reduction) of fuel treatments is challenging due to the considerable variation between regions and vegetation types, and across a range of factors including topography, landscape variability, weather and season. These factors often interact, making it hard to apply results from fine-scale empirical studies to a landscape scale, or to generalise them to other regions [3, 9]. Fuel load and structure varies widely within and between regions, as do the shape of vegetation responses post fire [115].

One of the primary goals of fuel treatments at the landscape scale is the modification or removal of fuels to reduce fire spread, intensity and ember propagation, to reduce the likelihood of a fire impacting the WUI and people and property. However, the efficacy of fire risk reduction varies between and within treatment types. Fuel treatments at the landscape scale can moderate fire behaviour but the magnitude of the effect is extremely dependent on weather. In Australia, the McArthur Fire Danger Index is widely used as a means of quantifying fire danger [Table 12.2, 40]. High temperatures, high wind speeds and low relative humidity contribute to the occurrence of dangerous fire conditions. The index relates the likelihood of a fire starting and spreading, as well as its intensity and containment likelihood. Lower values represent mild fire weather conditions, higher values represent fire behaviour that is much less likely to be controlled. Tolhurst and McCarthy [58] argue that at a forest fire danger index of 50, fires shift from having fuel-dominated fire behaviour to weather-dominating fire behaviour. This is supported by numerous studies that demonstrate the dominant effect of weather in predicting fire severity across landscapes [for example 33, 35, 58]. While most of these studies have only considered the effect of time since burning, there is no evidence to suggest that these patterns would not equally apply to mechanical or biological fuel reductions.

Fuel load and structure affects fire behaviour which has a strong influence on the ability of suppression crews to contain a fire [117–120]. Empirical analyses of fuel management at the landscape scale and its influence on containment likelihood are limited. There are several case studies that report recently burnt areas having enhanced suppression effectiveness [58, 121–124]. However, effectiveness diminishes with time since fire and under more extreme fire weather. Similar results have been recorded through simulation studies [125–127]. Studies on the effectiveness of fuel reduction for limiting the extent of wildfire exist for a range of vegetation types in the fire-prone regions of the world, however the results are often contradictory. There are examples of where a prescribed burn has stopped or slowed the spread of a single wildfire [see review by 3]. The efficacy of fuel treatments in reducing the extent of wildfire can be considered as the probability of encountering a prescribed burn area(s) while the fuel is in a reduced state that moderates fire behaviour sufficiently to stop a wildfire or allow successful suppression [6, 128].

Table 12.2 The McArthur Forest Fire Danger Index (FFDI), which represents the degree of fire danger in both forests and grasslands. The index is based on temperature, wind speed, relative humidity and a variable representing fuel availability – drought factor [116]

CATEGORY	FIRE DANGER INDEX	
	FOREST	GRASSLAND
Catastrophic/Code Red	100+	150+
Extreme	75-99	100-149
Severe	50-74	50-99
Very high	25-49	25-49
High	12-24	12-24
Low-Moderate	0-11	0-11

The contribution of landscape scale fuel treatments to reducing the effects of wildfires can be quantified in a variety of ways: using basic combustion science; well-documented case studies; analysis of fire statistics; and computer simulations [3, 129, 130]. Empirical evidence relating to the efficacy of fuel treatments such as prescribed burning or mechanical thinning remains highly debated, largely because regional variations are rarely acknowledged. In recent years the rise of advanced simulation modelling has allowed much greater quantification of the efficacy of different temporal and spatial applications of fuel treatments across landscapes.

Fire weather is the dominant driver of fire severity, with time since fire and topography being of secondary importance [35, 56]. Recently burnt areas (less than 5 years since fire) are more likely to have lower severity fire than long unburnt areas [33, 35, 57, 58], however these affects are reduced or disappear as the fire weather exceeds a forest fire danger index of 50 [58, 59]. Relationships between fire severity and time since fire are complex in that they do not increase linearly with time since fire [e.g. 35, 131]. These non-linear responses have been supported by empirical studies of flammability [132, 115].

The effectiveness of mechanical treatments is determined by measuring changes in vegetation structure, observing fire behaviour in the field and laboratory and predicting fire behaviour using simulations. Studies that measure changes in fuel structure as a result of mastication report reduced density of shrub fuels, increased surface fuel compaction and increased coarse fuel load on the forest floor [65, 133, 134]. Changes to fuel moisture dynamics are also reported, with deep, masticated fuel beds retaining moisture for long periods [135], however, this may be counterbalanced by reduced shrub cover increasing the exposure of the fuel bed to the drying effects of solar radiation. Studies examining the efficacy of mechanical treatments in reducing the risk of fire at a landscape scale are limited. The greatest reductions in wildfire intensity occur when mechanical treatments are combined with prescribed burning, as mulching/thinning reduces canopy density while burning reduces the surface and ladder fuel loads [68, 136–138].

There is no standardised approach for monitoring the effectiveness of grazing. Grazing will have a more varied outcome than mechanical fuel reduction approaches [77]. Measuring effectiveness will vary considerably between different vegetation communities, the herbivore species used; stocking rates; time since previous treatment (i.e. grazing and or fire), and length of grazing time, for example. Herbivores generally do not reduce dead biomass or larger fuels, so combining grazing with mastication, low-intensity prescribed burns and thinning may prove to be an effective means for increasing containment likelihood and reducing impact to assets. However, undertaking this on a large scale may prove to be prohibitively expensive, or impractical to implement [81].

12.4.3 Spread and Impact at the Wildland-Urban Interface

Fire impacts on human assets in WUI areas may be driven by direct flame contact, radiant heat, or from embers (firebrands) [139]. Fuel treatments at the WUI are primarily focused on preventing fire reaching an asset or modifying the behaviour of fire in an attempt to lessen the impact, should it reach human assets. The frequency of threats from fire in WUI areas is predicted to increase as populations expand and the severity of fire weather increases [99, 140]. Therefore, individual home-owner driven strategies are important to complement landscape-scale strategies to minimise the loss of human assets.

Most simulation studies show that fuel treatments in the area immediately around houses (500 m–2 km) are more likely to reduce the risk of impact to houses at the WUI than landscape treatments [12, 141–146]. For example, prescribed burning in the WUI was found to be more effective in reducing the probability of fires reaching houses, as well as reducing the likelihood of high intensity fire [145, 147, 148]. Conversely, landscape treatments can reduce the extent of wildfire [149], but the effect on the risk to property is small for two reasons. Firstly, wildfires that ignite well away from property only reach the property under severe or extreme weather conditions when fuel treatments are known to be less effective at altering fire behaviour. Secondly, the risk to property from fires that start close to houses is independent of landscape treatment rates as they do not overlap.

Risk to property is not purely a factor of fuel treatments. Suppression effort, fire development patterns and actions of communities and individual property owners [150–155] all alter the probability of a house surviving a fire. There are no methods that allow for an analysis of all these interacting factors to understand the relative importance of fuel treatments in reducing risk to houses. Costs of treating fuels at the WUI are significantly higher on a per hectare basis, but the extent of area requiring treatment is considerably lower [145]. This makes it more difficult to achieve the amount of prescribed burning required to mitigate wildfire impact.

12.5 Fuel Management Under a Changing Climate

Land managers and fire agencies have limited budgets for undertaking fuel management, and this is further complicated by the environmental, social and financial risks of undertaking fire–based fuel treatments [156]. As the climate changes, the window for safely undertaking fire-based fuel treatments such as prescribed burning is changing [60, 61]. In fire prone regions globally, there are less and less opportunities for prescribed burning (i.e. when fuel is dry enough to successfully ignite but weather conditions are mild enough to safely ignite), and this is putting increasing pressure on fire managers to undertake fuel treatments whenever and wherever possible.

Future climate change scenarios predict an increase in wildfire activity, characterised by increases in fire extent, severity or frequency for many ecosystems [157, 158]. Climate change will affect individual fires through changes to fire weather components (temperature, rainfall, humidity and wind), resulting in changes to fuel which may exacerbate fire behaviour [159]. The effects of climate change on the fire regime are driven by: the rate of vegetation growth; the rate of drying; the occurrence of suitable fire weather; and patterns of ignitions. Under a changing climate, fire weather is expected to become more severe, fuel mass and type is expected to change due to fluctuations in rainfall, ignitions will change as a function of climate and patterns of human settlement, for example.

Climate predictions suggest there will be a decline in the coincidence of suitable weather (for prescribed burning) and suitable fuel moisture (for ignitability) due to increasing variability in climatic conditions [160, 161]. Fire seasons are also expected to start earlier and last longer, further reducing the window for safely treating fuel using fire-based treatments. Climate change scenarios suggest that the main changes in conditions are to occur at the extremes, with shifts in the abundance of periods of extreme wet and extreme dry conditions [162]. This is likely to result in high productivity during the wet – which will have the effect of increasing fuel loads – and the generation of mass fuel production via plant death during the dry-which may increase the flammability of fuels. Both of these conditions will likely contribute significantly to more extreme fire behaviour [163].

Under more severe climate conditions, the use of fire-based treatments during conventional burning periods (e.g., autumn in temperate regions) may become more difficult to implement, while more opportunities may become available at other times (e.g., winter in temperate regions) [161]. Consequently, other fuel treatments will become more important, including grazing, mechanical treatments and landscaping [164, 165].

12.6 The Complexities of Fuel Management

There is a diverse range of fuel management options in the toolbox of fire managers, however the main actions are through prescribed burning or mechanical treatments. Both treatment types can immediately reduce fuel load and/or structure, but the extent to which this occurs is variable. There is considerable variation both between and within treatment applications. Variation in coverage is driven by fuel properties, topography, climate and weather at the time of the treatment [156]. In theory, there should be greater control over the heterogeneity of mechanical treatments due to decisions made by the machine operator, but this is yet to be quantified.

The use of fire in treating fuels continues to provoke considerable public and scientific debate. The primary concerns are related to environmental/ecological impacts, risk of escape, smoke hazard and reduced air quality, decreased aesthetics, financial responsibility and the longevity of treatments [3, 9, 28, 43, 44]. Land and fire managers must carefully assess the trade-offs between undertaking fire-related fuel management actions and human health and well-being. Undertaking prescribed burning in areas where the risk reduction to human life from future fires is likely to be low, but the impacts from smoke may be high, must be carefully considered as to the importance of these burns going ahead. However, assessing the potential impacts from smoke is a complex issue. While the spread of smoke from a hazard reduction burn may be predicted, the flow-on impacts to people is much harder to measure. Outcomes which are influenced strongly by the actions of people are very hard to quantify.

Non fire-based fuel treatments are increasingly being considered as a means of reducing wildfire risk without the associated human impacts. Mechanical fuel treatments offer some advantages over prescribed burning. They are not subject to a narrow range of weather conditions; can be designed to target individual plants; do not produce smoke; and can be applied to fuel types that are difficult to safely burn in a planned manner. Furthermore, some studies show that mechanical treatments are preferred over prescribed burning by community groups, especially closer to towns [63]. A major disadvantage is that they can be more costly to implement than prescribed burns, which means they can only be used in small areas. Furthermore, for ecosystems dependent on fire for regeneration, they do not provide a fire or smoke stimulus for regeneration.

The efficacy of fire mitigation strategies varies between and within treatment types. Fuel treatments have been shown to moderate fire behaviour, but the magnitude of these effects is extremely dependent on weather. No single solution will achieve all stated objectives. Fire managers need to consider where and when it is appropriate to apply various fuel management actions to achieve the greatest risk reduction across the range of values. They also need to consider whether the risk reduction benefit is outweighed by the harm it may do to human health or to environmental values. It is becoming increasing important for managers to consider the implications of a changing climate on when, where and how they apply fuel treatments. Fuel management on public land is just one approach to fire management. Other approaches such as fire suppression, community engagement for home-owner preparedness and ignition management should also to be incorporated into the decision-making process.

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Chapter 13
Sustainable and Fire Resilient Built Environment (SAFR-BE)

Brian J. Meacham and Margaret McNamee

13.1 Introduction

Sustainability and resiliency are terms one often hears today in discussions about the built environment. While some use the terms interchangeably, they embody different concepts, which sometimes align, but in other cases, can result in competing objectives. Good building design should address both sustainability and resiliency concepts as part of a holistic approach. This is also true for planning of communities and critical infrastructure for all hazards. Developing a design philosophy which embodies sustainable and fire resilient concepts for buildings, infrastructure and communities is a critical aspect of managing fire impacts to and from the environment.

13.1.1 Sustainable and Resilient – Concepts and Definitions

Sustainable, Sustainability and Sustainable Development

The terms *sustainable*, *sustainability*, and *sustainable development* have numerous definitions and it is critical at the outset of this chapter to present these definitions to be able to juxtapose resiliency to sustainability later in the chapter. In the context of our world and its inhabitants, the principle of sustainability is based on a simple

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and long-recognized premise that: *everything that humans require for their survival and well-being depends, directly or indirectly, on the natural environment* ([1] as cited in [2]). Current conceptualizations of sustainability emerged out of growing concerns in the 1960s and 1970s about whether industrial and economic development was creating long-term impacts on the planet and its flora and fauna, and the desire to promote a more sustainable environment for all [2, 3]. A result was to consider sustainability in terms of three driving factors: economic, social, and environmental goals. A widely used image which reflects the interconnection of these goals is presented in Fig. 13.1.

The concept of sustainable development, which came to the fore in the Brundtland Commission report, *Our Common Future* [5], was born out of concerns over the depletion of earth's finite resources and the potential for irreversible damage to the environment as a result of growing industrial activity, energy demands and transportation needs, and the desire to find ways to address both as part of continued expansion of the built environment (e.g., see [2, 3, 6]). Indeed, the concept of planetary

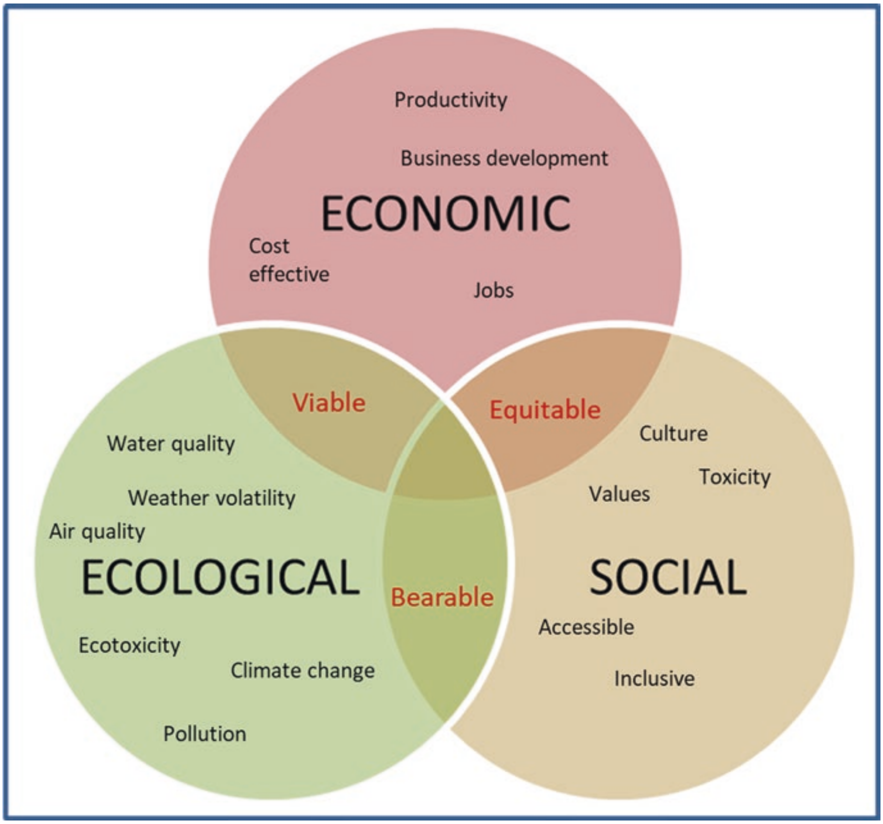

Fig. 13.1 Sustainability in the context of economic, social and environmental goals. (Adapted from McNamee et al. [4])

boundaries has grown out of these concerns [7, 8]. According to the Brundtland Commission, "a sustainable society meets our present needs without compromising the ability of future generations to meet their needs" [5].

Concurrently, sustainability became coupled with reducing the production of greenhouse gases and subsequent climate impacts, as investigated through the Intergovernmental Panel on Climate Change (IPCC) [9–11] starting in 1998,[1] the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, and the Kyoto Protocol in 1997. Within these efforts there was a clear and global imperative to reduce carbon emissions, and early on it was identified that the built environment was responsible for a significant percentage of carbon emissions, driven largely by energy consumption but also embodied carbon (e.g., see [12]).

Given the coupling of greenhouse gas emissions and material conservation, the application of sustainability concepts to buildings has often been focused around reductions in fossil fuel energy dependency and minimisation of unsustainable material. This in turn gave rise to a focus on development of sustainable materials, technologies and design concepts aimed at reducing energy demands, carbon emissions and material use as part of 'green' buildings (see e.g., [13–15]), of associated assessment methods and rating schemes which recognize such features (e.g., see [16, 17]), of regulation (e.g., the Energy Performance of Buildings Directive [18, 19]) and of design guidance for green or sustainable buildings (e.g. [20]).

With respect to design guidance, as stated in the U.S. National Institute of Building Sciences (NIBS) *Whole Building Design Guide*, the main objectives of sustainable design are [20]: "to reduce, or completely avoid, depletion of critical resources like energy, water, land, and raw materials; to prevent environmental degradation caused by facilities and infrastructure throughout their life-cycle; and to create built-environments that are liveable, comfortable, safe, and productive." Many of the core principles of sustainable design focus on reducing or optimizing energy, resource and material usage. This can be seen in the US Federal Government's *Guiding Principles for Sustainable Federal Buildings* [21, 22]. These Guiding Principles include several factors associated with energy-efficiency, ventilation, lighting, and material usage, including:

- For new construction, ensure energy-efficiency is 30% better than the current American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 Standard (or alternatives listed).
- Evaluate and implement, where appropriate, life-cycle cost-effective renewable energy projects on-site; consider long-term off-site renewable sources and renewable energy certificates (RECs); and utilize clean and alternative energy where possible.

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[1] The IPCC was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) with the objective to provide governments at all levels with scientific information that they can use to develop climate policies (https://www.ipcc.ch/about/)

- Maximize opportunities for daylighting in regularly occupied space, automatic dimming controls or accessible manual controls, task lighting, and shade and glare control.
- Procure products that meet the following requirements where applicable: Resource Conservation and Recovery Act section 6002, Federally recommended specifications, Standards and ecolabels or are on the Federal Green Procurement Compilation for other green products, as appropriate.

There are also Guiding Principles related to indoor air quality, safety, and climate adaptation, among others. Principles such as these can lead to a variety of design features that may be considered, including:

- Significant use of day lighting
- Double-skin façade systems for heating, cooling, and ventilation
- Natural ventilation schemes (vertical, e.g., atria, and horizontal)
- Increased thermal insulation
- Lightweight, high-strength materials
- Local alternative energy generation and storage systems (for normal and emergency power)
- Vegetative features (e.g., shading, walls, roofs)

More recently, resiliency has become associated with sustainability, but resiliency is not always reflected in rating schemes or design guidance (e.g., resilience is a ‘related concept’ in the NIBS guidance [20]), and often encompasses a different and broader scope.

Importantly, sustainability in the context of this chapter will be considered in terms of the Brundtland Commission definition [5], and implicitly containing the three dimensions of economic, environmental and social sustainability.

Resilient, Resilience and Resiliency

Similar to the preceding discussion, there are many definitions and interpretations of the terms *resilient*, *resilience* and *resiliency.* With respect to our natural and built environments, and to society as a whole, the terms are broadly accepted as the ability to return to normal after suffering some type of stressor or loss. Hassler and Kohler [23] provide a good overview of resilience in the built environment in their editorial article which sets the stage and summarises key points addressed by contributing authors in the journal volume on this topic.

As a design principle, Hassler and Kohler [23] note that resilience was an implicit part of traditional construction knowledge before the nineteenth century, embodying such concepts as oversizing of components and spaces, redundancy, and reparability. Specifically for fire safety, the concept of layers of fire protection has been leveraged to support fire resilience. This concept builds on the idea of six basic layers, including active (I–IV) and passive (V–VI) protection, co-operating in support of redundancy and reparability:

I. Prevention
II. Detection
III. Suppression
IV. Evacuation
V. Compartmentation
VI. Structural resistance.

The layers of fire safety recognize that the best way to reduce the harm due to fire (and improve resilience) is to avoid its occurrence in the first place, through prevention. Should a fire occur, early detection and suppression will reduce the potential loss of functionality due to the fire, while evacuation will ensure minimal risk of harm to occupants. Compartmentation will reduce the risk of fire spread from one part of the building to another and structural resistance will support all of the previous layers in performing their function.

The meaning of resilience in design transformed over time with the creation of calculation methods for optimizing safety and use of materials to achieve required stability to static and dynamic forces (e.g., response to earthquake or wind forces). The risk in this change of focus is that layers of fire safety are lost and redundancy reduced.

In the 1970s, as the environmental sustainability thinking was developing, the concept of ecological resilience was developed [24] to reflect the ecosystem's ability to adapt. This idea was then further extended to a more general (system) theory with the hopes of providing a new and useful framework for understanding how individuals, communities, and organizations, as well as ecosystems, are able to respond and adapt in the face of known and not yet known uncertainties, challenges and opportunities [23].

By the early 2000s, resiliency took on new meaning relative to performance of buildings and infrastructure under extreme loading from events such as earthquakes, large hurricanes and terrorist attacks (e.g., see [25–27]), and with consideration of societal and economic impacts, became more broadly discussed in terms of disaster resiliency and community resilience (e.g., see [28, 29]). A widely used definition which emerged is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events [2]. A graphical representation of this concept of resiliency is provided in Fig. 13.2.

Figure 13.2 derived from considering the resiliency of infrastructure and complex systems when subject to extreme events [25, 27], but can be applied to buildings as well [30–32], which are also complex systems. The initial design of the system targets a certain level of acceptable operational functionality. With regular maintenance, the functionality can remain consistent with time. If proper maintenance does not occur, the functionality decreases. If enhancements are made, functionality can increase. When some type of negative event occurs, one can anticipate that some interruption of function can occur. However, the magnitude of the impact can vary widely. If the event has been considered, and system functionality enhanced, the impact can be less in terms of magnitude, time of disruption and resources needed to get back to normal. If the event has not been considered, the impacts can

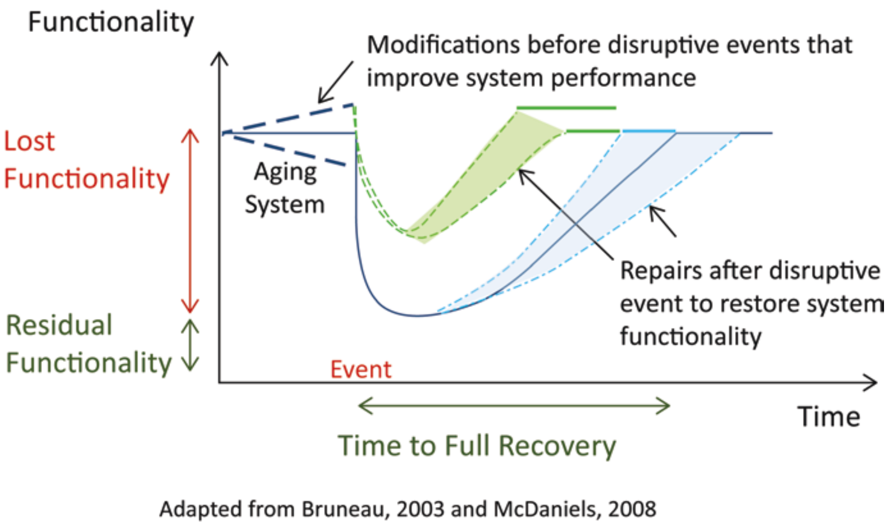

Fig. 13.2 Representation of impact, response and recovery [30]. (Used with permission)

be much more significant. If regular maintenance has not occurred, and 'normal' functionality has decreased, the impact can be severe or even catastrophic.

The need to apply disaster resiliency concepts to communities came into focus for many in the early 2000s. In the USA, for example, the terrorist attacks of September 11, 2001, Hurricane Katrina in 2005 (see Fig. 13.3), devastating tornados in 2011 and Superstorm Sandy in 2012 were watershed events. In more recent times, the harrowing dual destruction of the town of Paradise by the Camp wildland fire in November 2018 has highlighted the continued relevance of disaster resiliency in at risk communities.

The 2012 report from the US National Academies, *Disaster Resilience – A National Imperative*, noted that in 2011 alone, economic damages from natural disasters in the USA exceeded $55 billion, with 14 events costing more than a billion dollars in damages each [2]. While targeted at US national policy leaders, several recommendations from this effort are applicable more broadly, including:

- Resilience should be a guiding principle to inform the mission and actions of the government and the programs it supports at all levels.
- The public and private sectors in a community should work cooperatively to encourage commitment to and investment in a risk management strategy that includes complementary structural and non-structural risk-reduction and risk-spreading measures or tools. Such tools might include an essential framework (codes, standards, and guidelines) that drives the critical structural functions of resilience and investment in risk-based pricing of insurance.
- A national resource of disaster-related data should be established that documents injuries, loss of life, property loss, and impacts on economic activity. Such a

Fig. 13.3 Lone home standing in area hit by Hurricane Katrina. (Source: US FEMA/Mark Wolfe)

database will support efforts to develop more quantitative risk models and better understand structural and social vulnerability to disasters.

Increasingly, as climate change results in hotter temperatures, increased drought conditions, and increased wind events and speeds, a significant growth in the number, magnitude and impact of wildland fires has resulted, see for example Fig. 13.4.

In 2016, the US National Institute of Standards and Technology (NIST) estimated the total annualised economic burden of wildland fire in the US alone to be between US$71billion and US$347billion [33]. The situation has only gotten worse, with 6 of the costliest wildland fires in the USA being recorded in 2017 and 2018 [34]. In Australia, by the end of the 2019–2020 bushfire season, the estimated impacts from some 15, 344 bushfires were similarly immense: 18,983,588 hectares burned, 3113 houses lost, 33 fatalities, and an estimated to have had a A$20 billion impact on the economy [35].

Sustainability and Resiliency Interactions

While sustainability and resiliency are arguably different concepts, it is clear they are interconnected with respect to protection of the environment and human settlements. A review of the literature which explored similarities, differences and current management frameworks for increasing sustainability and resilience in an environmental management context reflects inconsistency in the use of the terms [36]. As reflected in the historical overview above, the Marchese et al. [36] study

Fig. 13.4 Fire at Whiskeytown National Recreation Area, California. (Source: US National Park Service)

found that sustainability was largely defined through the triple bottom line of environmental, social and economic system considerations, and that resilience was largely viewed as the ability of a system to prepare for threats, absorb impacts, recover and adapt following persistent stress or a disruptive event.

Overall, the study found that three generalized management frameworks for organizing sustainability and resilience dominate the literature: (1) resilience as a component of sustainability, (2) sustainability as a component of resilience, and (3) resilience and sustainability as separate objectives. Regardless of the approach, however, implementations of these frameworks were found to have common goals of providing benefits to people and the environment under normal and extreme operating conditions, with the best examples building on similarities and minimizing conflicts between resilience and sustainability.

One sees this with respect to design. The Resilient Design Institute, for example, defines resilient design as "intentional design of buildings, landscapes, communities, and regions in order to respond to natural and manmade disasters and disturbances – as well as long-term changes resulting from climate change – including sea level rise, increased frequency of heat waves, and regional drought" [37]. There is growing literature about sustainable and resilient design, largely focused on natural hazard events, in particular events potentially driven by climate change, such as more extreme storms, drought and wildland fire (e.g., [38–41]). A few references, however, have looked particularly at sustainability and fire resilience of buildings from more of a technology use component, that is, fire performance of sustainable building technologies (e.g., [12, 42, 43]).

13.2 Sustainability, Resiliency and Fire Safety

13.2.1 Sustainable and Fire Resilient Built Environment (SAFR-BE) Concept

As discussed in Sect. 13.1, while resiliency is sometimes considered an attribute of sustainability, this is often not the case. A prevalent view of sustainability focuses on managing the earth's resources and limiting damage to the biosphere in order to allow for continued use of planet and its resources without depleting them or causing irreversible damage. A prevalent view of resiliency is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. Within the built environment, sustainability often focuses on reduction in fossil fuel energy sources and carbon emissions from these sources, and reduction in the life cycle impacts of material use. Resiliency, on the other hand, focuses on minimizing the impact and recovery from adverse events, including fire.

As a means to advance the need for the built environment to be both sustainable and resilient with respect to fire as an adverse event, it can be helpful to think in terms of a Sustainable and Fire Resilient Built Environment (SAFR-BE). A representation of the concept is provided in Fig. 13.5.

As used in this chapter, the built environment includes buildings, infrastructure and communities. Sustainable and Fire Resilient buildings (SAFR Buildings) are ones in which sustainable or 'green' objectives do not conflict with fire safety objectives, and where the building is resilient to internal and external threats from fire. SAFR Infrastructure reflects such infrastructure components a non-fossil fuel (sustainable) energy sources or materials and sustainable technologies that are at the

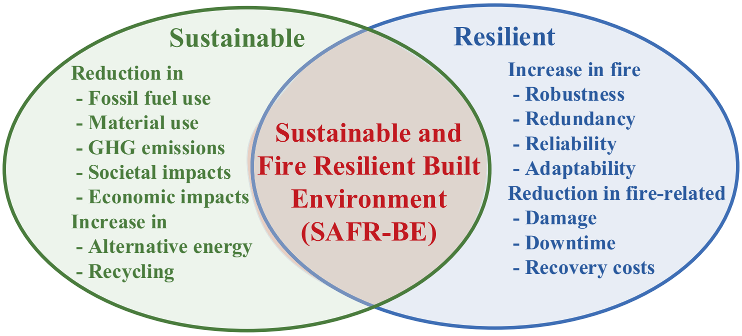

Fig. 13.5 SAFR-BE concept. (Adapted from Meacham, McNamee [12])

same time resilient to fires resulting from the technologies or that impinge upon the infrastructure from external fire events. SAFR Communities are those in which sustainable urban planning and resilience to wildland and other large open fire events is addressed. An attribute of SAFR Communities would be SAFR Buildings and SAFR Infrastructure.

13.2.2 Sustainable and Fire Resilient Buildings (SAFR Buildings)

The SAFR Buildings (structures) concept aims to promote buildings which are designed to both be sustainable (in terms of use of resources and GHG emissions) and resilient to fire starting within or external to the building, regardless of the external initiators, and in the situation of multiple hazard effects [12, 43]. If a SAFR Building philosophy is adopted, it should facilitate holistically designed buildings which seamlessly integrate sustainability and fire resiliency objectives and minimize the potential for unintended consequences as illustrated in Fig. 13.6.

With respect to sustainability and fire, some rather significant fires associated with sustainable or ‘green’ building features, attributes and technologies have been observed, some of which seem to related to a lesser focus on fire safety objectives (e.g., see [12, 44, 45]). In part this can be attributed to a building regulatory focus on sustainability as a function of energy performance, and a lack of regulatory focus on resilience [45]. Concerns related to unintended consequences arising from focus on a single attribute of building performance, such as sustainability, without concurrent consideration of other important building performance objectives, such as fire safety, is not new (e.g., [12, 42, 44, 45, 46]). Research has shown that there can exist a potential for:

- Fire and health hazards due to the flammability and/or fire retarding treatment of thermal insulating materials, see Fig. 13.7 which shows the Grenfell Tower fire

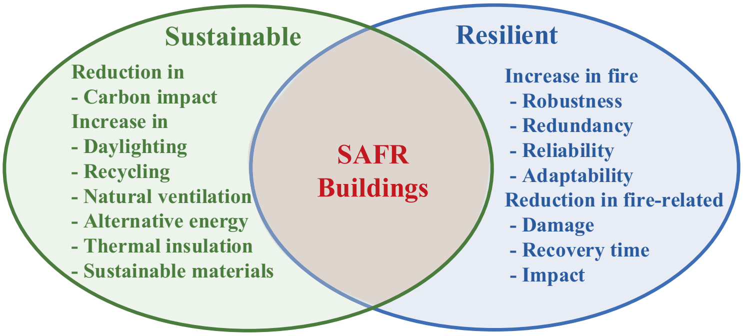

Fig. 13.6 SAFR buildings concept. (Adapted from Meacham, McNamee [12])

Fig. 13.7 Grenfell Tower Fire. (Source: Natalie Oxford, 2017. This file is licensed under the Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0/deed.en). Photo downloaded from https://commons.wikimedia.org/wiki/File:Grenfell_Tower_fire.jpg)

in which combustible façade material, installed as part of building renovations to improve energy efficiency, was a significant contributer.

- Fire and smoke spread potential through the use of double-skinned façades,
- Ignition and fire spread potential with a coupling of photovoltaic (PV) systems and combustible insulation,
- Potential contribution of unprotected / inadequately protected lightweight engineered lumber (LEL) or mass timber to fire severity and potential structural failure,
- Increased potential of high strength lightweight concrete to spall during a fire and present potential for structural failure,
- Ignition, explosion and fire hazard potential associated with energy storage systems (ESS),

- Potential fire hazards and impediments to emergency responders associated with interior and exterior use of vegetation, PV / building-integrated PV systems and other 'green' features and elements, and
- Potential fire hazards of exterior vegetation for shading or other in the wildland-urban interface,

Finding a suitable balance between sustainability and fire safety objectives can be particularly complex due to the multidimensional aspects of each [45]. For example, timber is a sustainable material but is also combustible, so if not addressed appropriately can present a significant fire safety hazard [12]). High strength concrete requires less material and is more sustainable than regular strength concrete, but can be highly susceptible to spalling during a fire [47]. Insulation and alternative energy sources are good for sustainability, but photovoltaic panels which can cause ignition, and together with flammable insulation material, can be a catastrophic combination [12, 44].

As with concerns of competing objectives with respect to sustainability and fire safety, similar gaps have been observed in the case of building performance in the case of multi-hazard events, such as post-earthquake fire performance of buildings (e.g., [48–52]). It can often be the case that building engineering analysis and design is undertaken in 'silos' wherein each discipline considers hazards (loads) independently, such as earthquake but not fire, or flood but not fire, or fire alone without consideration of concurrent natural hazards.

For example, Fig. 13.8a shows damage to a reinforced concrete beam-column connection which occurred during earthquake and post-earthquake fire testing of a reinforced concrete frame specimen [48, 49] and Fig. 13.8b shows a damaged gypsum board ceiling system, which became initially dislodged during ground motion tests, and became further damaged during post-earthquake fire tests [50]. While the specimen reflected in Fig. 13.8a did not collapse due to ground motion, should a


(a) (b)

Fig. 13.8 (**a**) Damage to reinforced concrete beam-column connection [44]; (**b**) Damage to gypsum board ceiling system post ground motion and fire [49] post-earthquake fire occur, the damaged connection would be further damaged by fire to the point of collapse potential. In the case of the specimen in Fig. 13.8b, loss of fire protection cover for a light gauge steel framing system could likewise lead to structural failure in a post-earthquake fire situation. Examples such as these illustrate that multi-hazard impacts should be part of resilient design, in particular a SAFR Buildings approach.

The need to consider a SAFR Buildings approach is also a reflection of the evolution of building regulations in some countries where some have suggested that fire resilience of buildings may have inadvertently decreased over time (e.g., [53–55]). Changes in US building regulations with respect to fire resilience was one research area of the FAIL-SAFE project of the National Association of State Fire Marshals [55]. The FAIL-SAFE project was designed to study the impacts on fire and life safety in structures equipped with multiple layers of both active and passive fire protection features to understand how active and passive fire protection features interdepend on one another in providing the level of safety the public and the fire service have come to expect. An aim was to provide quantifiable data to better understand the relationship between multiple layers of fire safety features and occupant survivability and to provide critical insight into methods of increasing building and business resiliency when exposed to the effects of a fire event.

Reasons for how potentially competing objectives could be introduced into the regulation and design of buildings, and the uneven levels of building performance that can result, have been explored in other contexts as well. Contributing factors include changes in policy-level focus, a siloed approach to building regulation development and building design, lack of clarity between sustainability and resilience, introduction of new materials and systems without adequate testing and design understanding, and inadequate enforcement mechanisms [45, 56]. In addition to a SAFR Buildings approach to building regulation and design, socio-technical systems (STS) thinking and an STS approach for the whole of the building regulatory system [57] would greatly assist in identifying and managing competing objectives and deliver on holistic building performance [12].

13.2.3 Sustainable and Fire Resilient Infrastructure (SAFR Infrastructure)

A society's physical infrastructure includes the industries (agricultural and manufacturing) and utility, communication, and transportation systems that keep an economy operating, connected and moving. In some definitions, buildings are included as well.

Sustainable infrastructure systems, like sustainable buildings, are components of sustainable development. There are many definitions, but the draft *Good Practice Guidance Framework for Sustainable Infrastructure* [58], which is being developed as part of the implementation of United Nations Environment Assembly (UNEA)

Resolution 4/5 on sustainable infrastructure (UNEP/EA.4/Res.5), suggests the following:

> Sustainable infrastructure systems are those that are planned, designed, constructed, operated, and decommissioned in a manner to ensure economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire infrastructure lifecycle. Sustainable infrastructure can include built infrastructure, natural infrastructure, or hybrid infrastructure that contains elements of both. Implicit in the term "sustainability" are the concepts of inclusiveness, health and well-being, quality, service delivery, resilience, and value for money.

In the above definition, 'natural' infrastructure is largely ecological systems, and 'hybrid' systems contain aspects of built and natural systems, such as 'green' roof and wall systems. The rationale behind the *Good Practice Guidance* document is that existing guidelines, standards, and tools for integrating sustainability into infrastructure and spatial planning are usually only applied at the single-project level and often too late in the process to have an impact, and thus a more integrated, upstream, systems-level approach to sustainable infrastructure planning, preparation, and delivery is needed [58].This approach is compatible with the Envision framework developed by the Institute for Sustainable Infrastructure [59], which is a rating scheme, much like 'green building' rating schemes, but for application across the realm of physical infrastructure. The Envision framework contains 64 sustainability indicators, called credits, that are organized into five categories and 14 subcategories by subject matter to cover the full dimensions of infrastructure sustainability [59]:

- Quality of Life: Wellbeing, Mobility, Community
- Leadership: Collaboration, Planning, Economy
- Resource Allocation: Materials, Energy, Water
- Natural World: Siting, Conservation, Ecology
- Climate and Resilience: Emissions, Resilience

Quality of Life addresses a project's impact on host and affected communities, from the health and wellbeing of individuals to the wellbeing of larger social fabric as a whole, assessing whether infrastructure projects align with community goals, are incorporated into existing community networks, and will benefit the community in the long term. Leadership reflects the need that successful sustainable projects require a new way of thinking about how projects are developed and delivered, and that project teams are most successful if they communicate and collaborate early on, involve a wide variety of people in creating ideas for the project, and understand the long-term, holistic view of the project and its life cycle. Resources are the assets that are needed to build infrastructure and keep it running, and the assessment focuses on the quantity, source, and characteristics of these resources and their impacts on the overall sustainability of the project. Natural world recognizes that infrastructure projects have an impact on the natural world around them, including habitats, species, and nonliving natural systems, and considers the way a project is located within these systems and the new elements they may introduce to a system and create unwanted impacts on these ecosystem services. Climate and Resilience reflects the need to minimize emissions that may contribute to climate change and other short-and-long-term risks, and to ensure that infrastructure projects are resilient.

Within the Envision scheme, the above components collectively address areas of human wellbeing, mobility, community development, collaboration, planning, economy, materials, energy, water, siting, conservation, ecology, emissions, and resilience, and collectively become the foundation of what constitutes sustainability in infrastructure [59]. Within the Envision structure, emissions associated with fire in infrastructure systems, as well as emissions associated with materials, construction and use of buildings and systems, would be considered.

Critical infrastructures (CI) are those infrastructure systems where their incapacities or destruction could result in debilitating impacts on security, economy, public health, safety, environment, or any combination of these factors [60]. Resilience of CI has been a specific focus, at least in the USA, since the terrorist events of September 11, 2001, as further brought into focus from natural hazard events such as Hurricane Katrina in 2005, Superstorm Sandy in 2012 and the wildland fires in 2017–2020. Particularly critical are six critical infrastructure networks (CINs) types [61]: water distribution networks (WDNs), drainage distribution networks (DDNs), gas distribution networks (GDNs), transportation networks (TNs), electric distribution networks (EDNs), and communication distribution networks (CDNs). Figure 13.9 shows an example of a fire in a TN, illustrating the destruction potential of such an event.

Whereas vulnerability of these CINs to any type of threat is important, only a handful of approaches and methodologies appear to consider fire as a specifically identified hazard as identified in the Lui and Song [61] review [63–66]. Furthermore, it is noted that a lack of system-based thinking exists. While many studies have explored resilience on individual CINs, an important consideration is that urban CINs and other infrastructures, such as buildings, fire protection, and energy systems, can be viewed as a "system of systems" or as a composite system. The

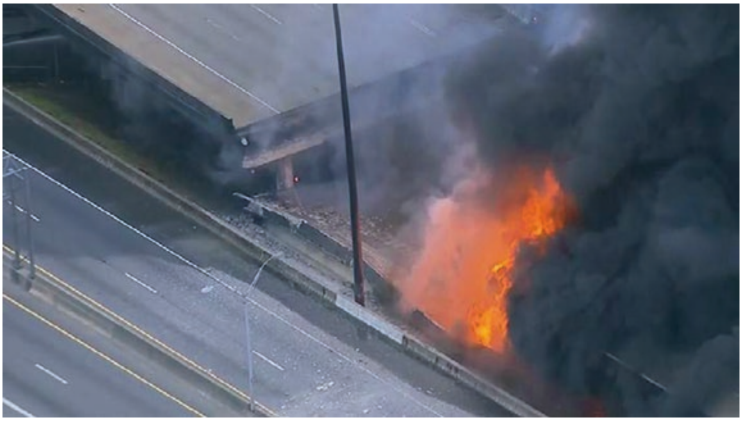

Fig. 13.9 Fire-induced collapse of I-85 bridge section, Atlanta, GA, USA [62]. (Photo placed under public domain)

importance of taking a systems-oriented approach, in particular a socio-technical systems (STS) approach, to CINs [67–70] and to buildings as complex systems of systems (e.g., [57, 71]) has been identified by others as well. Failures that can arise when such systems thinking is not undertaken can be significant; however, means to assess gaps and manage risks exist (e.g., [71, 72–74]).

Certain fire resiliency aspects of critical infrastructure have been investigated by [75] and [76], in particular, fire performance of structural elements. The effort by Mostafaei et al. [75] focused on protection and resilience of critical infrastructures against extreme fires, e.g. fuel storage or tanker fires, in light of the collapse of the World Trade Centre buildings in 2001 and the collapse and the MacArthur Maze Bridge in Oakland, CA, in 2007. A significant finding of this work was the need to develop methods and technologies for property protection of critical infrastructures, *in addition to the current life safety requirements* (as is the focus of building codes), since fast recovery of critical infrastructure after an incident is essential.

Gerney et al. [76] expand upon this, citing Ouyang et al. [77], which describes the need for infrastructure to reflect resistive, absorptive and restorative capacities, meaning it should have means to limit impact from a fire event, limit the loss of function should an event occur, and be able to be readily repaired and returned to normal operation.

A SAFR Infrastructure concept would reflect the ideals of the various approaches overviewed above, with a specific focus on assessment related to fire events. Figure 13.10 illustrates the SAFR Infrastructure concept.

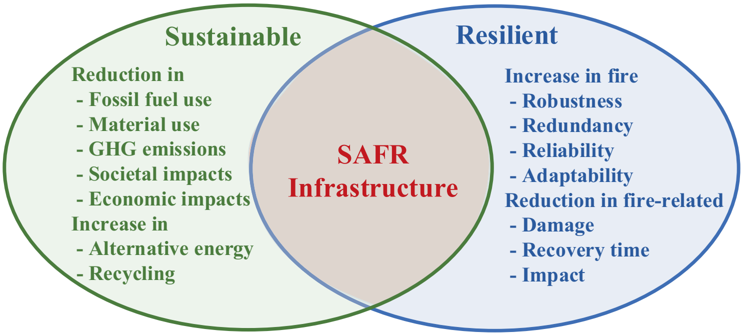

Fig. 13.10 SAFR Infrastructure concept. (Adapted from Meacham, McNamee [12])

13.2.4 Sustainable and Fire Resilient Communities (SAFR Communities)

Sustainable Communities

The nebulous term "sustainable communities" can encompass many activities or interventions, but in essence it refers to communities that explicitly incorporate sustainable objectives in their planning and governance. Numerous initiatives focus, however, on the built environment rather than on the community as a whole, see for example the description of tools for environmental assessment described in Chap. 9 of this book.

Some initiatives have, however, chosen to focus on the community as a whole, e.g. initiatives by the Institute for Sustainable Communities [78] or the United Nations Sustainable Development Goal 11 Sustainable cities and communities [79]. According to the United Nations, in 2018 approximately 55% of the worlds population lived in cities and just over 800 million of these 4.2 billion city dwellers live in slums. Further, it is expected that the vast majority, some 90%, of urban expansion in the coming decades will be in the developing world. The economic significance of these urban centres is profound with some 80% of the GDP being generated there. Clearly, increasing sustainability in these urban centres is crucial.

Fig. 13.11 Examples of sustainability objectives for the three dimensions of sustainability, from left to right, environmental sustainability, economic sustainability and social sustainability based on definitions from ISC [78]

The Institute of Sustainable Communities defines sustainability objectives in terms of the three dimensions of sustainability, i.e. in terms of environmental sustainability, economic sustainability and social sustainability. Examples of relevant sustainability objectives are summarized in Fig. 13.11. As can be seen, there is some clear overlap to resiliency concepts in terms of use of renewable resources, investment in the local economy and adaptability to change, just to name a few. Indeed, while sustainability is typically expressed in terms of increasing the quality of life in terms of the environmental, social and economic dimensions of sustainability; resiliency is typically expressed in terms of the ability of a system (which might be environmental, social, or economic) to stress [36]. Indeed, Marchese et al. [36] indicated in their review of literature into resilience and sustainability found that an increasing number of papers incorporate aspects of both sustainability and resiliency considerations into their research.

Resilient Communities

As for sustainability, the term “resilient communities” is somewhat nebulous and there is no common definition. In some cases resiliency is incorporated in the concept of sustainable, in some cases the opposite, in yet others the concepts are dealt with as essentially separate [36]. In the US, the National Institute of Standards and Technology (NIST), has recognised the fact that community resilience needs to be

Fig. 13.12 Aerial view of homes destroyed in Rancho Bernardo, CA neighborhood. (Source: US FEMA, Andrea Booher)

designed with response to numerous hazards in mind. In their Community Resilience program [80], activities across the whole emergency response cycle are developed and disseminated in relation to a variety of hazards.

Several international initiatives have incorporated the concept of resiliency as the ability of a system to recover to perturbation and have fostered the development of resilient cities or communities through the development of best practices and exchange of ideas, e.g. the Rockefeller Foundation's initiative focusing on the 100 Resilient Cities [81, 82] which has since 2019 been transformed into the 100 Resilient Cities Network [83]. In most cases, community resilience does not only relate to fire resilience, it relates to the ability of a community to minimise the impact of a perturbation due to any major event, be it a natural or man-made hazard.

Increasing recognition of the impact of wildland fires on communities in the wildland urban interface, see Fig. 13.12, has led to the development of numerous programs aimed at increasing community resilience by understanding and reducing community vulnerability to fires. Initiatives such as FireWise (US) [84], FireSmart (Canada) [85] or SaferTogether (Australia) [86] all foster the development of communities with improved resilience specifically to wildland fires, a key aspect of community fire resiliency.

FireWise and FireSmart have been developed through close collaboration between authorities having jurisdiction in the US and Canada and have significant similarities. In the case of FireWise, resilient communities are created by following their system comprised of the following parts: organise, plan, do, tell in a cycle, see Fig. 13.13. Communities that register and follow this methodology are labelled as

Fig. 13.13 Steps to becoming a FireWise USA® Community [84]

"FireWise Communities" and gain access to support documentation and a community of communities to discuss and share experience based on individual needs.

As part of the development of a community action plan to increase wildfire resilience, training is provided on how to conduct a vulnerability assessment. The vulnerability assessment is divided into eight parts:

1. Identify assessment participants
2. General site description
3. Description of properties within the boundaries
4. Topography
5. General home observations
6. Attachments
7. Findings summary
8. Recommendations.

The aim of the FireWise USA® vulnerability assessment is to create a community snapshot and identify strengths and vulnerabilities on which the community can direct its focus. Neighbors must work collaboratively to take care of shared risk which is identified. Significant resources have been developed and can be downloaded from the website, including interactive tutorials, fact sheets with clear

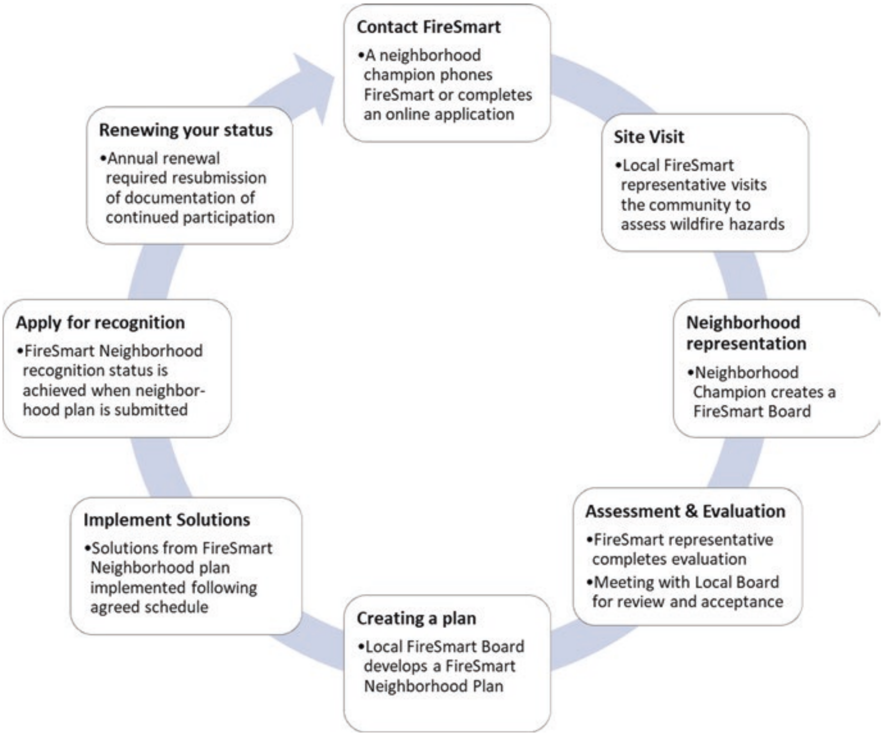

Fig. 13.14 Steps to becoming a FireSmart Canada Community [85]

presentation of key information, renewal information, contacts to other FireWise USA® communities, and much more. The information is under continual development and the interested reader is referred to the website for the latest updates [84].

Numerous other countries which are faced with wildfires are developing their own similar support for wildfire resilient communities, similar to the FireWise USA® initiative. In Canada, the program is called FireSmart Canada® [85]. It is modelled on the FireWise USA initiative and refers to close collaboration with the NFPA. To become a FireSmart Canada community, however, there is a more detailed eight step approach, see Fig. 13.14.

As in the case of FireWise USA, FireSmart Canada offers numerous advantages to participating communities in terms of, e.g. support staff, information material and contact to a broader community of communities facing similar wildland fire challenges. The interested reader is recommended to seek updated information directly from the programs website [85].

A final example that we will deal with in this chapter is the Australian Victorian program Safer Together® [86]. In Australia, Victoria is the state with some of the most pressing wildland fire challenges, or "bushfire" as it is termed in Australia. Safer Together is the Victorian approach to reducing wildland fire risks in Victoran. The Safer Together methodology builds on community partnership with science and technology to effectively target actions. The difference between this program and those espoused by FireWise USA and FireSmart Canada is the clear connection to ongoing research initiatives. The Safer Together program clearly identifies ongoing research into fuel management, fire fighting, egress, and climate change, just to name a few areas. Therefore, the program provides a conduit for rapid dissemination of research results into real applications. As in the case of the other initiatives

Fig. 13.15 Wildland fire encroaching on neighbourhood. (Source: US Federal Emergency Management Agency (FEMA) [89])

outlined, the interested reader is directed to the program website for more up to date information [86].

The need for programs to protect communities against wildland fires is due to the increasing extent of wildland-urban interface (WUI) around the world. Since the 1970s it has been recognised that the incursion of low-density residential development in the area between urban centres and wildland areas is growing and represents one of the greatest fire challenges faced by the United States [87]. While exact estimates of the extent of WUI areas in various countries is not available, it can be established that the number of evacuations due to wildland fires in recent years has increased [88]. Figure 13.15 shows just one example of a neighborhood close to wildland areas with an encroaching fire.

SAFR Communities

It has been established earlier in this chapter that SAFR Communities are those in which sustainable urban planning and resilience to wildland and other large open fire events, is addressed. An attribute of SAFR Communities would be SAFR Buildings and SAFR Infrastructure. Using the same basic framework as presented for SAFR buildings and infrastructure we can infer that SAFR Communities will require sustainable and fire resilient buildings, infrastructure, society and economy, see Fig. 13.16.

SAFR Communities need to include an underlying consideration of both sustainability and fire resilience in their policy and planning documents. These documents can be improved by using this framework as it prompts town or community planners to think outside the box. One poignant example is the tendency to think in terms of single natural hazards. In 2012, the tropical hurricane, Sandy, occurred bringing significant flooding with it. This flooding required a particular type of response and was likely to cause damage to infrastructure making the accessibility of first responders to different disaster scenes difficult. While the community planners had considered both fires and flood, they had no provisions on how to deal with fires in floods or the event of a flood while a major fire was taking place, despite the fact that fire following flooding has been a longstanding concern. When an area floods, there is often loss of electricity and other infrastructure, roads become impassable, and

Fig. 13.16 SAFR communities concept. (Adapted from Meacham, McNamee [12])

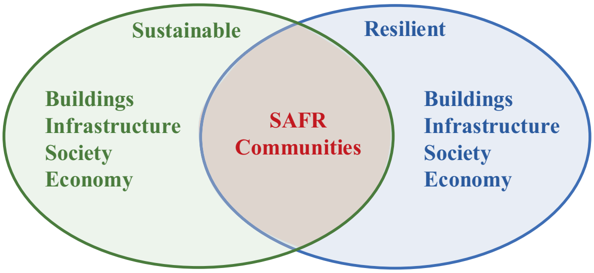

Fig. 13.17 Aerial view of flood and fire damage caused by Hurricane Sandy, Breezy Point Neighborhood, Queens, NY, 2012. (Source: US FEMA, Andrea Booher)

should a fire occur, it can be impossible for the fire service and other emergency responders to undertake their mission.

The fire following the flooding initiated by Superstorm Sandy in 2012 in the US state of New York, occurred in the Breezy Point neighborhood of the borough of Queens [90, 91]. Due the high flood waters, some volunteer firefighters could not respond, and the fire department was unable to get the fire apparatus near the initial fire location. Further, the cause of the fire was the interaction between high levels of sea water and electrical power lines. Given the high winds of the storm, the fire soon spread, ultimately destroying 127 homes. The disaster mitigation planning that had been in place had not considered fire during or following flooding – just flood control. Figure 13.17 shows devastation in Breezy Point as a result of the fire. SAFR Communities, not only respond better to incidents, but through preparation for large scale events, they are also better equipped to recover rapidly.

13.3 Sustainability and Resiliency in Building Regulations

13.3.1 Sustainability and Resiliency – Competing Regulatory Objectives

As introduced in Sect. 13.1 and discussed throughout, there have been historical differences in how concepts of sustainability and resiliency have been perceived, defined, and incorporated into design of the built environment. Historically, resiliency was significantly associated with the ability withstand an event – earthquake, fire, even attack. More robust walls, redundant support systems, use of stronger materials etc. Sustainability, while arguably equally as old a concept as resiliency, has evolved to focus more on resource reduction. Use less materials, create fewer environmental impacts, cause less harm. In this manner there is somewhat of an inherent set of 'competing objectives' – more (strength) versus less (materials). In addition, or perhaps as a result, the focus has been different – resilience being an attribute of structure, sustainability an attribute of energy usage. These factors have resulted in challenges for building regulations with respect to how best to include and balance the concepts.

13.3.2 Sustainability and Resiliency Objectives in Building Regulations Today

Research has found that challenges exist in incorporating sustainability and resiliency objectives into building regulations for both new and existing buildings, and that there is significant diversity between countries [12]. As used here, sustainability objectives reflect the focus on reducing energy usage / energy use impact on the environment as a primary aim, and resiliency reflecting a focus on withstanding disaster (hazard) events.

While it can be argued that different foci can be used, it seems clear with such regulatory instruments as the Energy Performance of Buildings Directive / Regulation in Europe [18, 19], the International Energy Conservation Code in the USA [92], and similar in other countries, that energy reduction is inherently tied to sustainability. Resilience, on the other hand, is often closely associated with the ability to withstand natural and technological hazard events [25, 28, 30, 40].

A 2012 analysis of building code formulation within and outside the Asia-Pacific region explored the extent to which sustainability and resiliency were addressed [38]. In this work (ESCAP Report), four reference countries were selected – USA (California), Singapore, Australia and the United Kingdom – along with five target countries in the Asia-Pacific region – Thailand, India, Bangladesh, the Philippines and Sri Lanka. All building codes were analysed for six elements of environmental sustainability (material conservation, energy conservation, water conservation, soil/land conservation, solid waste reduction and air pollution control) and six elements of disaster resilience (wind loads, snow loads, seismic effects, rain/flood resistance, wildfire and landslide resistance).

With regards to environmental sustainability, the ESCAP report found that this is a relatively new element in Asian building codes and is therefore not well integrated. Of the five target countries, India was the only country that addressed all six elements of environmental sustainability. However, most of the building code is voluntary, and the parts that are mandatory have low compliance levels. The main conclusion regarding disaster resilience is that some hazards have been addressed reasonably well (e.g., storms and typhoons in all codes) and others not, and that a variety of approaches were employed to encourage better disaster resilience (e.g., fiscal incentives (Japan), financial incentives (India), zoning incentives (Republic of Korea) and a combination of all (Singapore). In the end, the analysis suggested that it is possible to improve environmental sustainability and disaster resilience of the built environment in all counties. A significant challenge is to find incentives that work in a specific context considering financing, human capacity, enforcement capacity and stakeholder cooperation, in addition to robust regulation.

Also in 2012, a workshop organized by the U.S. Department of Homeland Security on community resiliency identified a role for codes and standards in disaster resiliency, but found that gaps exist and changes are needed [93].

> Traditionally, building codes have regulated life safety issues. New building codes and standards should extend beyond life-safety aspects to include resilient design concepts in a performance-based approach as well as continuity of operations. They should rely on common and widely adopted methods of measurement, provide a flexible framework to address different facility types, address types of structures (from residential to large commercial and industrial structures), and recognize the differing levels of performance that are required. Uniform adoption of resiliency objectives by jurisdictions requires including resiliency requirements in the current model building codes, educating regulators and their constituents, and incentivizing the application, inspection, and regulation of resiliency approaches. This process begins with the development of criteria, codes, and standards that address resiliency objectives and the supporting tools and validation for their use.

As a means to further facilitate adoption of resiliency into building codes as standards, the U.S. National Institute for Standards and Technology (NIST) identified research needed to facilitate development of guidelines and standards for disaster resilience of the built environment [94]. As with the DHS report noted above, it was identified that performance goals and resilience metrics are needed for all building systems. It was suggested that one starting point would be to identify such goals and metrics in current building codes and standards.

This topic was explored in the USA in a 2014 project by the Fire Protection Research Foundation that identified how disaster resiliency is, and could be, addressed within NFPA codes and standards [95]. The report notes that “applying many of the concepts of resiliency to fire related incidents would introduce some new language but would not radically change the fire safety requirements. It could, however, require more explicit definitions of performance objectives.” This finding is in line with outcomes from a 2010 DHS workshop report noted above and the 2016 assessment [49], which found that overall:

- Mechanisms are needed to define and quantify better levels of tolerable building performance, be they in terms of health, safety, welfare, risk, sustainability or other measures.
- Quantified performance metrics must be developed and incorporated into regulations. Recognizing that some metrics may be best addressed prescriptively (e.g., rise and run of a stair), there remains significant scope for performance measures, for which associated verification methods are needed.
- Tools and methods for helping with the enforcement of performance-based building regulations are still lacking. In part related to the lack of quantified performance measures, those responsible for approval of designs and enforcement of regulations are faced with the challenge of making decisions in the face of significant uncertainty.

Research as recent as 2016 identified that challenges and discrepancies in incorporating sustainability and resiliency into building regulation remain [45]. Much like the outcomes from the 2012 ESCAP study and 2012 U.S. DHS workshop, it was found that although the building regulations in the considered countries included some sustainability and resiliency objectives, these societal objectives were not yet being viewed as having the same level of importance, or equivalent level of social compact between government and the public, as providing for minimum levels of health and safety in buildings. Furthermore, the 2016 research found that holistic or integrated performance (i.e., making sure that adding a new objective does not result in an unanticipated impact somewhere else) – that should be obtained through application of the regulations and guidance – has not yet been fully assessed, creating a potential for unintended consequences.

Unfortunately, 2017 Grenfell Tower fire in London [96–100] illustrated what can happen when building regulations, and the whole of the building regulatory systems, do not holistically reflect the desired performance of buildings from both a sustainable and fire resilient perspective [71]. Moving forward, concepts of sustainability and fire resilient (SAFR) buildings needs to be integrated into building regulatory development. This can be facilitated within a holistic, socio-technical systems approach.

13.3.3 A Socio-technical Approach to Building Regulatory Systems

There are no easy solutions for developing building regulatory systems that are holistic and balancing of multiple objectives, such as sustainability and resiliency, since while the problems are easy to recognise, the solutions are difficult to agree and implement [12, 45, 101, 102]. Often there is not a single policy area which has responsibility. For sustainability, energy, resource management, and environmental regulation have impacts, not just building regulation. For resiliency, planning, zoning, environmental and resource legislation all have a significant effect on the susceptibility of buildings to natural hazard events. If policy makers wish to avoid moving people or restricting expansion into hazard-prone areas (e.g., flood, earthquake or wildland fire prone), that presents limits on regulating against such development. Decision-making in such environments is complex. The challenges become even more amplified when addressing existing buildings, as there can be less regulatory oversight, more extra-regulatory tools in use (e.g., LEED, BREAM), and often less economic capacity to manage change from the ownership side (i.e., older buildings, particularly residential, house a higher percentage of lower income families).

These challenges exist in part because 'newer' objectives such as sustainability are not viewed holistically with existing objectives, such as health and safety, and are 'layered on' rather than integrated into regulation. The relatively recent entry of new policy objectives around sustainability has created a wide range of fire resiliency challenges, from regulatory development to enforcement, to design, to operational safety, with potentially the most significant issues around existing building stock and trying to assure regulatory and market instruments adequately address the spectrum of policy objectives without increasing hazards, risks or costs, or decreasing building performance [12, 45]. The literature suggests that one step that can be taken towards resolving these challenges is better engagement of stakeholders, better characterization of use of risk and hazard data, and better clarification of roles, responsibilities and accountabilities of system actors through implementation of a socio-technical systems approach to building regulation and design of complex systems [57, 71, 100].

Socio-technical systems (STS) theory developed from studies of organizations that identified linkages between social and technological components, whether at an individual organizational level or as a collection of organizations and institutions operating at the overall level of society [57]. Building regulatory systems reflect well the STS concepts at the societal level when considering the interaction of actors (stakeholders), institutions and innovation in defining and achieving acceptable building performance in both regulatory and market environments [56, 57, 71].

It is important to think of building regulatory systems as STS especially in times of rapid system change and increases in complexity, either in regulation, technology or both, since systems that are not structured to consider influence across the institutional or actor levels can lead to failures [56, 72, 73]. When all parts are simple, adherence to the rules without deviation is likely and adequate, so prescriptive regulation works well. As complexity of the system increases (buildings, technology, regulation), specification of every detail is not possible, and solely identifying minimum requirements may be inadequate. The combination can lead to noncompliance with simple rules and incomplete consideration of competing objectives in complex systems.

As complexity increases, information associated with deviations from the simple approaches needs to get to all pertinent actors, many of whom will be working within different parts of the systems. This might not occur in an adequate manner if the speed of change is fast paced compared to the institutional structures. As a result, external factors may influence the system at a faster pace than originally anticipated, rendering the system ill-equipped to deliver on its target objectives. A more holistic, integrated, STS approach to building regulation, and the whole of the building regulatory system can help [56].

The Socio-Technical Building Regulatory System (STBRS) model developed by Meacham and van Straalen [57] was adopted from the system model outlined by Petak as applied to environmental management [101] and earthquake resiliency [102]. This foundation was seen as a suitable framework for describing building regulatory systems as STS, and for illustrating how that structuring could facilitate incorporation of risk as the basis for performance requirements in next-generation performance-based building regulation. In the original form [57], the STBRS model focused fire as a hazard of concern, noting that other hazards could be considered in a similar manner (as Petak did for earthquake hazards). To illustrate how not only other hazards, but other societal objectives, could be addressed within the STBRS framework, the model has been modified.

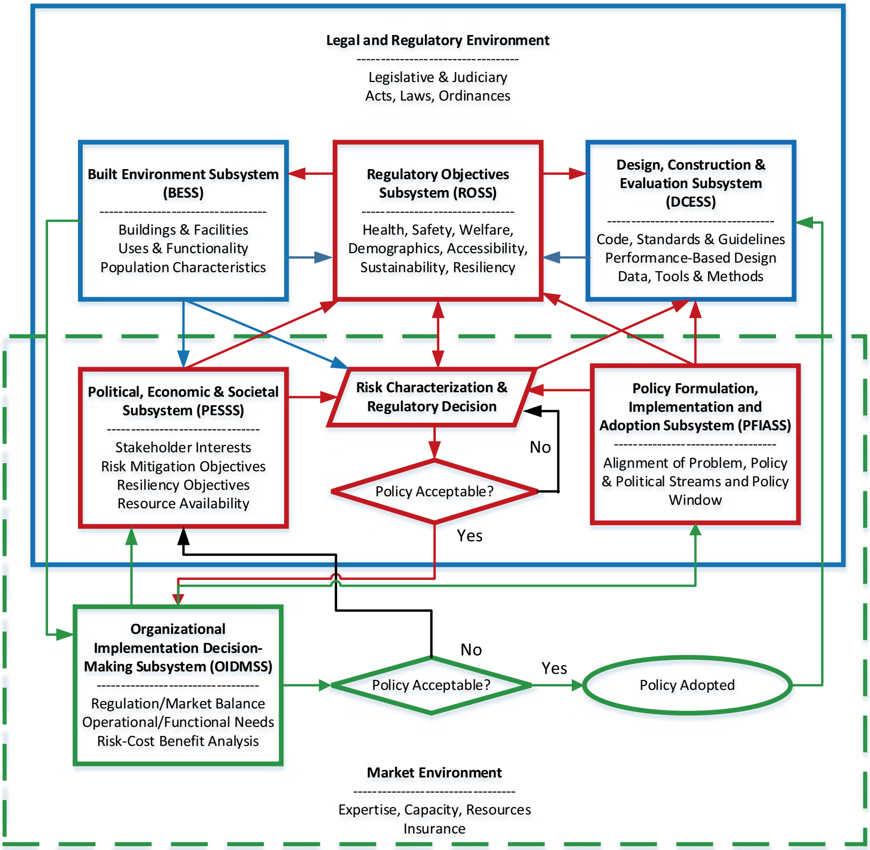

Fig. 13.18 High-level illustration of STBRS interactions. (Figure from Meacham, Van Straalen [57]. Reprinted by permission of Taylor & Francis Ltd. https://www.tandfonline.com)

As in the original STBRS framework, there are two operational environments, ‘Legal and Regulatory’ and ‘Market’, along with an ‘interactions’ environment within which decisions are made. Within each environment are several subsystems. In this iteration, the Fire Hazard Subsystem (FHSS) has been replaced by a Regulatory Objectives Subsystem (ROSS). All other subsystems remain the same (Built Environment (BESS), Design, Construction and Evaluation (DCESS), Political, Economic and Societal (PESSS), Policy Formulation, Implementation and Adoption (PFIASS), and Organizational Implementation Decision-Making (OIDMSS). Figure 13.18 illustrates the high-level interactions between the sub-systems.

There are many interactions between the subsystems, each of which is itself a socio-technical system. A few of the interactions are described here to help illustrate how the framework can be used. More detail can be found in [57]. The ROSS, PESSS and PFIASS interact with each other to describe/define regulatory objectives, facilitate risk characterization and develop regulatory decision, taking account of political, economic and social influences. The ROSS, BESS and DCESS interact

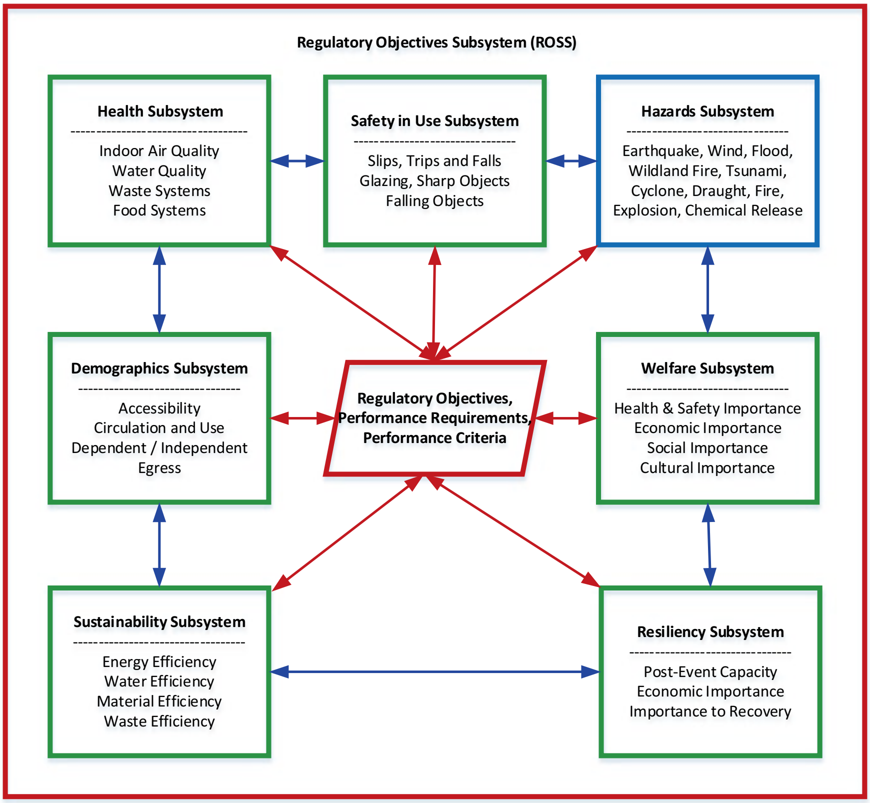

Fig. 13.19 ROSS interactions

to describe how regulatory objectives are translated into such aspects as building use classifications, population characteristics, and such within the regulations, codes, standards and guidelines used to design buildings. The policy decisions and supporting regulatory instruments are vetted and balanced with market options in the OIDMSS. In the model it is recognized that standards are developed in the private sector, and may or may not become part of the regulatory environment, as they may be used on a voluntary basis. However, the placement of standards within the DCESS reflects the role they play within the regulatory environment, and how their development is influenced by other subsystems.

Focusing in on the ROSS, one can envision both the diversity in regulatory objectives, and the need for these objectives to be considered holistically. This is shown in Fig. 13.19.

In brief, while regulatory objectives are nominally focused on diverse areas, such as health, safety and sustainability, they must be considered together, so as not to create 'competing' objectives, such as inadvertently permitting combustible thermal insulation for energy efficiency, resulting in an unintended increase in fire hazard, or permitting the use fire retardant chemicals in foam insulation, which might create unintended human health hazards. In order to minimize the potential for such competing objectives and unintended consequences, the regulatory objectives, performance requirements and criteria need to be developed in an integrative and comparative manner. There will be need for iteration between objectives, and as associated with the risks and risk perceptions through interaction with PESSS and PFIASS during this process (Fig. 13.18).

13.4 Summary

The comparatively recent introduction of sustainability objectives to building regulation, facilitated by environmental impact concerns and fossil fuel energy shortages in the 1970s, and more recently by climate change impacts associated with buildings, has created the potential for competing objectives and unintended consequences as related to building performance. One area in which impact has been observed is an increase in fire hazard protection, which is a decrease in fire safety resilience. However, buildings need to be sustainable and fire resilient, which means a change in thinking and approach is needed. This need for a new approach extends beyond buildings to infrastructure and communities as well, encompassing an approach to a SAFR Built Environment.

This chapter has discussed the concepts of sustainability and resiliency as used within the built environment – buildings, infrastructure and communities – and has presented discussion of how a SAFR Built Environment approach to planning, design and regulation can result in a built environment that more holistically meets the fire safety and sustainability needs and expectations of society.

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