Civil Protection, Disaster Management, and Resilience

TEXTBOOK



Aurélia Bony-Dandrieux
Ingrid Canovas
Laurent Aprin *Editors*

# Industrial Hazards

## From Physical Understanding to Risk Management

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# Civil Protection, Disaster Management, and Resilience

## Volume 7

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Aurélia Bony-Dandrieux · Ingrid Canovas · Laurent Aprin
Editors

# Industrial Hazards

## From Physical Understanding to Risk Management

Funded by the European Union

Springer

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# Foreword by the Commissioner to the EUMA Book Series Volumes

Crises today are more complex and interconnected than ever before.

The world is warming at an unprecedented pace, especially in Europe, with global temperatures now approaching 1.5 °C above pre-industrial levels. In this context of growing geopolitical uncertainty, the need for strong preparedness and response systems has never been clearer.

Recent record-breaking wildfires, floods and other extreme weather events—all linked to climate change—illustrate the mounting impact of a heating planet and the urgency of building resilience not only to natural disasters but also to human-made crises such as conflict.

One of the European Commission's top priorities is to strengthen crisis management and civil preparedness across Europe—to move from reacting to crises to being ready for them. This means fostering a genuine culture of preparedness and resilience, one that is woven into every part of our societies—from schools and communities to governments and businesses.

But we cannot do this alone. Collaboration is key—and the academic community has a crucial role to play. By educating students and practitioners in Disaster Risk Management, universities help us raise awareness, build a shared understanding of the risks we face and inspire the innovation and mindset needed to turn preparedness into a way of life.

This book series marks an important milestone for the EUMA project—Creating a European Higher Education Network for Master's Programmes in Disaster Risk Management—and for the postgraduate Master's degree in International Disaster Management and Civil Protection it has developed.

Supported by the EU's preparedness capacity-building tools, the EUMA series represents a renewed drive to bring research, innovation and practical action closer together. It reflects the European Commission's commitment to embedding knowledge-based strategies into preparedness and response, and demonstrates the concrete value of EU programmes that strengthen our collective resilience.

The Preparedness Union Strategy is our compass—guiding us towards a new level of collective readiness that is proactive, interconnected and truly integrated.

This book series supports one of its key actions: bringing preparedness into education. By focusing on higher education and developing a robust Master's programme, the EUMA project has helped build a holistic approach to preparedness—one that equips future generations with the knowledge and skills needed to manage disaster risks effectively.

I want to warmly congratulate all those who contributed to this series. I am confident that your work will offer valuable insights for our shared mission—a safer and better-prepared Europe.

As the risks we face become ever more complex, we remain committed to deepening partnerships with academic and research institutions, and to promoting lifelong learning. Together, we can harness knowledge and innovation to build a resilient Europe—one that is always ready for what lies ahead.



Brussels, Belgium

Hadja Lahbib
European Commissioner for Equality
Preparedness and Crisis Management

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Within the framework of the EUMA project, a curriculum for a new international Master's programme (M.Sc.) has been developed. The postgraduate Master programme, entitled **'International Disaster Management and Civil Protection'**, will be launched in **October 2026** at the **Postgraduate Center of the University of Vienna**.

Building on the outcomes of EUMA, the follow-up project **EUMAplus—'Creating Open Access Digital Educational Material in Disaster Risk Management and Civil Protection' (2026–2027)** is developing open access teaching and learning materials.

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# 1 Introduction: Understanding and Managing Industrial Hazards

Ingrid Canovas and Aurélia Bony-Dandrieux

**Abstract**

Industrial societies rely on complex technological systems that inherently generate systemic risks, as illustrated by major accidents such as Seveso, Bhopal and Deepwater Horizon. These events reveal that industrial disasters stem from interacting technical, organisational and environmental vulnerabilities rather than isolated failures. The European Seveso Directive provides a regulatory framework for preventing such accidents through hazard assessment, land-use planning, emergency preparedness and public information. Over time, risk analysis has evolved from reactive approaches to structured methodologies integrating human and organisational factors and fostering continuous improvement. Scientific understanding of explosions, fires and hazardous releases forms the basis for effective prevention and mitigation. Beyond industrial sites, technological risks increasingly involve marine pollution and NaTech events, both intensified by climate change. Managing these multi-scale hazards requires combining quantitative modelling, environmental knowledge and territorial governance. The chapter outlines this evolution and the need for integrated, adaptive technological risk management.

**Keywords**

Technological risk management • Industrial hazards • Risk analysis • NaTech hazards

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## 1.1 Industrial Activities and Systemic Technological Risks

Our contemporary societies rely on numerous and varied industrial activities: petrochemicals, chemicals, automotive, aeronautics, etc., which are based on technical production or processing systems that can be highly complex and contribute to technological risks. They arise from the intricate interconnections between human activities, industrial systems and the environment, and they embody both the creative potential and the destructive power of technological progress. Over recent decades, major accidents such as Seveso (1976), Bhopal (1984), Chernobyl (1986), Toulouse (2001), Deepwater Horizon (2010), Beirut (2020) and Leverkusen (2021) Aqaba 2022 have repeatedly demonstrated that industrial and technological failures can have severe and long-lasting effects on human health, ecosystems and economies. These events have also shown that accidents rarely result from a single technical defect or human error but rather from the convergence of multiple weaknesses—technical, organisational and institutional—within complex systems. They also demonstrate that several accidental phenomena can combine during such events (explosion and fire, fire and toxic gas dispersion, fire and marine oil spill, etc.)

## 1.2 Regulatory Framework and Prevention Principles

To prevent such major accidents and limit their consequences and harmful impacts, European member states adopted the Seveso Directive in 1982, most recently revised in 2012 (the latest version Directive 2012/18/EU is known as Seveso 3). The directive requires operators of installations to take all necessary measures to prevent accidents and limit their consequences by addressing 'assessment and management of hazards and risks, emergency planning, land use planning, inspections, information to the public, and accident investigation and reporting' (European Commission, 2023) (https://minerva.jrc.ec.europa.eu/en/content/minerva/ff6958de-16ad-455e-94f6-764e56668f58/the_seveso_directive).

To define and implement the most appropriate prevention and protection measures, it is essential to understand the circumstances/sequences or combination of events that can lead to a major accident which requires the use of risk analysis methods (Chap. 2). Secondly, the hazardous phenomena themselves must be fully understood: the conditions under which they occur, how they spread in the environment and their potential consequences for human health, the environment and property (Chaps. 3 to 6).

## 1.3 Evolution of Risk Analysis Methods

With this in mind, this book aims to provide some basic concepts of risk analysis and hazardous phenomena (explosions, fires, marine pollution). The scientific and technical foundations of risk management have evolved substantially since the emergence of industrial safety as a field of engineering.

Early approaches were primarily reactive, developed in response to accidents that revealed the vulnerabilities of industrial processes.

Over time, these approaches became structured into formalised methodologies designed to identify hazards, estimate their likelihood and assess their potential consequences (Chap. 2). Techniques such as Preliminary Hazard Analysis (PHA), Failure Modes and Effects Analysis (FMEA), Hazard and Operability Studies (HAZOP), and fault or event tree analysis have provided systematic frameworks for examining how failures can propagate within complex systems. These methods aim not only to quantify risk but also to guide decision-making by identifying preventive and protective barriers capable of breaking the chains leading to accidental phenomena.

Risk analysis methods have progressively integrated organisational and human dimensions, acknowledging that safety cannot be guaranteed by technical systems alone. The reliability of industrial operations depends as much on human behaviour, communication, maintenance and organisational learning as on design and automation. As a result, risk management has shifted from a compliance-oriented approach to a proactive and adaptive one, seeking to reduce risks to acceptable levels through continuous improvement, feedback and anticipation. This evolution reflects the broader transformation from traditional industrial safety to an integrated vision of risk management encompassing environmental protection, emergency response and resilience.

## 1.4 Scientific Understanding of Accidental Phenomena

The study of accidental phenomena provides the scientific basis for understanding how risks materialise. Explosions, fires and releases of hazardous materials remain the most common and destructive types of technological accidents.

Explosions, for example, can result from mechanical rupture, phase transitions or uncontrolled chemical reactions (Chap. 3). Their destructive power derives from the rapid conversion of energy into overpressure waves capable of devastating structures and injuring people. Understanding their dynamics requires knowledge of thermodynamics, fluid mechanics and combustion science, and its physics even well-known from a global point of view still requires constant reviews as new materials, processes, and technologies emerge.

Fires represent another fundamental and widespread hazard in industrial environments (Chap. 4). Their propagation depends on a combination of factors: ignition sources, fuel

characteristics, confinement and environmental conditions. The analysis of heat transfer, flame dynamics and radiative fluxes is essential for designing effective protection systems such as sprinklers, water curtains and thermal insulation. Fire safety engineering also emphasises the importance of scenario-based modelling to anticipate possible domino effects, in which a local fire can trigger explosions or secondary releases. The expertise of these physical processes, coupled with well-designed emergency response strategies, forms the core of industrial fire prevention and mitigation.

## 1.5 Broader Environmental Dimensions and Multi-scale Risk Governance

Beyond industrial site boundaries, technological risks extend into natural and maritime environments. Accidental marine pollution illustrates the transboundary and ecological dimensions of technological hazards (Chap. 5). While the number of major oil spills has decreased significantly over recent decades due to stricter regulations and improved ship design, the maritime transport of hazardous and noxious substances (HNS) introduces new types of risks that are less visible but potentially more harmful. Chemical spills at sea may not produce the dramatic images associated with oil slicks, yet they can cause long-term ecological damage, contaminate marine food chains and affect coastal communities. The complexity of these accidents lies in the diverse physical and chemical behaviours of substances (floating, dissolving, sinking, evaporating or a mix of these behaviours) and in the difficulty of detecting and tracking them.

Furthermore, the diversification of transported substances, the rise of alternative fuels such as LNG or ammonia and the opening of new maritime routes under climate change continue to challenge existing systems. Accidental marine pollution thus exemplifies the need for continuous adaptation of risk management frameworks to evolving technological and environmental realities.

An increasingly important dimension of technological risk arises from the interactions between natural hazards and industrial systems. These so-called NaTech events—Natural Hazard Triggering Technological Accidents—occur when floods, earthquakes, lightning or wildfires compromise the integrity of industrial assets, leading to secondary technological disasters. Climate change, by intensifying the frequency and severity of natural hazards, is amplifying the likelihood of such compound events. Wildfires in particular have become a growing threat in many regions, affecting refineries, storage tanks and chemical facilities located near forested areas. The analysis of the impacts of forest fires on industrial assets reveals the complex link between natural processes and technological vulnerabilities (Chap. 6). These approaches illustrate the integration of environmental science and process safety engineering required to address emerging multi-hazard scenarios.

Technological risk management today must therefore operate across multiple scales, from the micro-level of component reliability to the macro-level of territorial resilience.

It combines quantitative modelling, empirical knowledge and organisational learning. At the industrial site scale, this involves maintaining barriers, monitoring process parameters and fostering a strong safety culture. At the territorial scale, it requires a robust risk culture among the population, cooperation among operators, authorities and communities to manage land use, emergency preparedness and communication.

Thus, throughout its five chapters, this book traces a coherent path from analytical methods to concrete phenomena, from industrial processes to environmental and systemic dimensions. Each contribution combines scientific rigour with practical insight, reflecting the diversity of skills required to understand and manage today's technological risks.

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# Fundamentals of Risk Analysis Methods

2

Jérôme Tixier

**Abstract**

This chapter provides an examination of the main risk analysis methodologies applied in industrial and socio-technical contexts. It defines risk as the interaction between hazards, stakes and vulnerabilities, emphasising the assessment of both probability and consequence. The chapter highlights the strategic importance of risk analysis for regulatory compliance, operational reliability and stakeholder trust. A structured fourteen-step process is proposed, from defining objectives to validating mitigation measures. The document distinguishes between table-based methods and tree-based methods, outlining their principles, advantages and limitations. Table-based methods enable systematic scenario identification, while tree-based approaches facilitate causal reasoning and graphical representation of accident sequences. Key limitations include data uncertainty, methodological complexity and dependency on expert knowledge. Despite these constraints, risk analysis remains a central decision-support tool. It fosters continuous improvement of safety and enhances organisational learning.

**Keywords**

Risk assessment • Table-based methods • Tree-based analysis • Scenario modelling • Matrix

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## 2.1 Introduction

### 2.1.1 General Aspects

The characterisation of hazardous events and their impacts is based on three fundamental concepts: hazard, stakes and risk. These concepts form the basis of prevention and protection policies implemented at various territorial and sectoral levels.

Hazard is defined as the probability of occurrence, in a given space and time, of a potentially damaging natural or anthropogenic phenomenon. According to the United Nations International Strategy for Disaster Reduction (UNDRR) (UNISDR, 2009), it can be characterised by its intensity, duration, frequency and spatial extent. The stakes correspond to all the people, infrastructure, economic activities, heritage or ecosystems exposed to this hazard. Their vulnerability reflects their degree of sensitivity to damage and their capacity for resilience in the face of the undesirable event.

Risk results from the interaction between the hazard and the assets at stake. ISO 31000 (ISO, 2018) defines risk as 'the effect of uncertainty on objectives', which implies both the probability of an event occurring and the severity of its consequences. In the industrial sector, the European Seveso III Directive (2012/18/EU) (EU, 2012) requires operators of high-risk facilities to carry out hazard studies that include the identification of technological hazards and the assessment of vulnerable assets.

Furthermore, analysis of various industrial accidents with major consequences (human, environmental or financial) highlights that a lack of analysis and understanding of how the activity works, practices that differ from those prescribed, contradictions in the texts governing operations, design problems, maintenance issues, lack of training or skills can contribute to the occurrence of a sequence of more or less complex events leading to a major accident.

Risk management is therefore a major challenge for the proper functioning of a socio-technical system to try to ensure its stability and sustainability and thus provide help with decision support to manage risk. To do this, it is essential to understand how a particular undesirable event can occur and to assess its consequences in terms of severity or occurrence to make informed decisions to best manage the risks of a given situation. Risk analysis is one of the best tools for this.

The purpose of risk analysis is to identify and represent all possible paths leading to an accident scenario with consequences for the system itself or for the territory concerned. The main idea behind implementing this type of approach is to propose a systemic approach to ensure that the right dangerous situations are managed. Indeed, partial identification of possible accident scenarios can lead to inadequate risk management in the sense that events contributing to the occurrence of the major event would not be managed. The implementation of a risk analysis leads to a set of situations with varying levels of hazard, and as already mentioned above, it is essential to manage the situations with the greatest impact in terms of risk. This is why two concepts must be introduced: assessment and

acceptability. Assessment is necessary to classify the various scenarios obtained, as there may be many of them and it would be unrealistic to try to control everything. It should not be forgotten that the purpose of risk analysis is to support the activity. Generally, this assessment will be qualitative or quantitative, based on the severity of the consequences of the scenario and the probability of its occurrence. Once these scales have been chosen or built, it is necessary to define an acceptability threshold, i.e. the point from which the probability-severity pair is considered tolerable or justifiable. This acceptability threshold may be defined by the competent authorities (regulations) and/or by the company itself (management policy of the company).

These initial steps make it possible to highlight a list of risk scenarios for which technical and/or organisational risk control measures must be defined.

### 2.1.2 Reasons to Implement a Risk Analysis Method

The risk analysis approach has a significant cost in terms of human and financial investment, so it requires great commitment from plant operators. The potential benefits are as follows:

- to meet the requirements of the company's HSE policy,
- to meet the requirements of the administration,
- to establish emergency plans,
- to strengthen the confidence of internal and external stakeholders,
- to meet the requirements of insurers.

### 2.1.3 Main People Involved in Risk Analysis

Several individuals or entities of an organisation may contribute to a greater or lesser extent to the analysis. This may include people who formulate or express a need or expectation, experts who provide data for analysis, or people who operate the technical system. The following entities may be involved:

- Safety authorities.
- A developer or project owner responsible for the system.
- Independent organisations in charge of evaluating safety constructions.
- One or more project managers who design and build all or part of the system.
- At least one operator or user (not necessarily physically present during the design and study phases). Generally, these individuals are responsible for system maintenance.
- Possibly control bodies that will intervene after commissioning and throughout the life of the system to ensure compliance with safety requirements subcontractors.

Only some of these entities will be part of the risk analysis team; others may provide the necessary data.

### 2.1.4 Main Limitations of Risk Analysis Methods

One of the first limitations of the methods is the level of granularity of analysis that they allow. If the analysis is based on a macroscopic approach, it will not be possible to consider in detail the specificities of the activity being analysed. This type of approach has the advantage of being transferable to a wide variety of activities. Conversely, if it is based on a very detailed and specific analysis, it will yield more accurate results because it is closer to the actual functioning of a specific activity, but the approach will be difficult to transfer to other types of activity (Tixier et al., 2002).

A second limitation concerns the data used, particularly its availability, completeness, accuracy and updating, as systems evolve during design and use. There are two main categories of data: technical data and organisational or human data. It is essential not to neglect the human factor in these analyses, as most major accidents are caused by human error or failure (Tixier et al., 2002).

A third limitation concerns the skills required to carry out this analysis and the time needed to do so, which is often quite considerable. Indeed, risk analysis cannot be carried out by a single person as it requires a multi-perspective approach from the operator to the manager. Indeed, while the tools used in risk analysis may appear simple, their implementation can be quite complex and benefit from the use of a methodological framework. Therefore, a risk analysis specialist should be included in the working group to obtain relevant results (Tixier et al., 2002).

### 2.1.5 Main Steps in a Risk Analysis Process

A risk analysis process is usually based on 14 steps:

1. Obtain the requirements from your line manager or a competent authority, for example.
2. Identify the stakeholders involved in carrying out the risk analysis by asking yourself what skills are needed to carry out this analysis.
3. Set up the working group, plan the risk analysis and define the expected outcomes.
4. Define a shared objective: purpose and scope of the analysis.
5. Describe the analysed system in terms of subsystems: what is the relevant level of granularity?

These initial steps enable the working group to develop a shared vision of both the objective and the subject of the study. This may seem trivial, but it is essential because it ensures that all those involved share a common understanding of the problem.

6. Choose a risk analysis method which determines the results of the analysis and the data required.
7. Choose or construct a rating scale that is representative of the consequences of events likely to be caused by the system under study and/or the probability of these events occurring.
8. Define an acceptability level of risk. This threshold must be carefully considered, as it will contribute to excluding several scenarios (known as residual risk) for which no preventive or mitigating measures will be taken.
9. Collect the necessary information data (feedback, plans, organisation, data process, etc.).
10. Implement the risk analysis method, prioritising group work.
11. Classify each scenario.
12. For unacceptable scenarios, propose risk mitigation measures to reduce them to an acceptable level.
13. Have the proposed measures been approved by management (financial cost, security policy, etc.)?
14. Obtain the validation of this risk assessment from stakeholders such as the relevant authorities as part of a hazard study, for example.

The results of the analysis help managers to demonstrate risk management for a given activity.

### 2.1.6 Fundamental Risk Analysis Methods

There are several risk analysis methods commonly used:

- PHA (Preliminary Hazard Analysis) is generally used for less complex installations or for a broad study of a more complex system.
- FMEA (Failure Mode and Effects Analysis) is generally used for specified sub-assemblies to identify the failure modes that are likely to occur.
- HAZOP (Hazard and Operability) is dedicated to thermo-hydraulic systems.
- FTA (Fault Tree Analysis) which is based on a tree diagram, identifies the causes and conditions of a particular failure or event.
- ETA (Event Tree Analysis) which is also based on tree representation, identifies events following failure.

These analysis methods can be either qualitative or quantitative, deductive (starting from the effects and working back to the causes such as the fault tree analysis method) or inductive (starting from the causes to identify the effects such as ETA, PHA, FMECA and HAZOP) but also based on simple or combined failures (fault tree method).

This last criterion is quite important because, based on experience, a single failure is unlikely to lead to major consequences. This draws the user's attention to the level of granularity of the analysis, because if it is too macroscopic, the sequence of events leading to major consequences will not be described in sufficient detail, making it difficult to propose appropriate risk control measures. Nevertheless, these methods make it possible to begin constructing fragments of scenarios, which will be very useful for building, for example, a fault tree.

To help the group conduct the most comprehensive analysis possible, the methods rely on lists of hazards or potential sources of hazards, such as electrical hazards (risk of electrocution, overheating); mechanical (risk of cuts, impacts, breakages); chemical (risk of corrosion, poisoning, explosion, etc.); biological (risk of illness, poisoning, etc.); fuel-related (risk of fire, overheating, etc.); atmospheric (risk of asphyxiation, etc.). For a more complete list of hazard sources, see MOSAR (Organised Systemic Risk Analysis Method) (Perilhon, 2000).

Next, we propose to further describe certain methods by dividing them into two categories: table-based methods and tree-based methods.

## 2.2 Table-Based Methods

Table-based methods include PHA, FMECA and HAZOP and its derivative, the What If method. For all table-based methods, there is a set of common steps regardless of the approach chosen.

The first of these concerns the definition of the objective. As mentioned above, the objective stems from an expressed need and must be understood and shared by all stakeholders involved in the risk analysis.

The second step involves defining the system under study. This definition is crucial because it will determine the resulting risk control. It must be carefully considered, understood and interpreted in the same way by all those involved in the analysis project.

The definition of the system can be based on the constituent elements of the system (technical, human and organisational) and their interactions, on the conditions surrounding the system in the different phases of its life cycle (environment, aggressions, etc.) and on the conditions of its use, operation, maintenance and even withdrawal from service.

This will make it possible to define the scope of the system under study and divide it into subsystems for analysis to conduct a systemic risk analysis.

The risk analysis tool itself takes the form of a table, the specifics of which will vary depending on the method used. Each of the table-based approaches will be presented in the following paragraph.

Finally, the last step common to all methods concerns the tools for classifying and assessing the acceptability of the situations identified during the analysis. Generally, this will be based on two scales, one concerning the severity of the consequences and the other the probability of the consequences, and on the concept of an acceptability threshold/limit. These three concepts are formalised through a matrix known as a risk, criticality or acceptability matrix.

Although the so-called 'table' methods share a common methodological framework, as discussed above, each has specific characteristics that determine its use, effectiveness and limitations.

### 2.2.1 PHA Method

Preliminary Hazardous Analysis (PHA) (Mortureux, 2020a) is a generalised, qualitative approach implemented from the early stages of system design. Its appeal lies in its simplicity and speed of implementation, allowing for broad identification of potential hazards. However, its scope remains limited due to its global nature, which does not always allow for accurate anticipation of complex scenarios.

The objective of a PHA is to identify the causes of a major event or hazardous situation to propose risk control measures for situations deemed unacceptable.

In a first step, it is necessary to establish the risk/criticality matrix, which is constructed based on three elements: a severity scale, a probability of occurrence scale and an acceptability threshold.

When severity and probability scales do not exist in the organisation or in regulatory documents, it is advisable to construct them with an even number of levels (to reduce the use of the middle level). In addition, each level must be qualified and/or quantified to clearly explain the different levels according to the system in question and the objective of the study. Once the matrix has been defined, the acceptability threshold must then be defined. To do this, the analysis group must define for each pair (severity, probability) whether the situation is acceptable or not (Table 2.1).

The concept of time can also be used to define the threshold. Certain situations can be considered acceptable in the short term. This gives us a matrix with two zones: acceptable as is, acceptable in the short term and unacceptable. This threshold represents the level of risk control desired by the entity coordinating the analysis.

At this stage, all the elements are ready for the risk analysis to be carried out, i.e. identifying cause/consequence pairs (scenarios) for each subsystem, which can be rated using severity and probability scales, and placing each scenario in the matrix to identify whether it is acceptable or unacceptable. To construct these scenarios, the analysis

**Table 2.1** Example of a matrix with an acceptability threshold for PHA

| Severity<br>Probability | Catastrophic | Serious | Significant | Minor |
|---|---|---|---|---|
| Almost certain | Unacceptable | Unacceptable | Unacceptable | Acceptable |
| Likely | Unacceptable | Unacceptable | Acceptable | Acceptable |
| Unlikely | Unacceptable | Acceptable | Acceptable | Acceptable |
| Rare | Acceptable | Acceptable | Acceptable | Acceptable |

*Source* Adapted from Mortureux (2020a)

**Table 2.2** Example 1 of table for PHA

| Subsystem or equipment | Cause | Consequence | Severity | Probability | Acceptable Y/N | Risk control measures |
|---|---|---|---|---|---|---|
| Road adhesion system | Excessive tyre wear | Loss of control of the car | Important | Low | No | Visual inspection, training, regulations |

group will complete a PHA table during a working session. Two versions of the table are presented below (Tables 2.2 and 2.3).

The use of the first table reinforces the fact that a cause generates a consequence (the concept of simple failure, which is one of the limitations of these table-based approaches), providing a very macroscopic view of the scenarios. The second table allows for an initial sequence of elements (events causing a hazardous situation/hazardous situation/event causing an accident), which makes it possible to describe slightly more realistic scenarios.

One piece of advice to limit the effects of the simple failure approach is to adopt a level of analysis that allows a consequence to become a cause in the line below. This allows for short, interconnected scenario elements, thus providing a better representation of the sequences that can lead to an undesirable event.

Once this list of short scenarios is established, each will be judged acceptable or unacceptable. An acceptable scenario is a risk assumed by the entity that conducted the analysis. It is important to remember that, firstly, zero risk does not exist (it can only be approached based on the entity's willingness to invest in security) and, that the person carrying out the analysis is there to support an activity pursuing various objectives (financial, social, political, etc.), with security being only one element among others in the decision-making process.

For scenarios deemed unacceptable, risk control measures must be implemented such as risk elimination, prevention measures, protection actions or risk transfer.

**Table 2.3** Example 2 of table for PHA

| Subsystem or equipment | Phase | Hazardous entity | Event causing a hazardous situation | Hazardous situation | Event causing an accident | Accident | Consequence | Severity | Probability | Acceptable Y/N | Risk control measures |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Road adhesion system | While driving | Road adhesion system | Excessive tyre wear | Running off the road | Loss of control of the car | Collision with tree | Serious injuries | Catastrophic | Low | No | Lane keeping system |

Regarding elimination actions, the following questions should be answered: can the element generating the hazard be replaced/modified/substituted with another less dangerous element? If feasible, the technical feasibility of this modification is examined and implemented. It is rare for an industrial system that has been in place for many years to be able to apply this risk management solution, but it is the most effective because it eliminates the risk.

The second phase will focus on prevention and/or protection measures. There are two or three options: reducing the severity, reducing the probability, or reducing both. Preventive action reduces the probability of undesirable events occurring. Protective action reduces its severity. The choice between prevention and protection measures must be based on the effectiveness of the measures and their cost in achieving an acceptable level of risk. In general, manufacturers favour prevention measures while first responders such as firefighters prefer protection measures to reduce the severity of an incident, because by the time they intervene, the undesirable event has already begun.

The final measure consists of transfer, which will not reduce the severity or probability but will mitigate the costs associated with the undesirable event and its consequences.

Once all these steps have been completed, the result obtained by the PHA al-lows for the systematic construction of short scenarios and demonstrates the level of risk control.

### 2.2.2 FMECA Method

Failure Mode, Effects and Criticality Analysis (FMECA) (Goddard Technical Handbook, 2024; Ridoux, 1999) is a more structured and detailed method, focused on the systematic study of the possible failure modes of a component or process. It allows failures to be prioritised according to their severity, frequency and detectability. Its main advantage lies in its rigorous framework for prioritising corrective actions. However, it is often time-consuming, depending on the availability of resources and may be unsuitable for highly complex systems where modelling multiple interactions is difficult.

The severity scale is constructed in the same way as for a PHA, but with a particular focus on the functioning of the system. The scales of Severity, Probability and Detectability are linked in their definition so the examples of them come from the same author (Ridoux, 1999). Therefore, the concept of downtime is generally included, as illustrated in Table 2.4.

The second scale is constructed based on the concept of failure detectability. An example is presented in the following Table 2.5.

The third scale is constructed based on the concept of failure frequency. An example is presented in the following Table 2.6.

Ultimately, criticality is assessed as the product of severity, frequency and detectability, and the concept of acceptability is defined in relation to a threshold value. For this approach, it is important to precisely define the following two terms:

**Table 2.4** Example of severity scale for FMECA

| Severity value | Severity of the failure |
|---|---|
| 1 | Minor failure: no significant damage to equipment (e.g., IT 10 min) |
| 2 | Moderate failure requiring short-term repair (e.g., 10 min < IT ≤ 30 min) |
| 3 | Major failure requiring long-term intervention (e.g., 30 min < IT ≤ 90 min) or non-compliant products identified and corrected during process |
| 4 | Very critical catastrophic failure requiring major intervention (e.g. IT > 90 min) or non-compliant product identified by customer internal to the company or Significant material damage (safety of goods) |
| 5 | Safety/quality: accident that could cause safety issues or non-compliant product sent to customer |

*Source* Adapted from Ridoux (1999)

**Table 2.5** Example of detectability scale for FMECA

| Detectability value | Detectability of the failure |
|---|---|
| 1 | The measures taken ensure complete detection of the initial cause or mode of failure, thus preventing the most serious effect caused by the failure during production |
| 2 | There is a warning sign of the failure, but there is a risk that this sign will not be noticed by the operator. Detection is actionable |
| 3 | The cause and/or mode of failure are difficult to detect, or the detection elements are not very actionable. Detection is poor |
| 4 | There is no way to detect failure before the effect occurs: this is the case without detection |

*Source* Adapted from Ridoux (1999)

- Failure: cessation of a component's ability to perform a required function.
- Failure Mode: effect for which a failure is observed (does not start, remains in open/closed position.

Then, for each failure mode observed, Table 2.7 can be completed.

As with PHA analysis, performing a FMECA demonstrates control over the identified short scenarios.

**Table 2.6** Example of frequency scale for FMECA

| Frequency value | Frequency of the failure |
|---|---|
| 1 | Failure virtually non-existent on similar installations in operation, at most one fault over the lifetime of the installation |
| 2 | Failure rarely occurring on similar equipment in operation (e.g. one fault per year) or component of a new technology for which all conditions are theoretically in place to prevent failure, but there is no experience with similar equipment |
| 3 | Failure occasionally occurring on similar equipment in operation (e.g. one fault per quarter) |
| 4 | Failure frequently occurring on a well-known component or on similar equipment in service (e.g. one failure per month) or component of a new technology for which not all conditions are met to prevent failure, and there is no experience with similar equipment |

*Source* Adapted from Ridoux (1999)

### 2.2.3 HAZOP Method

The HAZOP (Hazard and Operability Study) (Crawley & Tyler, 2015; Royer, 2009) method is particularly relevant to thermo-hydraulic systems. Based on the analysis of deviations from normal operating conditions, it uses standardised keywords to explore possible deviations. HAZOP is particularly suited to industrial processes, such as those used in the chemical and petrochemical industries, and provides a detailed overview of accident scenarios. Its main limitation lies in the complexity of its implementation: it requires experienced multidisciplinary teams and can be time-consuming, especially for large systems.

The main difference between the first two methods presented in the table is the introduction of the concept of drift. From a methodological point of view, the notion of drift is a combination of a parameter and a keyword. The parameters correspond to.

- physically measurable quantities such as temperature, pressure, level, quantity or time, for example,
- or operations to be performed, such as loading, heating or maintenance,
- or actions to be performed, such as starting, purging or closing,
- or functions/situations such as a utility failure.

The keywords are defined according to a type of deviation:

- Negative: No, Not, Not at all.
- Quantitative Change: More than, Less than.
- Qualitative Change: Also, Elsewhere, In addition to, In part, Less.

**Table 2.7** FMECA table

| Operation/ equipment | Functions/ status | Failure mode | Causes | Consequences | Severity | Frequency | Detectability | Criticality | Means of detection | Corrective actions | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheel drive shaft | Power transmission to the wheels | Breakage | Cardan bellows are damaged | Loss of transmission—risk of accident | 5 | 3 | 2 | 30 | Inspection at each service | Change cardan bellows every 150,000 kms | Add a note to the maintenance procedure |

*Source* Adapted from Ridoux (1999)

- Substitution: Other than, Inverse, On the contrary.
- Time: Earlier, Later.
- Order: Before, After.
- Sequence: Faster, Slower.

To systematically identify deviations, it is necessary to construct a deviation matrix by placing the parameters of the system under study on one axis of the matrix and the words on the other. At each intersection of the matrix, it must be asked whether this is a possible deviation. If so, then this deviation is retained for analysis. An example of a deviation matrix is shown in Table 2.8.

At this stage, simply take all the deviations selected in the previous step and complete Table 2.9.

**Table 2.8** Examples of drift for HAZOP

| HAZOP parameters | | Keywords | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | No | More than | Less than | Also | In part of | Inverse | … |
| Physically measurable quantities | Temperature | | X | X | | | | |
| | Flow rate | X | X | X | X | X | X | |
| | … | | | | | | | |
| Operations | Loading | X | X | X | | X | X | |
| | Heating | X | X | X | | X | X | |
| | … | | | | | | | |
| Actions | Start | X | | | | X | | |
| | Stop | X | | | | X | | |
| | … | | | | | | | |

*Source* Adapted from Royer (2009)

**Table 2.9** Table for HAZOP

| Parameter | Keyword | Causes | Consequences | Existing safety measures | Proposed improvements |
|---|---|---|---|---|---|
| Temperature | More than | Fires under the reactor | Increase in pressure | Temperature rise detector + alarm | Training of high-pressure operators |

*Source* Adapted from Royer (2009)

### 2.2.4 What If Method

Finally, the What If method (Dougherty, 1999; Royer, 2009), derived from HAZOP, is more flexible and less restrictive. It is based on a semi-structured approach, where the analysis is conducted using questions such as 'What would happen if…?' The list of typical questions is presented below.

- Lack of Utilities: What happens if power, water, gas supply is cut off?
- Change in Composition: What happens if the quality of the materials is not what is expected?
- Unusual Operating Conditions: What happens if the physical parameters like temperature, pressure, pH level are changed?
- Failure to Comply with Operating Instructions: What happens if the operating instructions are not mastered?
- Equipment Failure: What happens if the sensor gives false information?
- External Influence: What happens if flooding affects the units?
- Consequences of Incidents External or Internal to the Unit: What happens if a fire breaks out in neighbouring units?
- Product Handling: What happens if the product is spilled into water or released into the atmosphere?
- Safety Devices: What happens if an alarm system doesn't work?

This method is valued for its flexibility and adaptability, particularly in contexts where the formalism of HAZOP is considered excessive. However, its reliability depends heavily on the expertise and creativity of the analysis group, which can introduce variability in the quality of the results obtained.

### 2.2.5 In Summary

In summary, here is a reminder of the main steps in a table-based risk analysis method:

1. define the requirements,
2. identify the stakeholders involved in carrying out the risk analysis,
3. define a shared objective (spatial and temporal scope, object of analysis, etc.),
4. choose a method,
5. develop a severity scale,
6. develop a probability scale,
7. develop an acceptability matrix,
8. collect the information needed to carry out the study (RETEX, plans, organisation, etc.),

9. set up the working group (assess the duration of the study, plan meetings and deliverables),
10. complete the table,
11. place the scenarios in the acceptability matrix,
12. propose risk mitigation measures to achieve an acceptable level,
13. have the proposed measures validated by management (financial cost, security policy, etc.),
14. submit this risk assessment to the relevant authorities.

The choice between these methods depends on the context of application (preliminary design, operation, maintenance), the desired level of detail and the available resources (time, data, expertise). Their complementarity offers the possibility of developing hybrid approaches, combining the speed of implementation of the PHA, the precision of the FMECA and the depth of the HAZOP, according to the needs of the risk manager. Table 2.10 compares the table-based methods presented.

**Table 2.10** Comparison of table-based methods

| Method | Main objective | Advantages | Limitations | Areas of application |
|---|---|---|---|---|
| PHA (Preliminary hazard assessment) | Identify hazards at a general level during the design phase | Simple, quick, inexpensive, overview | Qualitative approach, not very precise, risk of omissions | Preliminary studies, system design, initial assessments |
| FMECA (Failure mode, effects and criticality analysis) | Systematically study failure modes and prioritise their criticality | Structured, rigorous, clear risk prioritisation, prioritisation of corrective actions | Difficult to implement, time-consuming and resource-intensive, limited for complex systems | Preventive maintenance, component reliability, aerospace, automotive and nuclear industries |
| HAZOP (Hazard and operability study) | Identify deviations from normal operating conditions | Comprehensive and systematic approach, suitable for continuous processes, detailed results | Time-consuming, requires a multidisciplinary team, significant resource commitment | Chemical, petrochemical and pharmaceutical industries, complex processes |
| What If | Explore possible accident scenarios through hypothetical questions | Flexible, adaptable, less restrictive than HAZOP, encourages creativity | Highly dependent on the experience and expertise of analysts, less structured results | Small installations, contexts where HAZOP formalism is excessive, rapid assessments |

The result obtained by these table methods will be a spreadsheet of short scenarios (usually cause/consequence pairs). The more complex the system studied or the finer the analysis granularity, the greater the number of lines. For some analyses, several hundred lines may be obtained, which will be classified by the matrix and associated with one or more risk control barriers for each line considered unacceptable. This table-based approach may seem tedious, but it has the advantage of identifying a set of short scenarios that can be used as 'raw material' for tree-based methods, such as fault trees, which allow scenarios to be logically associated.

## 2.3 Tree Methods

In the field of risk control, tree methods play a central role because they allow accident scenarios, their causes and their consequences to be represented graphically and logically. They are based on a structured approach, facilitating both the understanding of the mechanisms leading to a feared event and the assessment of its potential impacts.

These methods fall into two main categories: fault trees, which highlight the combinations of causes leading to an accident, and event trees, which illustrate the possible developments from an initiating event. Their combination gives rise to the Bow-Tie method, which offers an integrated view of causes and consequences.

Clear, visual and suitable for both qualitative analysis and quantitative assessment, tree methods are essential tools for preventing accidents, improving system reliability and enhancing overall safety. The methods detailed below are the fault tree, the cause tree and the event tree methods.

### 2.3.1 Fault Tree Method

Fault Tree Analysis (FTA) (Mortureux, 2020b; Stamatelatos et al., 2002) is a risk analysis method widely used in industrial and high-safety sectors such as aeronautics, nuclear power, space, rail transport and the chemical industry. Initially developed in the 1960s by Bell Laboratories for the US Air Force, it is based on a systematic approach aimed at identifying and representing all the possible causes of an accident or a feared event.

The principle of the fault tree is to start with a major undesirable event at the top of the diagram (explosion, breakdown, loss of containment, etc.), then break it down into intermediate causes and basic events, linked by logical gates (AND, OR, etc.). This tree structure highlights the various combinations of failures that could lead to an accident.

Beyond its visual clarity, the fault tree can be used both qualitatively—to identify critical scenarios and weak points in a system—and quantitatively, by integrating reliability data to calculate the probability of occurrence of the feared event.

FTA is based on a top-down approach. The analysis group first defines the feared event (or 'Top Event'), i.e. the accident or major malfunction to be avoided (fire, loss of control, total system failure, etc.). Starting from this event, it identifies and then gradually breaks down the intermediate causes and basic events which, when combined, can lead to the final event.

This breakdown is based on logic gates:

The 'OR' gate indicates that the higher-level event occurs if at least one of the causes occurs.

The 'AND' gate indicates that the higher-level event occurs only if all the listed causes occur simultaneously.

The tree is constructed until it reaches elementary causes, called basic events, which do not require further breakdown (equipment failure, human error, environmental conditions, etc.).

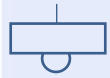
All the symbols used to construct the tree are shown in the following Table 2.11.

A fault tree therefore represents all the combinations of events which, under certain conditions, produce a given event, which is the starting point for the study.

Building a fault tree is equivalent to answering the question 'How can such an event occur?' or 'What are all the possible sequences that can lead to this event?' The 'qualitative' contribution is.

- to build a summary of everything that can lead to a feared event and to assess the effect of a change in the system,
- to compare the consequences of measures that can be considered to reduce the occurrence of the feared event under study,

**Table 2.11** Symbols used to construct the fault tree

| Elements | Representations | Elements | Representations |
|---|---|---|---|
| Top event |  | Top of a sub-tree |  |
| Basic event |  | Event pending decomposition |  |
| Condition |  | Logical gate OR |  |
| Reference to a sub-tree |  | Logical gate AND |  |

*Source* Adapted from Mortureux (2020b)

- assessing the number of scenarios leading to the event under study, and the minimum number of events or conditions sufficient for it to occur.

The 'qualitative' contribution is.

- To assess the likelihood of the studied event occurring based on the combinations of elementary events that can produce it.
- If the probabilities of these events are known, the probability of the event under study can be deduced and the impact on it of a reduction (or increase) in any of the elementary probabilities.

The creation of a fault tree generally involves several steps:

- The Definition of the Top Event: Specify the accident or major failure to be analysed. This is the peak event and is unique for a given tree. It must include everything that can cause this peak event. The definition of this event is crucial to the value of the conclusions that will be drawn from the analysis. The risk is not developing a tree that is wrong, but a tree that answers a different question than the one asked.
- Analysis of Immediate Causes: Identify the conditions that can directly cause this event.
- The Progressive Construction of the Tree: Develop the intermediate causes down to the elementary causes.
- Use of Logical Gates: Organise the relationships between events. For clarity of reading and use, there should only be one connector under each event.
- When should the breakdown stop and an event be considered a basic event?
- When it is sufficiently known (no need to identify the causes).
- When the causes of the event are of little interest.
- When the causes of the event will be studied elsewhere.

An example of fault tree analysis is presented in Fig. 2.1.

This is a rigorous and structured method, making the fault tree an essential tool for risk prevention in complex systems. It provides a systemic view of all the causes that contributed to the top-level event and their sequencing through an understandable graphical representation, thus facilitating understanding of the issues involved in risk control.

### 2.3.2 Cause Tree Method

The cause tree (Mortureux, 2020b; Stamatelatos et al., 2002; UNICE, 2023) is an analysis method developed mainly for the retrospective analysis of workplace accidents. Unlike forward-looking tools such as fault or event trees, cause trees methods are used after

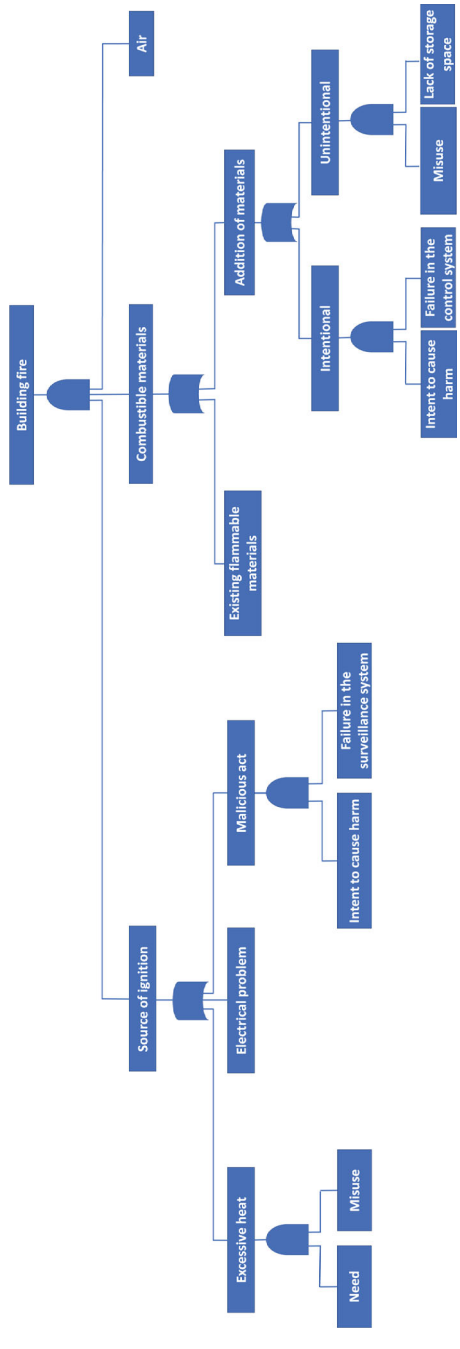



**Fig. 2.1** Example of a fault tree

an accident has occurred to understand how it unfolded and identify the factors that contributed to it.

Its principle is based on the idea that an accident never has a single cause: on the contrary, it results from a combination of technical, organisational, environmental or human circumstances. The cause tree therefore provides a graphical representation in the form of a tree structure that traces the chronology of events and highlights their interrelationships.

This approach not only provides a better understanding of the accident but also identifies appropriate preventive measures by addressing all the factors that led to the dangerous situation. A simple, visual and participatory tool, the cause tree is now widely used in companies to strengthen safety culture and prevent similar accidents from occurring or, at the very least, reduce their severity.

The cause tree is a retrospective analysis method designed to understand the circumstances that led to an accident. It is based on two fundamental ideas:

- An accident is always the result of a combination of factors, not a single cause.
- These factors are linked by conditional relationships: the presence of one factor enabled another to occur or develop.

The objective is therefore to trace the accident back to its root causes, whether technical (breakdown, defective equipment), organisational (inappropriate procedure, insufficient training) or human (error, risky behaviour). The cause tree method follows a structured process:

- Information Gathering
  - gather testimonies, observations, documents and data available after the accident,
  - focus on observable facts rather than value judgements.
- Identification of Facts
  - list the events that preceded or accompanied the accident (e.g. lack of protection, equipment failure, operational choices, workstation organisation).
- Tree Structure
  - connect the facts to each other using logical links. A line connecting two events, a conjunction or a disjunction may be used,
  - gradually build the tree by placing the accident at the end and working backwards towards the causes.
- Analysis and Search for Solutions
  - identify the immediate causes, root causes and their interactions,
  - Propose appropriate preventive measures (technical, organisational, human).

An example of cause tree analysis is presented in Fig. 2.2.

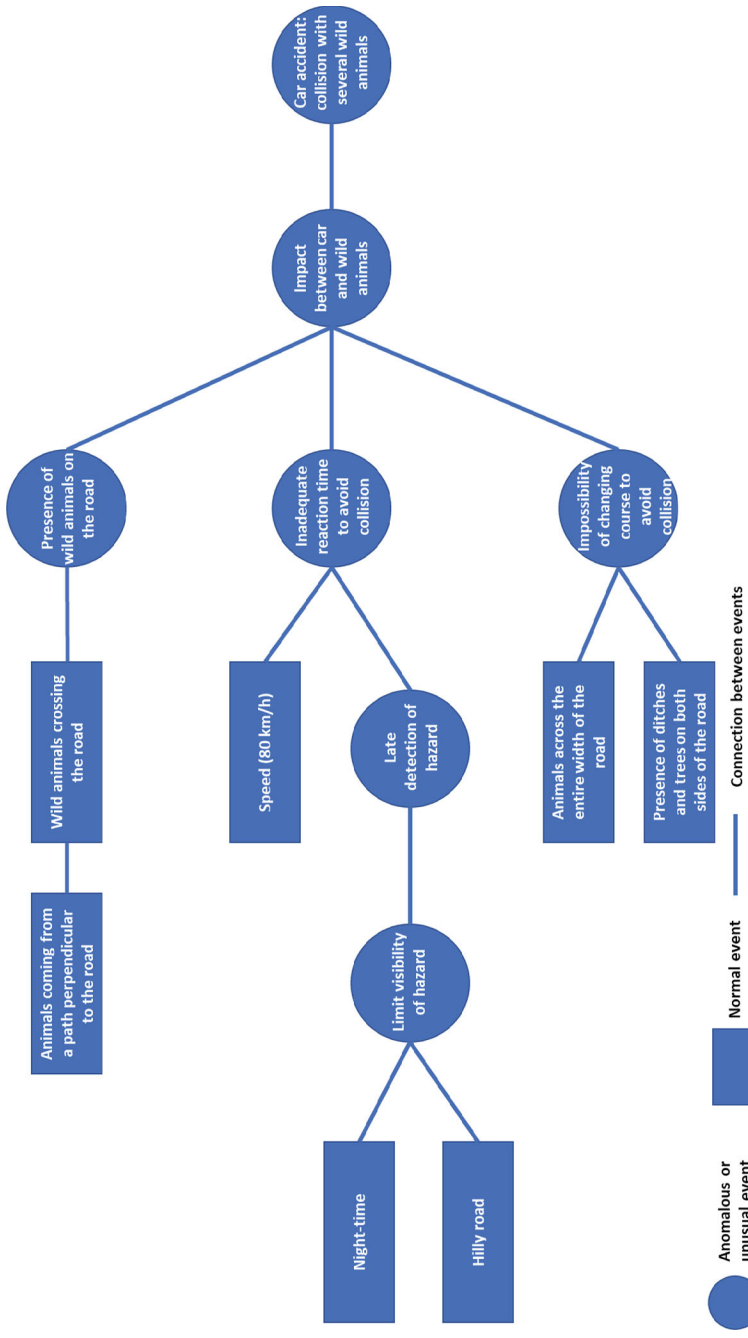



**Fig. 2.2** Example of a cause tree

The cause tree is therefore an essential tool in post-accident analysis. It not only helps to understand 'why' an accident occurred, but also to act to prevent the same circumstances from recurring, by strengthening preventive measures and improving work organisation.

### 2.3.3 Event Tree Analysis Method

Event Tree Analysis (ETA) (IEC 60300-3-9, 1995; UNICE, 2023) is a risk analysis method developed in the 1960s in high-safety sectors such as nuclear power and aeronautics. Unlike fault tree analysis, which focuses on the causes of an accident, event tree analysis concentrates on studying the possible consequences of an initiating event.

The principle is simple: starting with a triggering event (e.g. a gas leak, an electrical short circuit or a loss of containment), the successive effectiveness or failure of so-called 'alternative' protection and safety systems is analysed.

This tree structure makes it possible to identify and represent different accident scenarios, ranging from minor incidents to major accidents, each associated with a probability and a level of severity.

#### 2.3.3.1 Development of the Event Tree

Event tree analysis (ETA) is a bottom-up analysis method. It starts with an initiating event (gas leak, electrical failure, loss of containment, etc.) and examines, step by step, how the protection or safety systems respond. Each step can be broken down into two possible branches:

- Success: The barrier works, limiting or preventing consequences.
- Failure: The barrier does not function, and the event progresses towards a more serious scenario.

This series of binary choices results in the generation of several final scenarios, generally ranging from a minor incident to a major accident.

#### 2.3.3.2 Construction Stages

- definition of the initiating event (identify the starting point of the analysis, such as a pipe rupture or a fire starting),
- identification of safety barriers (determine the prevention or protection systems in place, such as an alarm, extinguishing system, containment, evacuation).

The tree is constructed by representing the succession of successes/failures of the barriers in a tree structure. Each path in the tree corresponds to a possible scenario.

Qualitative analysis allows the various scenarios identified to be described and compared, highlighting the dangerous ones.

Quantitative analysis is used to calculate the probability of each final scenario by assigning a probability of success/failure to each barrier.

An example of event tree analysis is presented in Fig. 2.3.

The event tree is therefore a forward-looking and systematic method and is thus a useful tool for exploring the consequences of a triggering event and evaluating the performance of safety measures, as well as for anticipating critical scenarios and strengthening risk prevention and management strategies.

## 2.4 General Conclusion

In an industrial and societal context marked by accelerating technological innovation, increasingly complex systems and stricter regulatory requirements, risk management must be viewed as a dynamic, evolving and integrated process. It is not limited to simple compliance but is part of a process of continuous improvement in safety, supported by feedback, knowledge management and the development of a shared safety culture.

Risk analysis plays a central role in the governance of complex systems, whether technical, organisational or socio-economic. It is a strategic tool that not only identifies potential hazards, causes and consequences, but also supports decision-making with a view to eliminating, preventing or protecting against risks, anticipating them and optimising risk management. Based on proven methodological frameworks, such as table-based approaches (PHA, FMECA, HAZOP, What If) and tree-based approaches (fault tree, cause tree, event tree), it offers a systemic reading of risk, integrating a variety of technical, human and organisational factors.

Although these methods differ in their principles and purposes, they share a common objective: to provide a structured representation and understanding of the mechanisms leading to an undesirable event. When implemented jointly, and when appropriate to the context of the study, they increase the robustness of the analysis and the reliability of the conclusions. However, their effectiveness remains dependent on the quality of the data used, the rigour of application of the method and the level of expertise of those involved. A purely technical approach is not sufficient: the human and organisational dimensions of risk are a determining factor in understanding failures and developing effective risk management strategies.

Risk analysis thus goes beyond the scope of methodological exercise: it is a lever for resilience and performance, contributing to the consolidation of safety practices, the empowerment of stakeholders and the development of collective risk intelligence. Through its scientific and strategic scope, it has established itself as an essential tool for the security and competitiveness of socio-technical organisations.

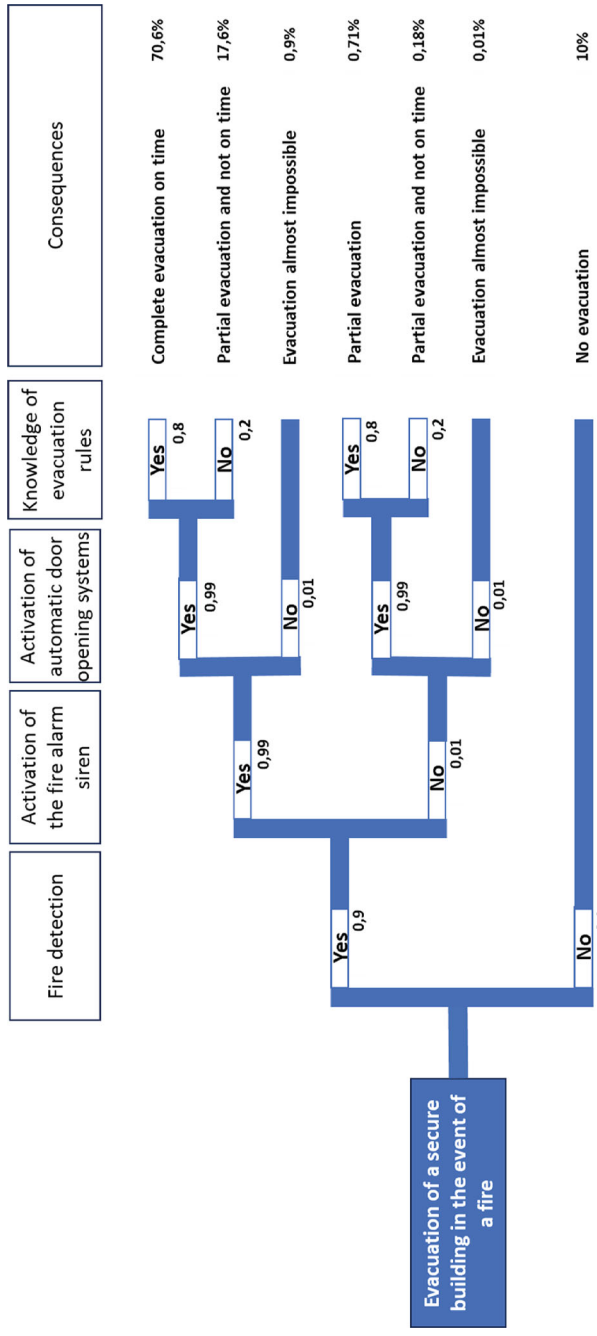



**Fig. 2.3** Example of an event tree

To take things further, based on these fundamental methods, various risk management stakeholders have developed new methods for analyzing and/or assessing risks. There are dozens, even hundreds of them, but they are all based on the basic principles presented in this chapter.

**Key Sentences**

- Risk arises from the interaction between hazard, exposed stakes and vulnerability, and effective management requires a clear assessment of both likelihood and consequence severity of hazard scenarios.
- Risk analysis provides a structured way to identify and classify accident scenarios, supporting decision-making through acceptability thresholds and targeted mitigation measures.
- Table-based (PRA, FMECA, HAZOP, What-If) and tree-based (fault tree, cause tree, event tree) methods offer complementary perspectives, from broad screening to detailed causal logic.
- The quality of a risk analysis depends on data reliability, methodological rigour and multidisciplinary expertise, integrating technical, human and organisational dimensions.

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# Explosion Hazard: The Worst Must Be Avoided

3

Jérôme Daubech, Frédéric Heymes, Michel-Olivier Sturtzer, and Sophie Trélat

**Abstract**

Explosion represents one of the most feared hazards in the industrial sector due to their destructive consequences on people, infrastructure and the environment. Explosion is defined as a sudden and violent release of energy—chemical, physical or nuclear—resulting in high pressures, temperature and mechanical effects such as blast waves and fragmentation. The chapter explores phenomenology, mechanisms and the main methods to quantify explosion effects and discusses prevention and mitigation strategies to minimise risks. Finally, the chapter examines human, structural and environmental consequences. Case studies of Beirut (2020), AZF Toulouse (2001) and Mount St. Helens (1980) highlight the social and ecological impact of both industrial and natural explosions. Finally, the chapter offers some thoughts on emerging research focused on Boiling Liquid Expanding Vapour Explosion (BLEVE) dynamics to improve predictive safety and resilience.

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**Keywords**

Explosion • Detonation • Deflagration • Blast • Overpressure

## 3.1 Some Examples of Accidents Involving Explosions

Explosions are impressive phenomena that leave a lasting impression. The intensity of the released energy and the long-distance propagation of the effects (particularly noise) mean that an explosion is a phenomenon that gets noticed. It is also the most feared phenomenon in the industrial sector due to its significant consequences on human lives, infrastructure and the environment.

An explosion is most fundamentally characterised as a sudden and violent release of energy, frequently involving rapid expansion of gases and resulting in mechanical effects such as pressure waves, high pressures and fragmentation. Explosions are desirable phenomena in certain applications (civil engineering, mining, weapons, combustion engines) where the mechanical effects of explosions are employed to achieve a task like breaking a rock or pushing a piston for example (in an internal combustion engine). But in this chapter explosions will be considered as non-desirable events occurring during accidents. Even if some natural explosions may occur (volcanic explosions), accidental explosions are mostly created by human activities in the industrial sector.

An analysis of accidents across 30 different countries between 1998 and 2015 revealed that gas explosions were the primary hazard in the chemical process industry. The analysis showed that 63% of major accidents that occurred in the chemical process industry were due to explosions (Koteswara & Yarrakula, 2016). The industrial sectors that are mainly threatened by explosions are:

- Oil and Natural Gas Activities: On/offshore installations, transportation, storage.
- Chemical, Petrochemical, Mineral and Metallurgical Process Industries: Chemicals, polymers, pharmaceuticals, pesticides, organic pigments, paints, pulverised-metal production (aluminium, magnesium, silicon, silicon alloys, etc.), production of cellulose, paper, etc. from wood.
- Energy processes (nuclear, coal, gas, oil).
- Food processing (grain, flour, sugar, etc.).
- Special processes (explosives, pyrotechnics and propellants).

History remembers a few very severe and unfortunately very well-known explosions:

- The Chernobyl (1986) and Fukushima (2011) explosions. Both explosions involving nuclear reactors led to powerful explosions, and these are the two nuclear energy accidents rated at the maximum severity on the International Nuclear Event Scale, with the consequences being among the worse industrial disasters. An important point that

must be stated is that in both cases, the explosion was not due to a nuclear explosion (like an atomic or hydrogen nuclear weapon), but by a loss of cooling control of the reactor which led to an increase of temperature and pressure and ultimately a rupture of the main pressurised reactor vessel.

- The Beirut (2020), Toulouse (2001) and Oppau (1921) explosions. In these cases, ammonium nitrate storage exploded and led to important human and structures losses. More than 600 human casualties were caused by the Oppau explosion. Major structural losses were observed in Toulouse and Beirut since the ammonium nitrate storages were in the cities.
- The Buncefield explosion (2005). The Buncefield fire was a major fire at an oil storage facility that started at the Hertfordshire Oil Storage Terminal. The terminal was the fifth largest oil-products storage depot in the United Kingdom, with a capacity of about 60 million imperial gallons (270,000 $m^3$) of fuel. The first and largest explosion was an unconfined vapour cloud explosion (also known as a fuel–air explosion). Because of an inversion layer, the explosions were heard up to 200 km away; there were reports that they were audible in Belgium, France and the Netherlands.
- The Feyzin accident was a catastrophic industrial explosion that occurred at a refinery near Lyon, France, on January 4, 1966. It is one of the deadliest industrial accidents in French history, and it had a major impact on global process safety standards. Workers were conducting a routine draining operation on a butane sphere (a spherical pressurised storage tank). But due to misoperation, liquefied petroleum gas was accidentally released, ignited and caused a fire that blew up propane tanks. Several firemen and plant workers were killed during response efforts.
- On 7 February 2008, a huge explosion and fire occurred at the Imperial Sugar refinery (Savannah, USA), causing 14 deaths and injuring 38 others, including 14 with serious and life-threatening burns. The explosion was fuelled by massive accumulations of sugar dust throughout building.

All the examples listed previously are similar in devastating effects. One or several strong blast waves were created, infrastructures were destroyed, fragments (pieces of infrastructures or vessels) were ejected, in some cases thermal effects were created by a fireball, in other cases a toxic cloud was dispersed. Another effect is the ground load effect of the explosion, leading in severe cases to seismic waves that can be recorded by earthquake stations. The ground effect of an explosion may destroy a bridge if the accident occurs with a truck, like in Bologna (2018) (Laamarti et al., 2025).

However, the underlying physical and chemical reasons that produced the devastating effects were different. The compounds involved were different (flammable gas or liquid, pressurised fluid, solid powder or dust, chemicals), the triggering event (human error, fire, loss of control) were different, and in fact, each explosion was totally different from the other. The following section will introduce the main differences.

## 3.2 Explosion Principles

### 3.2.1 Fundamental Mechanism of an Explosion

It is important to understand that all types of explosions correspond to energy release in the form of the expansion of a pressurised volume of gas. This pressurised volume of gas will be the source of aerial overpressure waves travelling through the atmosphere or other media. It must be noted that pressure waves can also travel in liquid or solid (water, soil). The propagation of a pressure wave from one medium to another (for example from air to water) is a complex phenomenon involving absorption, transmission and reflection properties of both media with an important influence on the incidence angle of the pressure wave propagation direction to the interface.

The key question is about the origin of the sudden volume of pressurised gas that will produce the effects (blast, mechanical effects, ground load). This volume of pressurised gas may.

- Exist previously to the explosion, for example a high-pressure nitrogen storage. The explosion happens when the vessel accidentally burst, releasing the pressurised volume of gas into the atmosphere.
- Be created by a chemical or nuclear exothermic reaction. In this case, the reaction energy will produce a mixture of high temperature gases which correspond to the adiabatic flame temperature (1963 °C for methane combustion, 3732 °C for aluminium dust flame and much more for nuclear reaction). The high temperature production of gases will lead to high pressure of the volume of gas.
- Be created by a physical transformation, like a flashing superheated liquid. In this case, unstable liquid will create a large amount of vapour. The origin of the instability can be a rapid temperature increase (for example when water falls into a molten metal) or a pressure drop (for example when a pressure liquefied gas is suddenly released into the atmosphere by a rupture of containment). Another cause of physical transformation can be a high intensity electric current, heating the air at high temperature (what happens in lightning or electrical short circuit for example).

### 3.2.2 Overpressure Wave Creation by a Pressurised Volume of Gas

Air is an elastic medium in which any local pressure perturbation will propagate into all directions of space. This propagating pressure is a pressure wave called overpressure since the pressure variation will be a modification of the atmospheric pressure. This is obviously the case with sound propagation. The classical setup to study aerial overpressure wave formation by a pressurised volume of gas is the so-called shock tube, in which a membrane separates an upstream compartment (driver section, at high pressure) and a

downstream compartment (driven section, usually atmospheric pressure). In this setup, the membrane ruptures instantaneously (in ideal case, not true in experiments) and releases the pressurised gas from driver section to driven section.

The disappearance of the membrane at time t0 will delete the force equilibrium between the two sections and the pressurised volume of gas will expand to the low-pressure compartment with a piston behaviour, pushing the air from low pressure. Pressure, temperature, density and velocity of both sides on the discontinuity are linked by the Hugoniot Rankine equations (Eckhoff, 2016).

In Fig. 3.1, at time t1>t0, the pressure wave will propagate to the right in a 1D configuration without any loss, supposing ideal gas (without viscosity). The pressure rise is instantaneous in ideal case (vertical pressure rise) and is called a shock wave.

Behind the piston, at t2>t1, the pressure will drop by a rarefaction wave moving upstream. When this rarefaction wave reaches the end of the tube, or the centre of a symmetric gas expansion, the overexpansion of the pressurised air will create a low-pressure zone following the aerial pressure wave.

The shock tube configuration represents proper explosions due to preexisting pressurised gas volume. This can happen with high pressure storage, but also other cases where pressure increases accidentally until containment vessel ruptures. The case of chemical runaway or overfilling of a vessel are typical causes of such explosions.

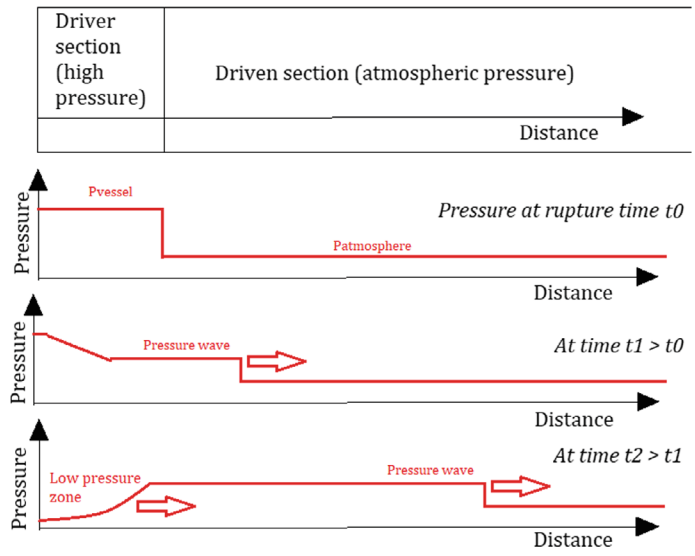



**Fig. 3.1** Shock tube pressure wave creation

### 3.2.3 Overpressure Wave Creation by Exothermic Reaction (The Case of Gas or Vapour)

Another mechanism of local pressure increase is chemical reaction, for example in a cloud of flammable gas mixed with air. A mixture of flammable gas with air can be ignited if the fuel concentration is in the flammability concentration range. The flammability range is defined by the lower flammability limit (LFL) and the upper flammability limit (UFL) of the fuel. The Lower Explosive Limit (LEL) or Lower Flammable Limit (LFL) is the minimum concentration of a combustible substance in air that can propagate a flame under test conditions. These values say that if the fuel concentration is too low, or if the oxygen concentration is too low (which means the fuel concentration is too high), the mixture is not flammable. Table 3.1 reports some flammability range data.

If a mixture of fuel and air is in the flammability concentration range and reaches an ignition source, the mixture ignites and a flame propagates. This is called a premixed flame propagation. In this case, the combustion zone (where the oxidation reaction takes place) propagates in the fresh mixture of fuel and air. The reaction entails a modification of the medium:

- The concentration of fuel and air decreases by the reaction.
- Reaction products concentrations increase to a level corresponding to the reaction conversion rate. Both fuel, air and combustion products concentration modification are linked by the chemical reaction stoichiometric coefficients.
- Since combustion reactions are highly exothermic, reaction zone temperature increases dramatically.

Figure 3.2 shows the evolution of concentrations and temperature in the case of flame propagation in a gaseous mixture. The reaction rate is also reported on the graph.

For a given quantity of gaseous mixture, the ideal gas equation links temperature, pressure and volume (Eq. 3.1).

$$P.V = n.R.T \tag{3.1}$$

where P is the local pressure, V is the volume of gas containing the quantity of gaseous mixture n, T is the local temperature and R is a constant.

**Table 3.1** Lower and upper flammability limits of some common compounds *Source* Adapted from (2022)

| Compound | LFL (%) | UFL (%) |
|---|---|---|
| Acetone | 3 | 13 |
| Hydrogen | 4.1 | 74.8 |
| Methane | 5.0 | 15 |
| Propane | 2.1 | 9.5 |

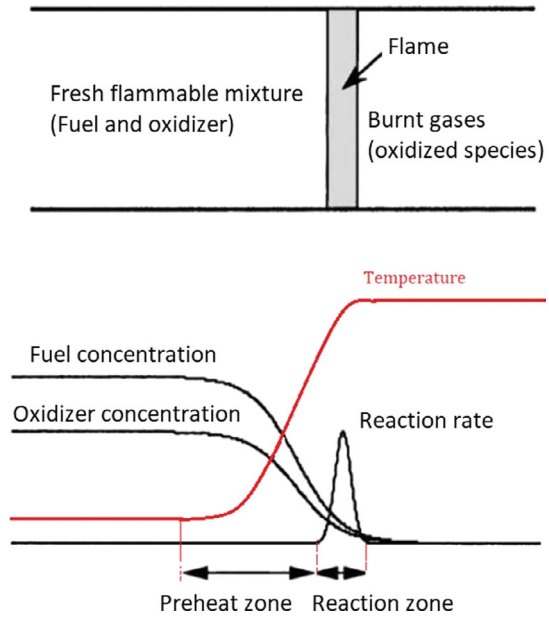



**Fig. 3.2** Propagation of combustion zone in a flammable gas (adiabatic assumption)

This equation shows that any increase in temperature will increase the product P.V. Therefore, the temperature increase of the reaction zone may increase pressure and/or volume. Depending on the reaction zone propagation velocity, the pressure increase may vary from zero (case of laminar burning) to tens of bars in case of detonation of a highly reactive flammable gaseous mixture.

To understand the link between pressure and volume increase, we must focus on the hydrodynamic aspect of the volume increase, which acts on the surrounding air with a pushing effect (like a piston). If the reaction speed is fast, the expansion in volume will be slowed down by the ambient air and will result in an increase in pressure in the combustion zone, but also in the air in front of the combustion zone.

#### 3.2.3.1 Deflagration

Figure 3.2 shows that before the combustion starts, a preheat zone is required to increase the fresh flammable mixture temperature. Indeed, the fresh flammable mixture ahead of the flame front must reach the ignition temperature by heat transfer. This heat transfer is complex and relies on conduction, convection and radiation (see Chap. 4). When the hydrodynamics of the phenomenon is laminar (no turbulence), the flame speed is mainly depending on the heat transfer to preheat zone since the rate or chemical reactions are very fast in case of combustion. This flame speed is a fundamental data for a given compound and is called laminar flame speed (SL).

However, the propagation flame is a complex structure that is mostly turbulent. This turbulence modifies the flame front structure by creating instabilities, resulting in an

increase of flame speed. The flame speed in turbulent conditions is called turbulent flame speed SL. Turbulent structures mainly have two effects on the flame front: wrinkling and thickening. The nature of this effect will depend on the scale ratio between the local turbulence in contact with the flame front and that of the flame front. Larger turbulent structures will wrinkle the flame front, and smaller ones will thicken it. The propagation of the flame front, via the thermal expansion of the fuel gas, will generate a flow of fresh gas upstream of the flame front. This flow, associated with possible obstacles, will naturally generate turbulent intensity by its acceleration upstream of the flame front propagation. In the case of an unconfined gas explosion, obstacles are an important source of turbulence increase.

The combustion of a flammable cloud driven by preheat zone heating is called a flash fire, and if the flame velocity is very high, a deflagration. Even if flame speed in case of deflagration can reach hundreds of metres per second, the phenomenon remains subsonic. Another phenomenon which is called detonation may be supersonic and is based on another type of propagation physics.

#### 3.2.3.2 Detonation

As explained previously, the volume expansion due to combustion in a deflagration regime will increase pressure ahead of the flame front by pressure propagation and piston effect of the volumic expansion. By applying the Ideal Gas Law to a quantity of fresh flammable mixture, the law gives (Eq. 3.2):

$$T = \frac{P.V}{n.R} \tag{3.2}$$

So, the pressure increase of fresh flammable mixture will lead to a temperature increase by compression, accelerating the speed of temperature increase for the preheat zone. Moreover, the ignition temperature of a mixture decreases with pressure, accelerating the flame speed. In the case of a very reactive chemical compound (such as acetylene of hydrogen for example), the flame velocity accelerates from ignition and reaches a state where the pressure increases ahead of the flame front. This is sufficient to ignite the fresh flammable mixture. In this case, the burning velocity is driven mainly by pressure propagation and becomes sonic or even supersonic. The main mechanism of detonation propagation is of a powerful pressure wave that compresses the unburnt gas ahead of the wave to a temperature above the auto-ignition temperature. In technical terms, the reaction zone is a self-driven shock wave where the reaction zone and the shock are coincident, and the chemical reaction is initiated by the compressive heating caused by the shock wave. Equations describing the detonation wave are the Chapman–Jouguet equations.

Other parameters, mainly in terms of geometrical conditions (such as partial confinement and many obstacles in the flame path that cause turbulent flame eddy currents), may accelerate a subsonic flame front to supersonic speed, transitioning from deflagration to detonation. The exact mechanism is not fully understood and while existing theories are



**Fig. 3.3** Propane–oxygen detonation *Source* Author's own photograph

able to explain and model both deflagrations and detonations, there is no theory at present which can predict the transition phenomenon. A picture of propane-oxygen gas cloud detonation is given in Fig. 3.3.

### 3.2.4 Overpressure Wave Creation by Exothermic Reaction (The Case of Liquid or Solid)

The main difference between explosion of a gas and a condensed phase (liquid or solid) is that oxygen cannot be the required oxidizer. Indeed, a vapour cloud of gasoline may explode if the concentrations are included in the flammability limits, but no explosion will happen if gasoline is considered as a bulk of liquid. The absence of oxidizer in the liquid gasoline or another flammable solid completely prevents the combustion reaction.

A condensed phase explosion may only occur in the case of a mixture of a fuel and an oxidizer, or if the chemical compound is composed of a fuel part and an oxidizer part. The first case is for example black powder which consists of a mixture of sulphur, charcoal (which is mostly carbon) and potassium nitrate (saltpeter). The sulphur and charcoal act as fuels, while the saltpeter is an oxidizer. The second case is for example TNT (trinitrotoluene), which is a single molecule composed of a fuel part (toluene) and three oxidizer groups (nitro-groups). In this case, no mixture is necessary since a pure amount of TNT may explode with an easy possibility of deflagration to detonation transition. Another well-known case is ammonium nitrate which exploded in the Beirut accident for example.

Liquid or solid phase explosions have a much more severe potential of destruction than gas explosions and require a high level of precaution to be handled safely.

### 3.2.5 Overpressure Wave Creation by Exothermic Reaction (The Case of Dust or Powder)

Dust or powder is composed by very small, divided solids (millimetric, micrometric, nanometric). Although they are composed of solids, dust clouds present similarities with gases. Their combustion and explosion require them to be suspended in the air, assuming that the mixture is within the limits of explosivity. Dust explosions can occur with many types of solid particles, including coal, flour, pigments, etc. However, major differences exist with gas explosions:

- The size of the solid particles is a determining factor in explosion severity. The smaller particles, the more reactional the dust could be.
- The combustion reaction between solid particles and air is very complex and involves phase change of the solid (from solid to liquid or vapour) but also pyrolysis and condensation of the reaction products.
- Dust clouds are much heavier than gas mixtures and represent a higher energy release per unit of volume during combustion.
- The preheat phase is slower, since the heat capacity of solid, phase change and pyrolysis require more heat than heating gas.
- Combustion of a solid in air can be limited by oxygen and chemical product diffusion and may involve porosity phenomena.

Depending on the dust identity, different combustion mechanisms are possible. The first possibility is an oxidation reaction directly on the surface of the particles and concerns metal dust. This is a heterogeneous reaction between the oxidising gas and the solid fuel.

The reaction can also take place in the gas phase. In this case, the mechanism is divided into two stages: first, the dust is partially transformed into the gas phase. Then a reaction takes place between the dust in the gas phase and the oxygen present in the air: the reaction is therefore homogeneous. Sulphur and polyethylene react according to this mechanism.

The third type of reaction is a combination of the previous two. First, part of the fuel becomes gaseous upstream of the flame front (preheating zone). Then, this gaseous fuel reacts in a homogeneous phase with oxygen. This combustion then allows the part of the fuel that has remained solid to react in turn: this time in a heterogeneous phase. This mechanism applies to most dust, particularly organic dust.

For these reasons, dust explosions are complex phenomena to model, only models derived from gas explosions models are suited (and only in some particular cases). Dust cloud explosions release a huge amount of energy and are very luminous (Fig. 3.4) but are rarely considered in the detonation regime.

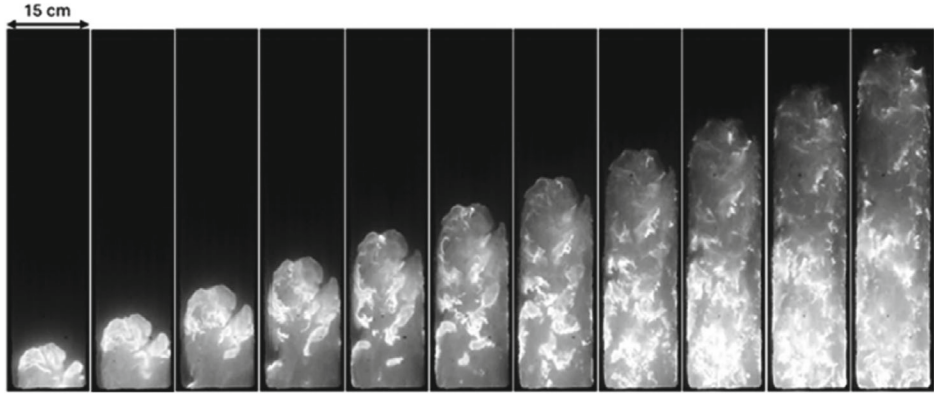



**Fig. 3.4** Sequences of direct visualisation images of flame propagation with a 20-μm aluminium powder *Source* Chanut et al. (2025)

### 3.2.6 Overpressure Wave Created by Phase Change

A local pressure increase may be the consequence of a rapid phase change from liquid to vapour. Since the volume of vapour created by a given volume of liquid is much larger (a factor of 1000 with water for example), the phase transition from liquid to vapour creates a large increase of volume. The speed at which this phase transition occurs determines if the phase transition will be explosive or not.

To observe an explosive boiling, it is necessary to achieve a rapid pressure or temperature change of a liquid, causing the liquid to enter a superheated state, which is a metastable state. This metastable state is in fact a state in which the liquid remains under temperature or pressure conditions in which it should not remain but rather should be in a vapour state. The phase change from a metastable state is very rapid and involves complex mechanisms of homogeneous or heterogeneous nucleation (creation of bubbles).

There are two ways to reach the metastable state of a liquid: by rapid change in temperature or by rapid change in pressure:

- Very rapidly decreasing the pressure of a liquefied gas, like propane for example (arrow 1 on Fig. 3.5). This kind of accident happens when a loss of containment occurs on the pressure vessel, for example during a road accident. This explosive phenomenon is called a BLEVE (Boiling Liquid Expanding Vapour).
- Mixing the liquid with a very high temperature other compound, rising the temperature of the liquid very rapidly (arrow 2 on Fig. 3.5). Typical examples are steam explosions when water falls in liquefied metals (or if a liquefied metal falls in a pool of water) or when cryogenic Liquid Natural Gas (LNG) falls in water (for example a leak from an LNG ship on the sea). In the first case, the temperature difference will be around

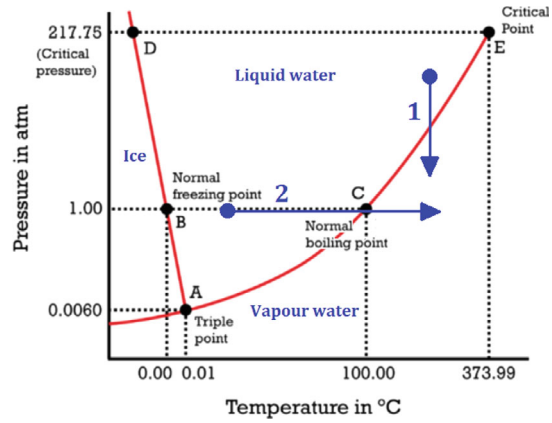



**Fig. 3.5** Pressure versus temperature phase diagram of water and phase transitions

1500 °C between water at ambient temperature and molten steel for example. In the second case, the temperature difference is lower and about 180 °C between LNG at − 162 °C and water at ambient temperature. It must be noted that water plays the role of cold commodity in the first case and hot commodity in the second case. This phase change is called rapid phase transition explosion (RPT explosion).

### 3.2.7 The Case of Chemical Runaway

Explosions were observed in chemical plants where a chemical runaway occurred. A chemical runaway can be described as the loss of control of temperature of an exothermic reactional process. Since an increase in temperature leads in most cases to an increase of the reaction speed and therefore heat released by the reaction, any cooling failure causes a self-sustaining drift leading to uncontrolled heating of the reaction mixture, and eventually a rupture of the vessel. The explosion may then be due to the release of a pressurised vapour, a vapour explosion, a dust explosion or a BLEVE, depending on the complex chemistry of the chemical runaway.

### 3.2.8 Creation and Propagation of the Aerial Overpressure Wave

According to the previous part, explosive behaviour of species can be due to.

- Intrinsic explosive properties of the compound (for example trinitrotoluene).
- Explosive properties of species in specific conditions (natural gas becomes explosive only if a certain concentration range is reached, while water can explode if a sufficient degree of superheat is reached).

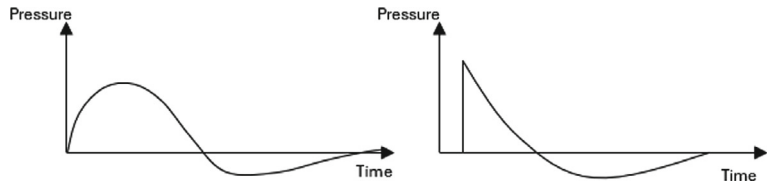



**Fig. 3.6** Characteristic shape of pressure signals

- Explosive properties due to the operating conditions (air can lead to an explosion if stored at high pressure for example).

All mechanisms may involve complex chemistry, compressible fluid dynamics, rapid heat transfer or thermodynamic instabilities. But all phenomena will produce aerial overpressure depending on the intensity and dynamics of volume production. External factors such as spatial configuration, turbulence increase and vessel rupture mechanisms will influence the creation of aerial overpressure. As said previously, a local pressure increase propagates outward at a speed comparable to that of sound. These pressure waves can be:

- A Blast Wave (Fig. 3.6, left): As long as the flame develops, both the surrounding atmosphere and the interior of the fireball are pressurised, leading to the emission of an overpressure wave. When combustion ceases, the fireball must depressurize and return to atmospheric pressure. This process generates a rarefaction wave that originates at the flame front and decelerates the gases both outward and inward.
- A Shock Wave (Fig. 3.6, right): When the flame propagates sufficiently fast—typically at a speed comparable to that of sound—the different waves generated during flame development merge and coalesce to form a 'steep front'.

## 3.3 Methods for Assessing the Effects of an Explosion

To assess the effects of an explosion, it is first essential to identify the scenario in which it develops. The consequences and the evaluation methods will vary significantly depending on the environment in which the explosion occurs:

- In Open Air: referred to as an Unconfined Vapour Cloud Explosion (UVCE).
- In a Confined Environment: referred to as a Vapour Cloud Explosion (VCE).

### 3.3.1 Unconfined Explosion

The threatened consequences of an unconfined explosion are the generation and propagation of a pressure wave. This wave is produced by the expansion of the fireball and vanishes once the fireball is extinguished.

Theories of explosions in free space are based on observations conducted both at laboratory scale and at full scale (Lannoy et al., 1989; Leyer, 1982). Cambray et al. (1979) proposed general analytical solutions, valid even for high Mach numbers. However, Deshaies and Leyer (1981) suggested a more general description of the pressure signal, in which the explosion effect is perceived as that of a monopole acoustic source emitting a sound wave into the surrounding environment, like the sound produced by a loudspeaker. This phenomenon is represented by Eq. 3.3:

$$\Delta P(r,t) = \frac{\rho_0.(1-\frac{1}{\alpha})}{4.\pi.r}.\frac{d^2V(\tau)}{dt^2} \tag{3.3}$$

where ΔP(r, t) (Pa) is the overpressure at time t and at distance r from the explosion, $\rho_0$ is the density of the atmosphere ($kg.m^{-3}$), α is the expansion ratio of the burnt gases (no dimension), V is the volume of the acoustic source ($m^3$), $c_0$ the speed of sound in air ($m.s^{-1}$).

This model served as a basis in the 1990s for the development of methodologies to evaluate the effect distances of overpressures generated by an explosion. Among the most used methods are.

- the TNT equivalent method,
- the Multi-energy method.

Both approaches rely on the same principle: overpressure effect distances are estimated using charts, where the distance is expressed in dimensionless form with respect to the energy involved in the explosion.

#### 3.3.1.1 The TNT Equivalent Method

This method assumes that the overpressure field generated by a given explosion (whether from a gas mixture, a condensed explosive, etc.) can be reproduced by detonating an equivalent amount of TNT. Accordingly, the TNT equivalent of a flammable gas mixture corresponds to the mass of TNT which, when detonated, would generate the same overpressure field as that produced by the explosion of 1 kg of the considered mixture. This TNT equivalent, hereafter denoted as MTNT is calculated using the following relation (Eq. 3.4):

$$M_{TNT} = \frac{E_{gas}}{E_{TNT}} \tag{3.4}$$

where $E_{gas}$ represents the energy that the considered fuel can release upon combustion, $E_{TNT}$ ($kj.kg^{-1}$) represents the energy released by the explosion of 1 kg of TNT, i.e. approximately 4690 kJ, $a$ denotes the efficiency factor of the gas explosion (dimensionless).

The efficiency factor $a$ has different meanings depending on how the explosion of energy Egas is defined. Indeed, $E_{gas}$ may represent either the combustion energy of the total mass of fuel accidentally released (acknowledging that only part of this mass will be within the flammability limits), or the combustion energy of the fuel mass mixed with air in explosive proportions.

Based on available feedback and practical experience (Lannoy et al., 1989), the following values are generally adopted:

- $a = 10\%$ if the total released fuel mass is considered,
- $a = 50\%$ if the considered fuel mass is that within the flammability limits of the released substance.

Overpressure effects at a distance are then estimated using charts (Lannoy 1984).

#### 3.3.1.2 The Multi-energy Method

The Multi-energy method is based on the following assumptions:

- The flame propagates at a constant velocity, which must be taken as the maximum possible for the installation under consideration.
- The maximum flame velocity is determined empirically as a function of the cloud's reactivity, geometry and congestion level.
- Outside an acceleration zone, the flame slows down and returns to its 'natural' velocity. Consequently, two flame-acceleration zones (for instance, two obstacle networks) separated by a region where the flame decelerates will, at a distance, produce two independent pressure peaks.

From this perspective, the explosion of a gas cloud should not be described as the 'bulk' explosion of the entire explosive volume, but rather as the succession of elementary, independent explosions occurring in the flame-acceleration zones present within the cloud.

The application of the Multi-Energy method therefore relies on two fundamental steps:

- Characterisation of the flame-acceleration zones within the flammable cloud: each acceleration zone is then treated as an elementary explosion.
- Determination of the flame velocity in each zone, i.e. quantifying the severity of the explosion.

To achieve this, several parameters influencing flame propagation velocity must be considered, including:

- obstacle density,
- degree of confinement,
- shape and dimensions of the flammable cloud,
- fuel reactivity,
- energy and location of the ignition source,
- turbulence level of the reactive mixture prior to ignition.

The 'severity' of each elementary explosion can then be characterised by an index ranging from 1 to 10, corresponding to a maximum overpressure level. Maximum overpressures and attenuation curves as a function of distance are provided, for each index, in charts. The method also allows determination of the pressure signal shape and duration.

The energy of the elementary explosions is evaluated by identifying potential pressure sources, i.e. regions where the flame may accelerate sufficiently to generate significant overpressures due to turbulence, confinement or obstacles. The energy is then obtained by multiplying the volume of this zone by combustion heat.

Several recommendations have been proposed for selecting the severity index. The most widely used are those initially proposed by the method's author (Van den Berg 1984), followed by Kinsella (1993), TNO (1997), and later from the GAME project (Van den Berg et al. 1996) and the GAMES project (Mercx et al., 1998).

A detailed analysis (Leprette, 2007) showed that the Multi-Energy method is difficult to apply due to discrepancies between industrial situations and the 'idealised' configurations of the experiments used to develop the method. Moreover, challenges may arise at each step of its application. Analysis indicates that several fundamental assumptions of the model may not always be satisfied:

- the flame propagates in a quiescent medium,
- the flame can be considered to propagate at a constant velocity,
- the effect of obstacles can be represented by a single global parameter, the 'VBR' (blockage ratio).

In addition, the method does not account for certain factors, such as the influence of heterogeneities in cloud reactivity, the impact of cloud shape or the superposition of individual explosions on a distant target.

### 3.3.2 Confined Explosions

The methods used to estimate the consequences of a confined explosion differ from those applicable to unconfined explosions. Their specificity lies in the fact that the explosion develops within a closed (partially or fully) volume that possesses a certain mechanical resistance to overpressure. The modelling process is generally divided into three steps.

#### 3.3.2.1 Analysis of the Mechanical Resistance of the Building Walls and the Venting (Frangible) Surfaces

For Building Walls: Either the data are available from scientific literature or construction guidelines, or simple strength of materials calculations—or more advanced finite element calculations—can be used to determine the static resistance pressure against explosion. The dynamic resistance is typically between half and twice the static pressure, or alternatively, experimental studies can be performed to determine the actual resistance of the walls.

For Frangible Walls: These surfaces may be certified venting devices (according to EN 14,797), in which case the certificate provides the static opening pressure. Otherwise, simple strength of materials calculations, finite element modelling or dedicated experimental testing may be used to determine the opening pressure (with fixings being of particular importance). It is also possible to consider frangible surfaces as permanently open walls, but this assumption may underestimate internal explosion overpressures.

#### 3.3.2.2 Analysis of the Reactivity of the Flammable Mixture

This requires knowledge of the hydrogen–air atmosphere (concentration, volume, initial turbulence). From this, the fundamental burning velocity and the expansion ratio of the combustion products can be determined as a function of the mixture concentration, as well as the turbulent burning velocity depending on the release conditions.

#### 3.3.2.3 Estimation of External Pressure Effects

If the internal pressure exceeds the resistance pressure of the building walls (excluding venting surfaces), building rupture occurs. If the internal pressure is below the structural resistance of the building walls, a secondary explosion phenomenon may occur, producing effects at a distance.

The building rupture can be evaluated using Brode's energy and the index 10 chart of the Multi-Energy method. For the pressure effects resulting from the secondary explosion, correlations are available (Grégoire, 2022) to determine the explosion severity and associated energy. In this case, the Multi-energy method can then be used to estimate overpressure effects at distance.

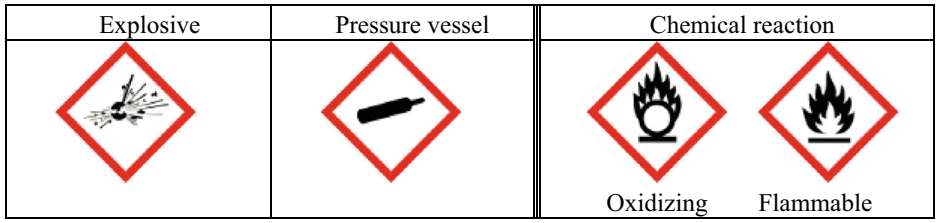



**Fig. 3.7** Hazard pictograms associated with explosion *Source* Adapted from United Nations ADR code

## 3.4 Safety Strategies

### 3.4.1 Explosion Risk Identification

Explosion hazard is highlighted by the labelling according to Regulation (EC) No 1272/2008 (CLP). The case of reactive compounds that may lead to explosion in certain conditions does not have a specific label, therefore attention may be given to compounds with an oxidising or flammable property. The explosive behaviour is described in the accompanying safety data, with the conditions in which the chemical may explode (Fig. 3.7).

### 3.4.2 Explosion Mitigation

Explosions are among the leading causes of human casualties and economic losses in the process industry. While fires represent the most frequent type of accident, explosions account for approximately 75% of total financial losses, compared to 20% for fires and 5% for toxic releases (Health & Safety Executive, 1988; Khan and Abbasi, 1999). Despite improvements in safety management systems, major accidents such as Feyzin (1966), Flixborough (1974), Piper Alpha (1988) and Pasadena (1989) demonstrate that explosion risk can never be eliminated.

Although actions aimed at preventing anomalies and failures or maintaining systems within safe operating limits are essential, they may not always be sufficient. Indeed, when the residual risk remains unacceptably high, additional prevention and protection systems must be implemented as the ultimate barrier. This section provides an overview of such systems, applicable to gas, vapour and dust explosions, and distinguishes between active and passive devices, as well as preventive and protective approaches (Pekalski et al., 2005).

### 3.4.3 Explosion Prevention

#### 3.4.3.1 Elimination of Ignition Sources

Suppressing or reducing the energy of ignition sources is effective for flammable mixtures with a minimum ignition energy (MIE)>10 mJ (Maurer & Glor, 1996; Schäfer, 1978). However, this becomes much more challenging for highly sensitive gases (MIE of a few mJ, or even lower, such as hydrogen). This is nevertheless the primary objective of ATEX-certified equipment (ATEX standards). In many processes that inherently generate sparks (e.g. milling, grinding) or mechanical heating, this approach is often unrealistic. Active spark or hot-spot detection and extinguishing systems can also be applied, as in the food industry (Pekalski et al., 2005).

#### 3.4.3.2 Control of Combustible Concentration

The goal is to keep the concentration outside the flammable range (below the lower explosion limit—LEL, or above the upper explosion limit—UEL). While feasible for gases, this method is much more difficult to implement for dust because of the spatial heterogeneity and transient nature of dust clouds (Eckhoff, 1991).

#### 3.4.3.3 Inerting

A widely used method which consists of reducing the oxygen concentration below the limiting oxygen concentration (LOC) through the injection of inert gases ($N_2$, $CO_2$, flue gas, Ar). Typical LOC values are 8–15% $O_2$ for organic dusts and 4% for some metal dusts (Bartknecht, 1981; Going et al., 2000), and around 5% for gases (Proust, 2004). While highly effective, inerting entails significant costs and introduces the risk of asphyxiation for personnel (Kletz, 1980).

### 3.4.4 Explosion Protection

Unlike prevention, protection systems do not prevent explosions but aim to limit their consequences.

#### 3.4.4.1 Frangible Surfaces or Explosion Vents

Panels, rupture discs, or explosion doors release overpressure at a predefined opening pressure (static activation pressure). Design rules are provided by NFPA 68, VDI 3676 and EN 14,994. Although simple and cost-effective, this approach has drawbacks: the opening of frangible panels can lead to the expulsion of part of the flammable mixture from the protected vessel, potentially creating an external explosion with pressure and thermal effects. To address this, flameless vents have been developed, designed to release explosion pressure while preventing flame ejection (Gregoire, 2025).

#### 3.4.4.2 Explosion Suppression

Active systems detect the onset of an explosion (30–100 ms) and rapidly inject an extinguishing agent (powders such as $KHCO_3$, $NaHCO_3$, MAP; inert gases; water in certain cases). The reduced explosion pressure (Pred) is typically maintained around 0.3 bar(g), enabling protection of low-strength equipment (Chatrathi & Going, 2000; Moore, 1986). This technique is effective for equipment volumes below 1000 $m^3$.

#### 3.4.4.3 Explosion Isolation

Intended to prevent flame propagation through ductwork. It can be active (chemical barriers, fast-acting valves) or passive (non-return valves, rotary locks, screw conveyors). This strategy confines the effect to the originating unit (Going & Snoeys, 2003).

#### 3.4.4.4 Flame Arresters

Applied to gases and vapours, they are based on the concept of the Maximum Experimental Safe Gap (MESG), i.e. the largest gap between two metal surfaces through which a flame cannot propagate for a given flammable mixture. This serves as a design criterion for flame arresters and explosion-proof equipment. Various designs exist (perforated plates, crimped ribbon, porous packings). They stop flame or detonation propagation but require regular maintenance and induce pressure losses (AIChE, 1993; Thomas et al., 2020).

#### 3.4.4.5 Confinement

Equipment can be designed to withstand the maximum explosion pressure (explosion pressure-resistant) or to tolerate limited deformation (pressure shock-resistant). Although reliable, this approach is costly and seldom applied on a large scale (Pasman & van Wingerden, 1988).

#### 3.4.4.6 Barriers and Physical Separation

For non-confined explosions, mitigation techniques can reduce blast intensity through:

- the use of water sprays or curtains,
- the interposition of walls or berms.

Regarding water sprays, experimental work (Mataradze et al., 2017; Mercx et al., 1995; Van Wingerden, 2011) shows that injection of water can.

- reduce flame propagation speed, although turbulence induced by injection may sometimes accelerate combustion,
- significantly lower explosion overpressure (reduction factors of 5 to 20) through droplet breakup and dissipation of shock wave momentum.

The effectiveness strongly depends on droplet size distribution, nozzle arrangement and timing of activation.

The installation of a wall or berm can also attenuate overpressure to some extent. Heudier and Daubech (2021) and Trélat et al. (2023) developed a predictive approach based on the ratio between the explosion wavelength and wall height. Small- and medium-scale experiments ($H_2$-air and TNT) were used to derive correlations for estimating the attenuation coefficient behind walls or berms. Results, however, indicate that attenuation is often very limited.

These approaches offer complementary solutions to reduce explosion effects, but their effectiveness remains highly dependent on application conditions and requires careful adaptation to industrial contexts. Prevention measures should always be prioritised, as they eliminate the initiating event, whereas protection measures act downstream by limiting intensity. Nevertheless, certain industrial situations require combining systems (e.g. inerting + suppression, venting + isolation). Despite the wide range of mitigation techniques, the development and study of explosion prevention and protection remain an open and active field of research.

## 3.5 Consequences for the Environment and Humans

### 3.5.1 Introduction

Explosions are among the most destructive accidental events that societies can face. They can occur in urban, industrial or natural settings, and their impacts extend beyond immediate destruction to long-term environmental, social and economic consequences.

On 4 August 2020, a massive explosion shook the port of Beirut, Lebanon. Caused by accidental detonation of approximately 2,750 tonnes of ammonium nitrate stored in unsafe conditions, the blast destroyed large parts of the city. More than 200 people lost their lives, thousands were injured, and entire neighbourhoods were flattened. The shockwave (Rigby, 2020) was felt over 200 kms away, and its consequences on humans, infrastructure and the environment remain visible today.

Similar accidents, such as the AZF plant explosion in Toulouse in 2001 (DGPR, SRT, BARPI, 2021), show that no country is immune. Understanding how explosions affect the modern human environment is therefore essential to improving prevention, preparedness and resilience.

**Table 3.2** Estimated thresholds for human effects of blast pressure

| Overpressure (kPa) | Consequences on humans |
|---|---|
| 2–3 | Eardrum rupture |
| 10–20 | Risk of lung damage |
| 30 + | Severe lung collapse, fatal injuries |
| 50 + | Almost certain death in exposed individuals |

*Source* Adapted from Kinney and Graham (1985)

### 3.5.2 How Explosions Affect Humans

Explosions harm people both directly and indirectly. The blast wave (Kinney & Graham, 1985) is the most dangerous factor, as the human body is vulnerable to sudden pressure changes (Table 3.2 based on Kinney and Graham (1985) and Legifrance (2007)).

In addition to direct injuries, flying debris and glass fragments often account for most wounds in urban explosions. People can also be thrown against walls or the ground, leading to fractures, burns or concussions.

Beyond physical harm, explosions leave psychological scars. Survivors may suffer from post-traumatic stress disorder (PTSD), anxiety or depression. In some cases, the release of toxic substances after an industrial accident can also cause long-term illnesses such as respiratory diseases or cancers.

### 3.5.3 How Explosions Damage Structures

Explosions strike buildings and infrastructures with brutal force. Windows are often the first to break (Table 3.3) (Legifrance, 2007), and once they are shattered, glass fragments become dangerous projectiles. In urban areas, the destruction of buildings also triggers secondary accidents: fires from ruptured pipelines, blocked roads preventing emergency access, and loss of electricity or water supply. In industrial facilities, explosions can ignite chain reactions, causing additional damage layers from a single event.

**Table 3.3** Typical thresholds for structural damage

| Overpressure (kPa) | Consequences on structures |
|---|---|
| 2–5 | Glass windows shatter |
| 10 | Collapse of lightweight walls or roofs |
| 30–50 | Severe damage to reinforced concrete structures |
| 100 + | Destruction of most civilian buildings |

### 3.5.4 How Explosions Impact the Environment

The environmental footprint of an explosion can persist for decades. In the short term, vegetation may be destroyed, animals killed and soils contaminated by hazardous chemicals. For example, after the Beirut port explosion in 2020, large areas of the city and surrounding land were covered with dust, debris and toxic residues, while nearby marine zones were polluted. Similarly, the AZF explosion in Toulouse in 2001 released ammonium nitrate and other chemicals into the surrounding soil and rivers, affecting plants, fish and farmland. At first, biodiversity often declines, air quality deteriorates due to dust and particles, and contaminated land can become unsafe for human use. Heavy metals and toxic substances can remain in soil and groundwater for many years, posing serious threats to agriculture and drinking water supplies.

Underwater risks are particularly severe. Millions of tonnes of munitions were dumped at sea after World War I and II, and these unexploded ordnances (UXO) continue to pose hazards for marine ecosystems and human activities (Sharma et al., 2025). During dredging, fishing, or offshore construction, contact with UXO can trigger explosions. Even when they do not detonate, corroding munitions slowly release TNT, heavy metals and chemical warfare agents, poisoning marine life and disrupting food chains. Controlled detonation, sometimes necessary for depollution, can also endanger marine mammals sensitive to acoustic shockwaves. For this reason, careful pyrotechnic remediation—including the controlled removal or neutralisation of underwater munitions—is particularly important to protect marine ecosystems, prevent the release of toxic substances and preserve water quality for ecosystem health.

Large explosions can also be triggered by natural phenomena, such as volcanic eruptions or meteoritic impact, which release enormous amounts of energy in a very short time. The Chicxulub crater was formed some 65 million years ago by the impact of an asteroid, which is believed to have caused the extinction of the dinosaurs and other species (DePalma et al., 2019). These natural explosions demonstrate that, whether caused by human activity or natural phenomena, sudden releases of energy share common destructive mechanisms and long-term environmental consequences.

Explosions therefore impact not only human societies but also the long-term health and stability of ecosystems, both on land and under the sea.

### 3.5.5 Case Studies: Beirut, AZF and Mount St. Helens

The Beirut accident demonstrated the devastating power of a massive urban explosion. Over 200 deaths, 6,000 injuries, and billions in damage left the city traumatised. Dust, asbestos and toxic chemicals contaminated the port and surrounding sea, turning a human disaster into an environmental one.

The AZF accident in Toulouse, France, on 21 September 2001, involved 300 tonnes of ammonium nitrate. It killed 31 people, injured over 2,500 and left 14,000 with psychological trauma. Thousands of buildings, including schools and hospitals, were damaged. Toxic residues polluted soil and water for years, and the site remained a hazardous wasteland long after the blast.

The eruption of Mount St. Helens (Bogoyavlenskaya et al., 1985) provides a natural example of explosive energy release. On May 18, 1980, the volcano erupted, producing powerful blast waves, pyroclastic flows and ash clouds. The eruption destroyed forests, damaged infrastructure and affected nearby towns. Approximately 57 people died, dozens were injured and large-scale evacuations were necessary. This event demonstrates that explosions are not solely human-made and can have devastating impacts on both ecosystems and human communities (Table 3.4).

Together, these examples show how explosive events—whether in cities, factories or natural settings—leave profound impacts on people and ecosystems. Thus, by understanding both natural and accidental explosions, we are better equipped to prevent tragedies, limit environmental damage, and build safer and more resilient societies.

**Table 3.4** Comparative overview of Beirut and AZF explosions

| Criteria | Beirut explosion (2020) | AZF explosion, toulouse (2001) | Mount St. Helens (1980) |
|---|---|---|---|
| Date and location | August 4, 2020—Port of Beirut, Lebanon | September 21, 2001—Toulouse, France | May 18, 1980—Washington, USA |
| Substance/ phenomenon | ~2,750 tonnes of ammonium nitrate | ~300 tonnes of ammonium nitrate | Volcanic magma, gases, pyroclastic flows |
| Human toll | >200 deaths, ~6,000 injured, thousands homeless | 31 deaths, >2,500 injured, ~14,000 psychological trauma | ~57 deaths, dozens injured, evacuations |
| Structural damage | Entire neighbourhoods destroyed; ~15 billion USD losses | Thousands of buildings damaged; schools and hospitals affected | Forests destroyed, infrastructure damaged, towns affected |
| Environmental impact | Toxic dust, asbestos, sea contamination | Soil and water pollution, industrial wasteland | Ash deposition, forest destruction, river and soil contamination |
| Geographical scale | Shockwave felt >200 km away | Severe damage several km away | Blast effects and ashfall over hundreds of $km^2$ |
| Aftermath | Ongoing reconstruction, political consequences | Regulatory reforms on industrial safety in France | Long-term ecological recovery, monitoring of volcanic hazards |

## 3.6 At the Edge of Knowledge: Research

The phenomenon of explosions is a very active research topic. A better understanding is still necessary to improve understanding, consequences modelling and operational safety strategies (mitigation, prevention, protection). A list of key challenges is given in Table 3.5. A common challenge to all types of explosions is the use of artificial intelligence to aid detection, but also the prevention, mitigation and protection from explosions.

This section specifically focuses on BLEVE. While this phenomenon has been studied for decades, its complexity and the difficulty in performing experiments limited the understanding of the physics involved in BLEVE.

BLEVE experiments are extremely dangerous and destructive. Any test involving a pressure vessel fitted with instruments will be destroyed after a successful test. Several large-scale tests were conducted previously, like the LPG railroad tests performed by BAM in Germany (Balke, 1999). This single test provided valuable data about the vessel heating and the aerial overpressure produced by the BLEVE, but with only three blast sensors.

It was decided to perform numerous small-scale tests to investigate the influence of key parameters (fill level, rupture pressure, size of rupture exit on the vessel) (Birk et al., 2019; Laamarti et al., 2024). A high-technology set of sensors and high-speed cameras were used to monitor in detail what was happening before and after the explosion. Figure 3.8 shows the small-scale test, filled with propane and heated by an electric plate, and the overall view of the setup with numerous aerial overpressure sensors in a 3D configuration.

High speed images just after the vessel rupture showed the dynamics of vessel opening and the ejection of the propane vapour, condensing by pressure drop (Fig. 3.9). The expanding vapour produced a pressure wave which was observable by shadowgraph optical technique (Fig. 3.10).

An optical access on the side of the tube allowed seeing the vapour ejection at the first time period, then the liquid started boiling and the flashed liquid was ejected. The timing

**Table 3.5** Challenges in explosion research

| Explosion type | Key challenges |
|---|---|
| Vapour cloud | Congestion effects, ignition sources, deflagration to detonation transition, hydrogen, mitigation and protection |
| Dust explosion | Particle combustion kinetics, flame acceleration, turbulence, nanoparticles |
| BLEVE | Phase change dynamics and contribution to overpressure creation, vessel rupture, prevention, fluid–structure interaction, cryogenic liquids, ammonia |
| Chemical runaway | Kinetics studies, early detection, prevention and protection, batteries |
| Under-ventilated fire | Backdraft, smoke explosion |

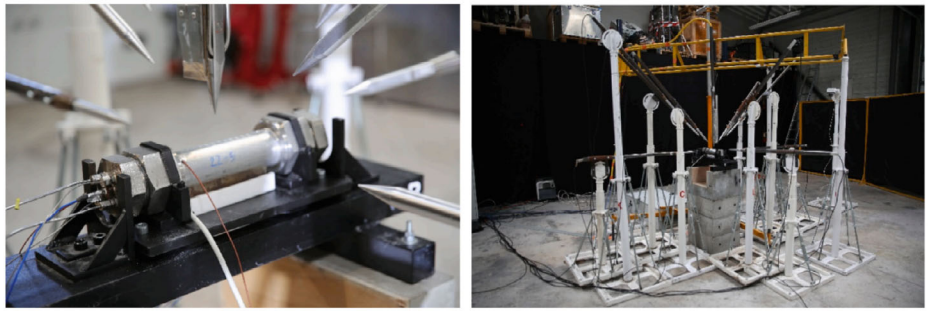


**Fig. 3.8** Experimental setup for BLEVE investigation

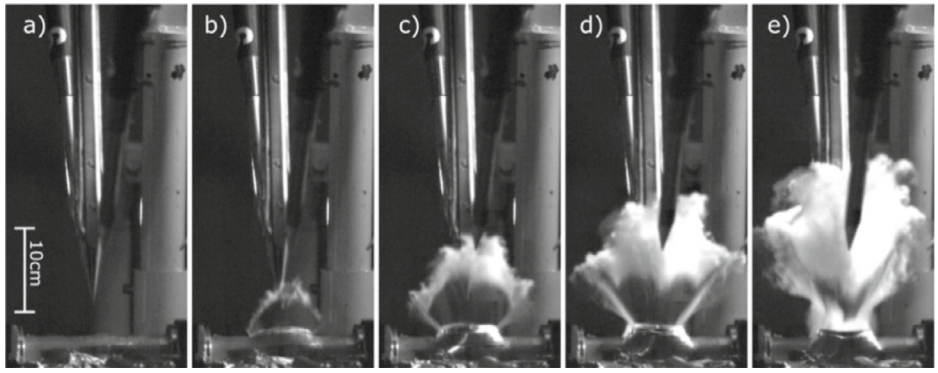



**Fig. 3.9** Side view with direct high-speed imaging (failure pressure = 18.6 bar; liquid fill = 56%)

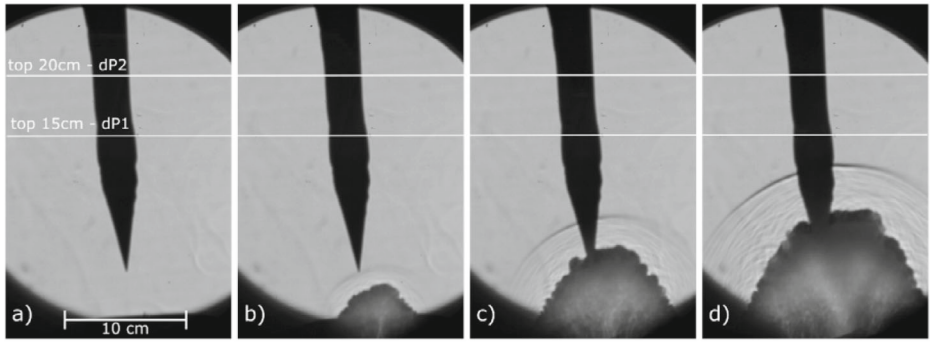



**Fig. 3.10** Radial view with shadowgraph high speed imaging (failure pressure = 19.3 bar, liquid fill = 84%)

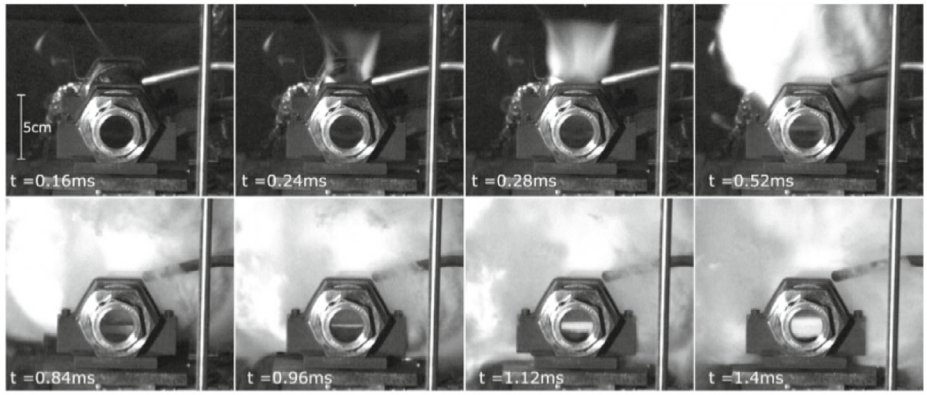



**Fig. 3.11** Axial view of the tube rupture, propane ejection and liquid phase change during BLEVE experiment

sequence of all events, and the comparison of rapid images with sensor data proved that the liquid boiling could not produce a significant overpressure wave (Fig. 3.11).

An example of pressure data is given on Fig. 3.12. The lead pressure peak is quite steep and reaches a high value of 0.8 bar, which is severe for consequences. The pressure peak is followed by a negative pressure phase and a second pressure peak, both of which are expected during pressurised gas release. There is no pressure peak that could have been created by the liquid boiling.

Figure 3.13 shows the internal pressure of the vessel during the BLEVE event. At the moment of failure, the pressure drops quickly, triggering the liquid boiling. This fast boiling is sufficiently intense to compensate for the pressure drop due to the vapour release and starts a pressure recovery at the maximum boiling phase. This pressure recovery lasts several milliseconds and then the slowing of the boiling decreases pressure until atmospheric pressure is reached.

Other conclusions concerned the aerial propagation of the pressure wave which was mainly oriented on a vertical axis above the vessel, dissipating the blast energy above the vessel and not on the sides where humans could stay. The force under the vessel, called ground force, was also measured and proved to be very intense, which may explain the collapse of a bridge during the BLEVE accident in Bologna in 2018.

Modelling work allowed establishing correlations to estimate the near field aerial overpressure and the ground loading.

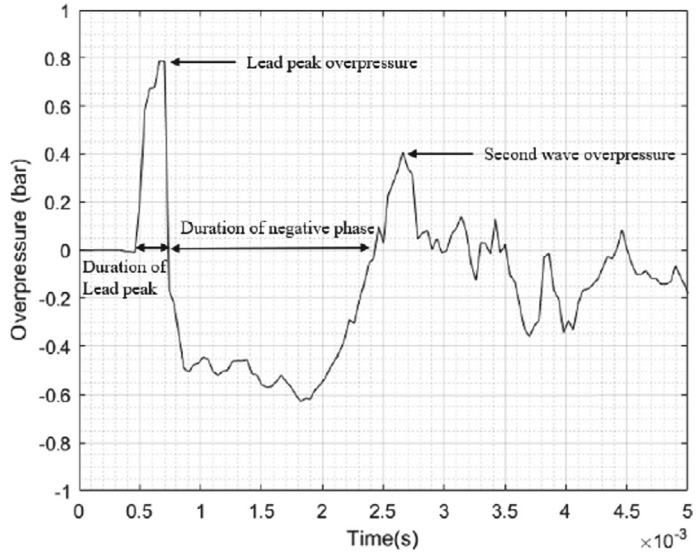



**Fig. 3.12** Blast overpressure profile at 15 cm above the tube (fill level = 57%; failure pressure = 33.7 Barg)

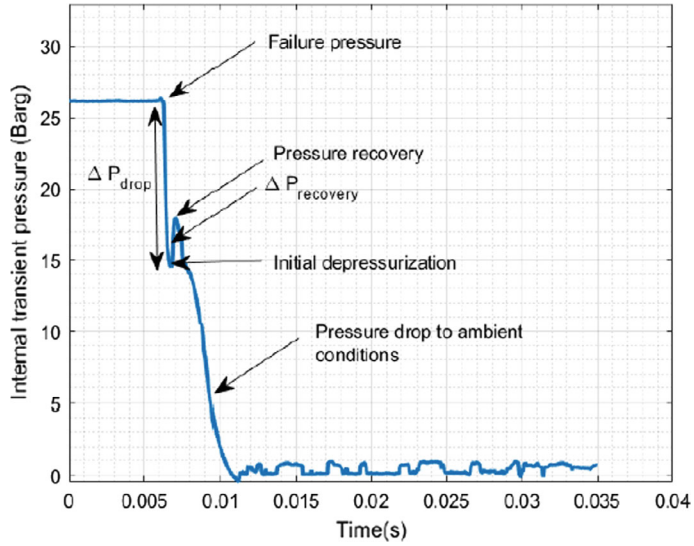



**Fig. 3.13** Internal transient pressure from test (fill level = 54%; failure pressure = 26.2 Barg)

## 3.7 Conclusion and Perspectives

The explosion risk was widely studied and resulted in a consistent achievement of scientific knowledge; modelling tools; prevention, mitigation and protection safety measures; regulations and standards and best practices.

However, society and technology evolve and new challenges offer rich perspectives of research and engineering knowledge. Some perspectives are.

- Hydrogen Safety: Even if hydrogen is used as a fuel in the future, and operating hazards are already known, introducing hydrogen in everyday life is a challenge since hydrogen is one of the most explosive and dangerous molecules that exist.
- Battery Explosion: The development of new batteries and the widespread use of batteries have recently shown that the explosion hazard is not fully controlled. Several cases of battery explosion have already occurred.
- Fusion: Nuclear fusion is hoped to be the new major source of energy for the future. Even if fusion is intrinsically not prone to lead to an explosion, the tokamak devices[1] can be threatened by hydrogen or metallic dust explosions
- Modelling: Explosion modelling by CFD is time consuming, and it is difficult to simulate explosions at a large scale. The transition from deflagration to detonation is still a challenge and requires supplementary work

**Key Sentences**

- Explosions result from rapid energy release—thermal, mechanical or chemical—producing hazardous effects such as overpressure, heat radiation, toxic dispersion or mechanical projection.
- The intensity and spatial extent of these effects depend on the underlying mechanisms, the quantity of material involved and environmental conditions.
- Understanding source-term dynamics is essential for modelling impacts, as the type of rupture, release mode and phase of the substance govern the evolution of dangerous phenomena.
- Accurate assessment of accidental scenarios requires integrating physical models and empirical correlations, enabling reliable estimation of lethal thresholds, damage distances and protection requirements for people and infrastructure.

[1] Experimental fusion devices that utilize magnetic confinement to produce, confine and heat plasma within a toroidal, doughnut-shaped vacuum vessel surrounded by magnetic field coils.

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# Understanding Industrial Fire Dynamics for Risk Management and Emergency Response

4

Guillaume Leroy and Laurent Aprin

**Abstract**

Industrial fires pose significant hazards to human safety, the environment, the economy and society. Their complexity and potential for rapid escalation require an integrated approach combining prevention, protection and organisational measures. This chapter analyses the risks associated with industrial fires, drawing on major incidents such as Buncefield in 2005 (UK) and Lubrizol in 2019 (France), and highlights the role of Seveso regulations in managing these risks. Protection measures include passive systems (firewalls, fire doors, intumescent coatings), active systems (detection, alarms and suppression technologies such as sprinklers, water mist, foam and inert gases) and organisational measures (staff training, emergency planning, equipment maintenance and coordination with external responders). Design and implementation rely on quantitative scenario assessment, thermal effect modelling and consideration of environmental conditions and equipment ageing. An integrated, adaptive strategy, continuously updated through technological innovation and stakeholder collaboration, is essential to mitigate the consequences of industrial fires and enhance resilience for facilities and surrounding communities.

**Keywords**

Industrial fire • Accident analysis • Fire dynamics • Safety barriers • Operational challenges

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## 4.1 Introduction

Industrial fires represent one of the most critical technological hazards due to their potential to cause severe impacts on people, the environment and the economy. Beyond immediate threats such as burns, toxic smoke exposure and explosions, large-scale fires in chemical plants, refineries or storage facilities often generate long-term health concerns for nearby populations. For instance, the 2019 Lubrizol fire in Rouen (France) led to widespread smoke dispersion and concerns about soil and food contamination over a large territory (Durand, 2025; Sainte-Claire Deville et al., 2021), while the 2005 Buncefield depot fire in the United Kingdom produced one of the largest explosions in Europe since World War II, causing massive structural damage and long-lasting environmental pollution (Atkins & Gant, 2014; Buncefield Major Incident Investigation Board (MIIB), 2008; Herbert, 2010).

Environmental impacts are equally significant, with massive emissions of pollutants into the atmosphere, soil contamination and large volumes of firefighting water carrying hazardous substances into rivers and aquifers (Fabiano et al., 2015; Stec et al., 2018). Economically, industrial fires can result in plant shutdowns, loss of production, supply chain disruptions and reputational damage for companies. The Badische Anilin- und Soda-Fabrik (BASF) fire in 2016 in Ludwigsha-fen (Germany), for example, disrupted supply chains across Europe and caused significant economic losses for multiple industries (BASF, 2017; OECD, 2018). Public authorities also bear high costs for emergency response, monitoring and remediation.

A growing challenge lies in the increasing proximity of residential areas to high-risk industrial zones, driven by urban expansion and land-use pressures (Reniers & Cozzani, 2013). This urban–industrial interface raises the stakes of fire scenarios, as larger populations are directly exposed to potential accidents. Moreover, climate change introduces additional stressors: rising temperatures, more frequent heatwaves and extreme weather events increase the likelihood of ignition, equipment degradation and cascading failures in industrial systems (IPCC, 2021; Krausmann et al., 2011). Recent fires in fuel depots triggered by extreme weather in Asia (Krausmann & Necci, 2021) and wildfires threatening industrial perimeters in Southern Europe illustrate how climate-related hazards amplify industrial fire risks (Planas et al., 2023).

Together, these examples underline the urgent need for improved fire prevention, land-use planning and resilience strategies to mitigate the risks associated with industrial fires.

## 4.2 Industrial Fires Past Accidents

The study of worldwide industrial fire accidents provides critical insights into the frequency, causes and consequences of fires in the chemical, petrochemical, energy and storage sectors. Globally, industrial fires remain among the most frequent technological

accidents, often resulting in fatalities, injuries, environmental pollution and substantial economic losses (Krausmann et al., 2011; Reniers & Cozzani, 2013). Large-scale databases such as the European Major Accident Reporting System (eMARS), the U.S. Chemical Safety Board (CSB) and France's ARIA (Analyse, Recherche et Information sur les Accidents) from BARPI (Bureau d'Analyse des Risques et Pollutions Industriels) provide comprehensive records of incidents, highlighting recurring patterns in causes and effects. Analyses show that most industrial fires result from human errors (improper operations, failure to follow safety procedures), technical failures (equipment malfunction, electrical faults, containment breaches) and hazardous material mismanagement (improper storage, chemical incompatibilities) (Cozzani et al., 2006; Stec et al., 2018). Specific fire scenarios such as pool fires, jet fires, tank fires, boilover (Laboureur et al., 2013) and BLEVE (Boiling Liquid Expanding Vapour Explosion) events frequently lead to domino effects, where an initial fire triggers secondary fires, explosions (see Chap. 3) or toxic releases in adjacent units, exacerbating consequences (CCPS, 2010).

Globally documented incidents illustrate both the scale and diversity of impacts. The 2005 Buncefield fuel depot fire in the United Kingdom produced a massive explosion and fireball, causing widespread structural damage and significant environmental contamination. In Asia, repeated fires at oil depots and chemical facilities in India, China and Pakistan have resulted in multiple fatalities, injuries and destruction of property, illustrating vulnerabilities in infrastructure and emergency preparedness (Chemical Safety Board, US (CSB), 2020). Statistical analysis of global databases indicates that fire incidents are more frequent in regions with high industrial density, particularly where older infrastructure or limited regulatory oversight exists, but the severity of accidents can be mitigated with robust safety management systems, preventive engineering and emergency planning.

In addition to immediate human and material impacts, industrial fires are increasingly recognised as multi-dimensional hazards, with environmental, economic and social repercussions that propagate far beyond the site of origin. Environmental impacts include air pollution, water contamination and soil degradation, while economic losses involve production downtime, repair costs and long-term market disruptions (OECD, 2018). Societal consequences include population displacement, psychological effects and erosion of public trust in industrial safety. The study of global industrial fire accidents, including Seveso relevant cases, underlines the need for comprehensive risk assessment methodologies, lessons learned integration, and harmonised reporting systems to enhance safety culture, regulatory enforcement and resilience against cascading incidents in industrial environments.

## 4.3 Risks Associated with Industrial Fires

Industrial fires represent complex and far-reaching hazards that go well beyond the immediate effects of flames. They can endanger human life, damage the environment, disrupt economic activity and generate widespread social concern. Beyond the direct physical risks, these events often release toxic substances that threaten health and ecosystems, while also causing significant financial and reputational losses for industries and authorities. Moreover, the increasing proximity between industrial and residential areas, combined with the growing influence of climate change, further heightens both the likelihood and severity of such incidents.

1. *Human Health and Physical Risks*: The most immediate risks concern human safety and physical harm. Workers and nearby populations can suffer from direct exposure to flames, thermal radiation and intense heat, which may cause first- to third-degree burns, heatstroke and even fatalities. Thermal radiation from pool fires, jet fires or BLEVE events can injure individuals even at considerable distances, depending on the fire size and shielding. In addition, fires in chemical and storage facilities often release toxic smoke and gases, including carbon monoxide, hydrogen cyanide, dioxins and other combustion by products, causing respiratory damage, asphyxiation and long-term carcinogenic effects (Stec et al., 2018). The 2019 Lubrizol fire in Rouen (France) demonstrated both acute exposure risks to emergency responders and public health concerns for surrounding communities (Sainte-Claire Deville et al., 2021).
2. *Environmental Risks*: Industrial fires can generate extensive environmental damage. Combustion releases large volumes of greenhouse gases, particulate matter and toxic chemicals into the atmosphere (Fabiano et al., 2015). Firefighting operations frequently involve significant quantities of water, which can carry contaminants into rivers, soils and groundwater, compounding environmental degradation (CIRIA 2019). For instance, post-incident analyses of Buncefield demonstrated widespread soil contamination and persistent pollutant dispersion resulting from firefighting water runoff (Buncefield Major Incident Investigation Board (MIIB), 2008).
3. *Economic Risks*: Industrial fires can severely disrupt production, destroy infrastructure, damage inventories and interrupt supply chains at both national and international levels. The BASF Ludwigshafen fire exemplifies the economic ramifications, with major supply chain disruptions and long-term financial losses for the chemical sector (BASF, 2017; OECD, 2018). Additionally, legal liabilities, remediation costs and reputational damage can further exacerbate economic impacts.
4. *Societal and Public Risks*: The proximity of industrial sites to urban areas heightens societal risks, as fires can endanger residential populations and trigger public concern and distrust towards industries. Media coverage may amplify these risks, influencing public perception and potentially affecting regulatory and corporate decision-making (Reniers & Cozzani, 2013).

5. *Emerging Risks due to Climate Change and Urbanisation*: Climate change introduces new stressors to industrial fire risks. Rising temperatures, heatwaves and extreme weather events can increase the likelihood of ignition, compromise equipment integrity and exacerbate cascading failures (IPCC, 2021; Krausmann et al., 2011). Simultaneously, urban expansion increasingly places residential areas near high-risk industrial sites, raising potential exposure and complicating emergency response planning (Cozzani et al., 2006).

**Important** Industrial fires are multi-dimensional hazards with cascading effects across human, environmental, economic and societal domains. Effective risk mitigation requires integrated strategies combining technical prevention measures, robust emergency planning, land-use regulations and adaptation to climate-related stressors.

## 4.4 Evolution of the Seveso Regulation Related to Fire Accidents

The Seveso Directive (European Commission, 2012), established in the European Union, represents the cornerstone of industrial safety regulation for sites handling large quantities of dangerous substances. Its origins trace back to the Seveso disaster in Italy in 1976, when a chemical plant released highly toxic dioxins, resulting in widespread contamination and health hazards. The initial Seveso Directive (1982) aimed to prevent similar major accidents by requiring industrial operators to identify hazards, implement safety measures and report incidents to authorities. Following successive accidents, the Directive evolved into Seveso II (1996) and later Seveso III (2012/18/EU), which incorporated lessons from events such as the AZF Toulouse fertiliser plant explosion (2001) and the Lubrizol Rouen fire (2019).

Seveso regulations explicitly address fire risks due to their frequency and potential for escalation. Industrial operators are required to perform Major Accident Hazard Assessments (MAHAs) that include fire scenarios, domino effects and potential thermal radiation impacts on nearby populations and infrastructure. Risk management obligations under Seveso III include prevention and mitigation measures, such as fire detection and suppression systems, safe storage arrangements, separation distances and emergency response planning. The Directive also emphasises land-use planning to minimise exposure of the public and sensitive environments to industrial fires. Over time, Seveso has increasingly integrated Quantitative Risk Assessment (QRA), advanced modelling of thermal radiation,

pool fires, and BLEVE events, and lessons learned from historical accidents to reduce both the probability and consequences of industrial fires.

Recent evolutions reflect a growing recognition of emerging challenges: urban expansion brings residential areas closer to high-risk sites, and climate change exacerbates fire risks through heatwaves, drought and extreme weather events. Seveso III thus promotes a systematic, proactive safety culture, requiring operators to continuously evaluate fire hazards, update safety reports and coordinate with local authorities for emergency preparedness. Overall, Seveso represents a dynamic framework that has progressively strengthened preventive and mitigative measures against industrial fires, ensuring that both technological and environmental risks are effectively managed across Europe.

## 4.5 Basic Principles of Combustion

### 4.5.1 Fundamental Principles of Combustion

Combustion is an exothermic redox chemical reaction between a fuel and an oxidizer, most often oxygen present in ambient air (Warnatz et al., 2006). It produces heat, light and smoke. Smoke consists of gases (water vapour, carbon dioxide, carbon monoxide, nitrogen oxides and possibly other components such as sulphur and/or halogen-containing molecules depending on the fuel composition) and solid particles (soot, molecules from the thermal decomposition of the fuel, unburned particles, etc.) For combustion to occur, three elements must be present: the fuel (matter source), the oxidizer (usually air) and an energy source (spark, flame, heating, etc.) This triad constitutes the ‘fire triangle’. When all three elements are simultaneously present under favourable conditions, a combustion reaction can initiate. In certain configurations, such as oxygen-enriched environments, the energy required for ignition can be very low because oxygen accelerates the reaction (Zabetakis, 1965).

### 4.5.2 Characteristics of Fuel and Oxidizer

Fuels can be solid (cellulose, polymers, textiles, etc.), liquid (hydrocarbons, solvents, ketones, etc.) or gaseous (methane, propane, hydrogen, acetylene, etc.) Since combustion generally occurs in the gaseous phase, solid or liquid fuels must undergo thermal decomposition (pyrolysis, vapourisation, cracking) to produce reactive gaseous species. This phase change requires energy, supplied by the heat of the reaction. Combustion kinetics strongly depend on the thermal and physical properties of the fuel, including thermal conductivity, heat capacity, flash point and ignition temperature.

The oxidizer is generally air, but some reactions may involve other oxidising gases (chlorine, pure oxygen) or oxygen molecules contained in the fuel itself, such as in

organic peroxides. In industrial or accidental contexts, oxygen enrichment can result in significantly higher reaction rates and heat release rates, making fires more intense and difficult to control.

### 4.5.3 Fire Development

A fire generally develops in four phases: ignition, growth, fully developed combustion and decay/extinction. During the ignition phase, the activation energy provides the thermal input required to reach the minimum ignition temperature of the fuel. This energy can originate from various sources: open flame, hot surface, electric spark, mechanical friction, electric arc, infrared radiation, etc. In industrial settings, these sources are ubiquitous: engines, portable tools, electrical circuits, heating equipment, heated metal surfaces, etc. The chemical reaction starts locally. If conditions are met and the fuel absorbs enough heat, the growth phase begins, temperature rises and gas emissions intensify.

Fully developed combustion is characterised by a dynamic balance between fuel supply, oxygen availability and heat dissipation. The flame heats the fuel, which reaches its flash point, generating vapours that mix with air oxygen; this mixture ignites from the energy contained in the flame. This self-sustaining phenomenon is commonly called the feedback loop.

The decay and extinction phase occur either when the fuel is fully consumed or when one element of the fire triangle is removed by.

- cooling (e.g. water application),
- isolation of the fuel by cutting off supply (applies mainly to torch fires),
- smothering (reducing oxygen concentration, foam, inert gas, etc.)

### 4.5.4 Parameters Affecting Combustion

In an enclosed space, ventilation becomes a critical parameter: combustion can be controlled by ventilation when oxygen is the limiting factor. In such cases, the reaction generates smoke containing a significant proportion of incompletely oxidised products (CO, HCN, soot, etc.), increasing atmospheric toxicity.

Combustion can be complete or incomplete depending on flame oxygenation. Complete combustion, usually well-ventilated, fully oxidises the fuel, producing mainly carbon dioxide and water vapour. This situation is rarely encountered in industrial accidents, as large fires often prevent efficient oxygenation at the flame centre. Incomplete combustion results from oxygen deficiency, poor mixing or insufficient temperature, producing carbon monoxide, unburned hydrocarbons, soot and toxic compounds, posing significant health and environmental hazards.

The combustion in confined or semi-confined industrial settings is governed by multiscale coupled phenomena:

- Thermal reaction and flame spread are related to the conduction, convection and radiative heat transfer that drive ignition and growth. The heat release rate (HRR), expressed in kW or MW, is the primary parameter characterising fire intensity and scaling accident scenarios.
- Fluid dynamics and turbulence flow impact strongly the mixing of air and fuel which governs flame stability and smoke propagation.
- Chemical kinetics govern the combustion pathways which also depend on fuel composition (aliphatic hydrocarbons, alcohols, polymers, halogenated solvents). This generates incomplete combustion products with acute or chronic toxicity.

### 4.5.5 Industrial Consequences of Combustion and Risk Control

Uncontrolled combustion in industrial environments is a critical undesired event with cascading consequences. A fire in an industrial facility can cause severe human, material, economic and environmental consequences. It can induce direct thermal damage to equipment (structural collapse, loss of containment, weakening of materials due to elevated temperatures) and indirect impacts, such as toxic gas emissions (CO, HCN, NOx, halogenated species), smoke-induced visibility loss, contamination of soil and groundwater through fire effluents or fire-fighting runoff, and disruption of critical utilities and production chains. Long-term liabilities often arise from corrosion, persistent pollutants and downtime in industrial processes.

Moreover, industrial fire can involve other dangerous phenomena such as flash-over (characterised by a rapid increase in HRR, typically >1 MW in compartments), backdraft (re-ignition due to sudden oxygen influx) and potential escalation via domino effects (e.g. BLEVE, Vapour Cloud Explosion (VCE), toxic cloud formation). These different phenomena can also be classified by flame propagation speed: slow (thermal degradation, pyrolysis), fast (typical fires) or very fast, up to deflagration or detonation in specific cases (e.g. dust or gas explosions).

**Important** Combustion is a complex phenomenon governed by multiple physical and chemical interactions. Thorough understanding is essential for preventing fire outbreaks, modelling accident scenarios and implementing effective fire risk control measures. Understanding combustion in industrial facilities requires a holistic approach combining thermodynamics, fluid mechanics, chemical kinetics and risk engineering. Mastery of these aspects allows engineers and safety professionals to

model credible accident scenarios, anticipate escalation pathways, and design robust fire prevention and suppression measures, thereby reducing both immediate and systemic risks.

## 4.6 Heat Transfer Mechanisms

### 4.6.1 Fundamental Principles of Heat Transfer

Heat transfer refers to physical processes by which thermal energy moves from one point to another due to a temperature gradient. It plays a key role in fire development, propagation and interaction with the environment. Three classical modes are identified: conduction, convection and radiation. They can act independently or coupled, depending on the medium, geometry and thermomechanical properties of materials. Understanding these mechanisms is crucial for assessing thermal risk and anticipating fire dynamics or thermal runaway.

### 4.6.2 Three Modes of Heat Transfer

#### 4.6.2.1 Conduction: Heat Transfer in Solids

Conduction is heat transfer within a solid or between solids in contact, without macroscopic matter movement. It results from particle agitation (atoms, electrons, molecules) transmitting energy via vibration and collisions. Heat flows from hot to cold zones, according to Fourier's law. The thermal flux vector is proportional to the temperature gradient, with thermal conductivity as the proportionality factor. Metals like copper or aluminium are excellent conductors, whereas insulating materials (mineral wool, polymer foam, ceramic fibre) have much lower conductivities. System geometry (thickness, contact surface) also affects transfer efficiency. In industrial settings, conduction transmits heat through firewalls, ducts or fire barriers and can gradually heat distant elements, potentially causing secondary ignition.

#### 4.6.2.2 Convection: Heat Transfer in Moving Fluids

Convection transfers heat in a fluid (gas or liquid) through fluid motion. It can be natural (density variation due to temperature) or forced (flow induced by ventilation or jets). Convective transfer depends on gas temperature, flow velocity and direction, fluid viscosity and obstacles. Newton's law states that heat flux is proportional to the temperature difference between the surface and the fluid, via the convective heat transfer coefficient, which varies with flow regime and geometry. In fires, convection transports hot smoke, moves

combustible gases, heats surrounding structures and contributes to vertical temperature rise in enclosed spaces.

#### 4.6.2.3 Radiation: Heat Transfer Without Contact

Thermal radiation transfers energy via electromagnetic waves and does not require material support, allowing heat transfer through a vacuum. All bodies at non-zero temperature emit thermal radiation, with intensity and spectrum depending on absolute temperature (Planck's law) and emissivity. Radiant power increases rapidly with temperature (Stefan-Boltzmann law), making it dominant in fully developed fires. Radiation propagates in straight lines, attenuated by absorption or scattering in smoke, and reflected by some surfaces (metallic, glass). In industrial settings, it can heat materials at a distance, trigger ignition or threaten temperature-sensitive structures. Accounting for radiation is essential in safety distance calculations, thermal shielding and cooling system design.

### 4.6.3 Interaction of Heat Transfer Modes

In practice, conduction, convection and radiation often act together. For example, in a warehouse fire with pallet racks, heat first conducts to adjacent pallets, hot gases circulate via convection in upper shelves and radiation warms nearby racks. The combination of the three modes governs fire development. Understanding these mechanisms is essential for assessing thermal hazards, preventing fire escalation, limiting spread and protecting sensitive installations.

## 4.7 Modelling Thermal Effects

### 4.7.1 Principles of Modelling

Thermal effect modelling is crucial in industrial risk analysis. It evaluates fire consequences, determines hazard zones, optimises protection measures and sup-ports risk control decisions. It relies on defining credible scenarios based on the substances handled and processes used.

Modelling assesses heat flux from the source to targets: population, operators, critical equipment or containment structures. Approaches include simplified empirical models as proposed in the Yellow Book (T.N.O., CPR 14E, 1996), intermediate phenomenological tools or advanced numerical methods such as Computational Fluid Dynamics (CFD). Model choice depends on study objectives, required detail and trade-off between precision and computation time.

Empirical models estimate incident heat flux at different distances using flame height, radiant power and emissivity. Phenomenological tools incorporate simplified physics of

radiation, convection and combustion kinetics to simulate fire scenarios realistically, e.g. using EFFECTS, PHAST (Process Hazard Analysis Software Tool) or FDS (Fire Dynamic Simulator) software. CFD models provide 3D simulations of radiation, convection, hot gas dynamics and site geometry, allowing detailed analysis for critical safety decisions.

#### 4.7.1.1 Analytical Models

Analytical models, as presented in the Yellow Book of TNO, provide a structured framework for assessing thermal radiation and fire effects using relatively simple mathematical formulations. These models rely on physical principles and empirical correlations to estimate parameters such as flame length, heat flux and impact distance. They are particularly useful for defining safety distances and hazard zones in quantitative risk assessments (QRA). The Yellow Book approach offers standardised methodologies that are transparent, reproducible and widely accepted by regulators, which makes them valuable in the context of regulatory compliance and preliminary safety studies. However, while analytical models are fast and cost-effective, they rely on simplifying assumptions (homogeneous atmosphere, steady flame behaviour, absence of complex geometrical effects), which may limit their accuracy in real accident scenarios, especially for large-scale fires or installations with congested layouts.

#### 4.7.1.2 Computational Fluid Dynamics (CFD) Simulations

Computational Fluid Dynamics modelling represents the most advanced approach for analysing thermal effects in industrial fire scenarios. By numerically solving the fundamental equations of fluid mechanics (Navier–Stokes equations) combined with combustion and heat transfer models, CFD provides a detailed three-dimensional representation of fire dynamics. Unlike analytical models, CFD simulations capture the complexity of flame radiation, convection, turbulent flows and the interaction with site geometry (buildings, equipment, obstacles). They allow the identification of critical effects such as flame impingement, shadowing and localised overheating of equipment, which are often underestimated by simplified models.

CFD tools (e.g. FLACS, Fire Dynamics Simulator—FDS, ANSYS Fluent) are particularly relevant for high-stakes decisions, such as designing passive fire protection, optimising emergency response strategies or assessing domino effects between adjacent units. They are also increasingly used to simulate non-conventional scenarios, such as fires involving new fuels (e.g. liquefied natural gas (LNG), hydrogen, ammonia). The main limitations of CFD remain their computational cost, the expertise required for model setup and validation, and the sensitivity to input parameters (combustion models, boundary conditions). Nevertheless, when applied with rigorous validation and calibration, CFD simulations provide a unique level of insight into fire dynamics, making them a cornerstone of advanced industrial risk analysis (Fig. 4.1).

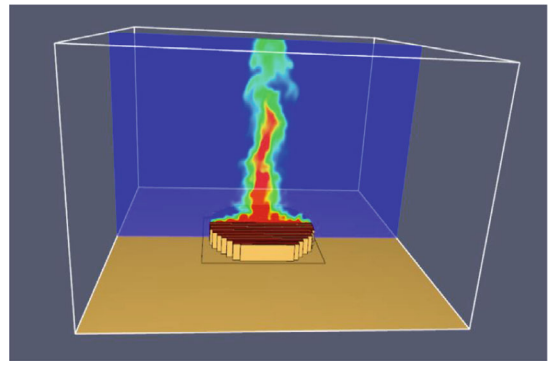


**Fig. 4.1** Illustration of a simulation of corn oil pool fire obtained with an FDS

### 4.7.2 Interpretation and Integration in Risk Management

Thermal modelling results must be carefully interpreted and integrated into prevention and protection strategies. Heat flux values are compared with tolerance thresholds from literature or experience (e.g. 3 kW/m$^2$ for prolonged human exposure; >8 kW/m$^2$ for potential domino effects for French radiative heat fluxes threshold regulations (French Ministry for sustainable development—DGPR/SRT/BARPI, 2013)). Impact zones help define safety perimeters, evacuation plans and protection system design (passive barriers, active suppression). Modelling assumptions and uncertainties require conservative interpretation, validation with experiments and updates when facility conditions change. Thermal modelling is thus a decision-support tool within a comprehensive industrial risk management approach.

## 4.8 Fire Protection Measures

### 4.8.1 Principles, Devices and Strategies in Industrial Environments

Industrial fire protection relies on technical, organisational and human measures to prevent ignition, limit fire spread and mitigate consequences. Protection strategies are structured into passive protection, active protection and organisational measures.

#### 4.8.1.1 Passive Protection

Passive fire protection measures are permanently integrated into the facility to slow down fire propagation or to contain its effects. They include structural barriers such as firewalls and fire doors, the design of adequate separation distances between hazardous units, containment trays for flammable liquids, as well as protective layers like intumescent coatings which expand under heat to shield steel structures. A key element is the fire resistance of construction materials, usually expressed in terms of standardised ratings (e.g. REI 60,

REI 120), which guarantee the load-bearing capacity (R), integrity (E) and insulation (I) of elements for a given duration under fire exposure.

In the industrial context, passive fire protection is closely framed by regulatory requirements and technical standards. European construction codes (Eurocodes, EN 13,501) and national building regulations define minimum fire-resistance levels depending on the type of occupancy, stored products and potential hazards. In high-risk industries, Seveso III Directive (2012/18/EU) requires operators to demonstrate robust fire prevention and mitigation measures, often including passive protection as part of the safety report. Similarly, international standards such as the National Fire Protection Association (NFPA) and International Organization of Standardization (ISO 834) provide testing methodologies and performance criteria to qualify fire-resistant structures and materials. Compliance with these regulations is not only a legal obligation but also a prerequisite for limiting liability, protecting assets and ensuring continuity of operations in the event of an accident.

Unlike active systems, passive protections operate continuously without requiring activation or energy supply, making them a reliable and indispensable part of industrial fire safety strategies. Their effectiveness lies in combining regulatory compliance, sound engineering design and long-term durability to reduce escalation risks and support emergency response.

#### 4.8.1.2 Active Protection

Active fire protection systems are designed to detect, alert and suppress fires through a combination of automatic and manual interventions. They include smoke, flame, or heat detectors, alarm and communication systems, and fixed extinguishing installations such as sprinklers, water mist networks, foam systems, $CO_2$ or inert gas flooding, and chemical powders. The selection of an active protection system depends on the nature of the combustible substance, the storage configuration (open areas, warehouses, confined rooms), potential chemical reactions and operational constraints such as accessibility or sensitivity of the equipment to water damage.

The most common systems are.

- Sprinklers, which automatically discharge water when exposed to heat, and are widely used for Class A fires involving ordinary combustibles (wood, paper, textiles).
- Water mist systems, which create very fine droplets that both cool the flames and locally inert the atmosphere, making them suitable for hydrocarbon fires and for protecting sensitive electrical installations.
- Foam systems, effective against flammable liquid fires, with varying expansion ratios (low, medium, high) adapted to fuel storage tanks, chemical facilities or spill containment areas.
- Gaseous extinguishing agents, including inert gases (e.g. nitrogen, argon) and chemical agents such as $CO_2$, FM-200 or Novec 1230, typically used in enclosed and unoccupied

technical rooms (server rooms, electrical cabinets, turbine enclosures) where water or foam would cause unacceptable collateral damage.

From a regulatory standpoint, the design, installation and maintenance of active fire protection systems must comply with recognised international standards. Notable references include NFPA codes (NFPA 13 and NFPA 15 for sprinklers and water spray systems, NFPA 11 for foam, NFPA 2001 for gaseous systems), ISO standards (ISO 14520 for gaseous extinguishing systems) and European Norms such as EN 12,845 for sprinkler systems and EN 54 for detection and alarm systems. In the industrial domain, operators subject to the Seveso III Directive (2012/18/EU) are required to integrate reliable and redundant active protection measures within their safety reports to prevent escalation of major accident scenarios.

**Warning** Unlike passive measures, which are always effective by construction, active systems depend on proper design, reliable detection and regular maintenance to function when required. Their effectiveness lies in rapid intervention: they not only limit fire growth and facilitate evacuation but also reduce the potential for domino effects in hazardous industrial facilities.

#### 4.8.1.3 Organisational Measures

Organisational measures represent a critical layer of fire protection in industrial settings, complementing passive and active systems by ensuring that people, procedures and resources are effectively mobilised in the event of an incident. These measures require personnel training programmes, which develop awareness of fire hazards, teach the proper use of extinguishing equipment, and clarify roles during emergency situations. The implementation of Internal Operation Plans (POI) defines the chain of command, communication protocols and predefined emergency actions to be taken by staff, thereby reducing confusion and delays during an outbreak. Preventive maintenance of fire safety equipment (detectors, sprinklers, hydrants, extinguishers) is also essential to guarantee that technical systems operate as intended when activated.

Organisational measures also require Regular emergency drills and simulation exercises to ensure that workers can respond quickly and efficiently, testing both human reactions and the robustness of procedures under realistic conditions. These exercises also strengthen familiarity with evacuation routes, assembly points and safe zones. Beyond the site perimeter, effective fire protection requires coordination with external emergency services, established through detailed intervention plans (such as the 'Plans Particuliers d'Intervention' (PPI) in France) and cooperation agreements with local fire brigades, hospitals and civil protection authorities. This coordination facilitates a rapid and coherent response in case of a major accident scenario, aligning on-site resources with external capabilities.

**Important** By integrating organisational measures into daily operations, industrial operators build a culture of safety where preparedness, vigilance and communication reduce response times, limit fire escalation, and ultimately protect people, assets and the environment.

### 4.8.2 Design, Integration and Reliability

Fire protection measures must be tailored to the specific scenarios identified through risk assessment, considering parameters such as fire development time, calorific load, exposed surfaces and the presence of obstacles. Quantitative evaluation and thermal effect modelling are essential to optimise both the type and placement of protective systems. Effective protection requires close coordination between detection, alarm, suppression, ventilation and containment systems, supported by independent safety loops and reliable backup power supplies. Since environmental conditions and material ageing can significantly affect performance, rigorous inspection, maintenance and periodic testing are indispensable. Industrial fire protection therefore relies on an integrated strategy that combines prevention, detection, suppression and emergency organisation, adapted to the nature of the facility, the hazardous substances handled and the risks to the surrounding environment. To remain effective over time, this strategy should be continuously reassessed, strengthened by technological innovation and supported by active collaboration among operators, regulators and emergency services.

## 4.9 Conclusion

Industrial fires constitute complex, multidimensional hazards that can trigger cascading effects across human, environmental, economic and societal domains. The analysis of past major accidents—such as Lubrizol (France, 2019), Buncefield (UK, 2005) and AZF Toulouse (France, 2001)—demonstrates the profound consequences of inadequate prevention, delayed detection or insufficient preparedness. These incidents highlight recurring vulnerabilities, including human errors, technical failures and mismanagement of hazardous substances, which can escalate into domino effects affecting adjacent units and surrounding communities.

Effective mitigation of industrial fire risks requires a layered and integrated strategy combining passive, active and organisational measures. Passive protections—firewalls, fire doors, separation distances and fire-resistant coatings—slow fire propagation and maintain structural integrity, providing critical time for intervention. Active systems—detection,

alarm and suppression technologies such as sprinklers, water mist, foam and inert gases—ensure rapid response to control and extinguish fires. Organisational measures, including staff training, emergency plans, preventive maintenance, drills and coordination with external responders, reinforce preparedness and response capacity, reducing human and material losses.

The design and implementation of these measures must be informed by quantitative risk assessments, thermal effect modelling and scenario-based planning, considering factors such as fuel characteristics, fire dynamics, environmental conditions and equipment ageing. Regulatory frameworks, particularly the Seveso III Directive, provide a robust foundation for risk management, emphasising hazard identification, emergency preparednessand land-use planning to protect both workers and surrounding populations.

Moreover, emerging challenges—urban expansion, climate change and increasing proximity of residential areas to high-risk industrial sites—further elevate the stakes, requiring adaptive strategies and continuous improvement. Investment in technological innovation, integration of lessons learned from past accidents and active collaboration between operators, regulators and emergency services are essential to build resilient industrial systems.

In conclusion, industrial fire protection is not a static process but a dynamic, multi-dimensional approach that combines engineering, operational and organisational strategies. Only through a comprehensive, continuously reassessed framework can industrial operators effectively prevent incidents, mitigate their consequences and safeguard human health, environmental integrity and societal trust. A proactive, integrated approach is therefore indispensable for ensuring the resilience and sustainability of industrial operations in an increasingly complex and high-risk environment.

## 4.10 Perspectives

Industrial fire safety is undergoing a profound transformation driven by environmental, technological and societal change. The convergence of new energy systems, digitalisation and climate-related stressors is reshaping both the nature of fire risks and the strategies used to prevent and manage them.

The transition towards low-carbon and alternative fuels—such as hydrogen, ammonia, methanol and biofuels—introduces combustion behaviours and explosion dynamics that differ significantly from conventional hydrocarbons. Understanding their flammability limits, radiant heat fluxes and combustion by-products is essential to design safe storage, transfer and transport systems.

Advances in sensors, real-time monitoring and data analytics are enabling predictive fire safety management. The integration of Artificial Intelligence (AI), machine learning and physical modelling (e.g. CFD) allows early anomaly detection, faster decision-making

and adaptive safety barrier management. Digital twins of industrial sites could transform fire protection from a reactive to a proactive process.

At the same time, rising temperatures, prolonged droughts and more frequent wildfires are increasing industrial vulnerability, especially at the wildland–industrial interface (see Chap. 6). This calls for hybrid models that couple industrial fire dynamics with natural hazard behaviour, and for the redesign of protection systems to resist combined stresses such as heatwaves and power failures.

Beyond technical measures, the social dimension of fire risk management—transparency, communication and trust—remains crucial. Experience shows that public perception and crisis communication can influence territorial recovery as much as physical damage. Strengthening resilience thus requires reinforced local governance, cross-sector cooperation and community participation.

Overall, industrial fire safety is moving towards an integrated, anticipatory paradigm combining advanced scientific understanding of combustion with digital innovation, climate adaptation and social engagement. Research and regulation must co-evolve to ensure that industrial systems remain both safe and sustainable in a context of accelerating energy and environmental transitions.

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# From Oil Spills to Chemical Accidents: Strengthening Marine Pollution Preparedness and Response

5

Stéphane Le Floch and Laurent Aprin

**Abstract**

Accidental marine pollution remains a major concern despite the decline in large oil spills from tankers in recent decades. The rapid growth of maritime transport, particularly of hazardous and noxious substances (HNS), introduces new risks that are less visible but potentially more severe than those associated with hydrocarbons. This paper reviews accident trends, regulatory frameworks and operational responses to oil and chemical spills at sea. The analysis highlights the variability of oil spill volumes, the toxicological and physio-chemical complexity of HNS, and the challenges posed by their detection and management. The Standard European Behaviour Classification (SEBC) provides a reference framework to predict the fate of substances spilled at sea (evaporation, dissolution, floating, sinking), and its integration into decision-support tools such as the HNS-MS database strengthens preparedness and response strategies. The study also considers the emerging risks related to the use of alternative marine fuels (LNG, ammonia, methanol, hydrogen), underlining the need for adapted response plans. Overall, strengthening monitoring, databases, modelling and inter-agency coordination is crucial to improve the effectiveness of marine pollution response in an evolving maritime transport context.

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**Keywords**

Marine pollution • Chemical substances • Maritime transport accidents • SEBC classification • Preparedness and response

## 5.1 Introduction

International maritime transport plays a central role in global trade, accounting for more than 80% of international trade volume in terms of tonnage (UNCTAD 2023). This transport is organised on a global scale around major maritime routes connecting the main industrialised regions. The intensity of this traffic depends both on the degree of urbanisation of the territories served and on the morphological configuration of their coastlines. These preferred maritime routes often run along coastlines, thus generating areas of high traffic density. Among the most strategic passages are the Straits of Malacca, Singapore, Hormuz and Gibraltar, as well as the Suez and Panama Canals. Certain seas also experience particularly heavy traffic, such as the Mediterranean, the English Channel and the North Sea (Mamaca et al., 2003). In addition to these areas, which are already considered sensitive, the Arctic route is now gradually opening up as global warming accelerates the melting of sea ice. Consisting of the Northwest Passage and the Northeast Passage, it offers the prospect of considerable time savings in trade with Asia. In mainland France, the Channel-North Sea region is a major hub for global maritime traffic, accounting for nearly 20% of the total. This shipping corridor, which is strategic for transit between the Atlantic Ocean and the North Sea, is characterised by exceptionally high traffic: on average, around 800 ships pass through it every day, excluding fishing and pleasure craft (Bahé, 2008).

## 5.2 The Evolution of Maritime Transport Accidents

Although maritime transport is more energy efficient per tonne transported than other modes of transport, it has a significant impact on the climate and can have catastrophic consequences for society, the economy and the environment in the event of accidental spills. These accidents are often associated with oil spills because of the media coverage they receive due to their high visual impact, major ecological and economic consequences, and symbolic importance in environmental and energy debates. Images of blackened beaches, oil-covered birds or oil slicks on the water's surface are particularly striking. These shocking scenes, often relayed through photographs or videos, allow for easy, rapid and emotional media coverage that elicits a strong public reaction. Oil spills cause serious damage to the environment by directly threatening marine wildlife and destroying coastal ecosystems, some of which are unique, with potentially lasting consequences for biodiversity. In addition, these disasters have a significant impact on key economic sectors

such as fishing, tourism and maritime transport, resulting in significant financial losses for local communities and requiring clean-up operations that can cost millions or even billions of pounds. These oil spills have a strong symbolic value and crystallise global issues: dependence on hydrocarbons, the fragility of marine ecosystems and the limits of a growth model based on the exploitation of fossil resources. They thus become catalysts for social debate, far beyond the event itself. Since the 1970s, the frequency and volume of spills from oil tanker accidents have declined significantly, thanks to a combination of stricter regulations (International Convention for the Prevention of Pollution from Ships—MARPOL double hulls), improved navigation practices and satellite monitoring. Accident analysis carried out by the International Tanker Owners Pollution Federation Limited (ITOPF) shows that the number of incidents involving tankers and resulting in spills >7 tonnes remained at historically low levels in 2023 and 2024 (10 cases/year), whereas it was much higher in previous decades (ITOPF, 2024). This finding is consistent with European satellite detections (EMSA, 2025), which recorded a ~2 fold decrease in possible oil spills per monitored area between 2007 and 2017.

However, another threat is just as real: the dangers associated with the maritime transport of chemicals. Today, the chemical industry is at the heart of the global economy and requires significant flows of goods between production sites and consumption areas. Some 37 million chemicals are used by the world's population and 2,000 are regularly transported by sea. Transport volumes are currently on the rise, with the maritime transport of chemicals having more than tripled over the last 20 years. The risks have become increasingly acute, particularly due to the growing number of ultra-large ships and the high intensity imposed by global market pressures. The threat of a chemical spill at sea is a concern for many public and private interest groups, as the pollution caused is often invisible and can seem difficult to manage. The maritime transport of hazardous and potentially dangerous substances (HPS) has increased over the last 20 years, leading to a risk of major pollution accidents that are potentially more dangerous than those involving oil. The European Maritime Safety Agency (EMSA) notes that chemicals can have long-term effects on the environment, and the risks to public safety can be more serious in the event of a chemical spill (EMSA 2007). Approximately 2,000 chemicals are transported by sea, and only a few hundred of these are transported in bulk, but they account for the bulk of the chemical trade (Purnell, 2009).

This growth in the flow of chemicals transported by sea increases exposure to HNS accidents. The literature highlights this structural increase in volumes and the corresponding increase in risk, as well as the toxicological and behavioural complexity (dissolution, evaporation, reactions) of these cargoes at sea (Galieriková, 2021). For example, the density of traffic in the English Channel makes this area particularly vulnerable to maritime accidents, which result from multiple factors. These include navigation errors—as evidenced by the collisions of the Bow Eagle in 2002 and the ECE in 2006, or the sinking of the Melbridge Bilbao in 2001—but also adverse weather and ocean conditions, such

as in the case of the Ievoli Sun in 2000, as well as various mechanical failures (Mamaca et al., 2009).

An analysis of past accidents shows that chemical tankers and cargo are the most often involved ships in marine accidents leading to a chemical spill at sea. In addition to this analysis, the investigation of the packaging type of chemicals spilled at sea shows that most of the chemical pollution is due to the rupture of the tanks of ships following a collision, grounding or an explosion on board. This type of accident, which is the most frequent, is generally the cause of a large spill of chemicals at sea and, as a result, the source of major pollution. Less frequent causes include the packaging in barrels, cylinders or small tanks. These packages are most often transported on board freight and container ships, and accidents correspond to losses at sea of these drums following unfavourable weather-ocean conditions. The analysis of maritime accidents also dealt with the chemical nature of the substances involved.

At the operational level, Europe has strengthened its Hazard and Noxious sub-stances (HNS) response capabilities (MAR-ICE assistance, dedicated stocks and equipment via EMSA), a sign of the growing prioritisation of this risk. In quantitative terms, although the scientific literature on HNS spills remains less well documented than for oil, several summaries indicate significant annual quantities of chemical discharges (in the order of 9,000–20,000 tonnes/year, mainly operational) and a substantial number of events recorded in historical databases (e.g. USCG 1992–1996: 423 HNS spills). These orders of magnitude shed light on the scale of a risk that is less visible but potentially more complex to manage.

Operationally, the situation highlights two main dynamics. Regarding oil, major oil spills caused by tankers have decreased significantly, but the annual volumes spilled remain variable (approximately 1,000 tonnes in 2020, 2,000 tonnes in 2023 and up to 10,000 tonnes in 2024), which justifies maintaining appropriate preparedness and response capabilities. For hazardous and noxious substances (HNS), the diversity of their physical and chemical properties (Neuparth et al., 2011) and the possible increase in flows and the difficulties of detection make it necessary to strengthen databases and models of behaviour at sea (such as HNS-MS), the implementation of monitoring protocols combining satellites and in situ sampling, and the development of specific management plans incorporating toxicological issues, risks of incompatibilities and equipment adaptation.

## 5.3 Identification of HNS

For several years now, the identification of risks associated with HNS spills has led to the implementation of structural works. Mamaca et al. (2003) identified the one hundred most transported products in terms of frequency and tonnage along the French coastline. This pioneering work was updated as part of the European HASREP project (Drogou et al., 2004), resulting in an initial consolidation of data. Following on from this, a database

summarising the main physical and chemical properties of these substances was developed as part of the CLARA II project, funded by the French National Research Agency (Aprin et al., 2006). This body of knowledge has since been enriched several times: it was made available via an online platform as part of the European HNS-MS project (2015), then extended to include new substances as part of the MARPOCS (2016) and HAZRUNOFF projects (2017).

These initiatives reflect ongoing research efforts aimed at improving understanding of the environmental risks associated with the maritime transport of hazardous substances. They now provide a reference tool for the scientific assessment of the potential impacts of these discharges on marine and coastal ecosystems, thereby contributing to the development of appropriate management and prevention strategies. In the event of a maritime accident involving HNS, spill response operations are difficult due to the chemicals spilled, particularly when gases or volatile substances are released. The vapour cloud created can be toxic, flammable or explosive, and it is necessary to protect the crew, the neighbouring population, the environment and those involved in combating marine pollution. As an example, the explosion of the chemical tanker Stolt Greenland that occurred in September 2019 in the port of Ulsan, South Korea, was the result of a styrene monomer leak, which caused a massive explosion accompanied by a fireball and a mushroom-shaped cloud with significant radiative effects on the surrounding environment (Marine Accident Investigation Branch 2021). In addition, the Aqaba accident on 27 June 2022 illustrated a toxic gas leak in the port of Aqaba, Jordan, when a container carrying 25 tonnes of chlorine fell from a crane onto a moored ship and ruptured, killing 14 people and injuring more than 265.

## 5.4 International Regulations

Maritime transport is governed by a set of international standards designed to ensure ship safety, marine environmental protection and port security. The International Maritime Organisation (IMO), a specialised agency of the United Nations created in 1948, is the central authority responsible for developing and adopting this regulatory framework. Among the most significant instruments are.

- **The SOLAS Convention** (1974, Safety of Life at Sea), which defines the fundamental safety standards for ships, from their construction to their equipment.
- **The STCW Convention** (1978, Standards of Training, Certification and Watchkeeping for Seafarers), which harmonises rules relating to the training and certification of seafarers.
- **The ISPS Code** (2004, International Ship and Port Facility Security Code), which sets security requirements to prevent criminal and terrorist threats.

However, one of the pillars of international regulation remains the MARPOL Convention (International Convention for the Prevention of Pollution from Ships), adopted in 1973 and reinforced by the 1978 Protocol. MARPOL is the main instrument for combating maritime pollution, whether accidental or operational. This convention is structured in six annexes, each targeting a specific type of pollution:

1. **Annex I (1973)**—Prevention of oil pollution: imposes rules on the design of tankers (double hull), oil transfer procedures and the management of oil residues.
2. **Annex II (1973)**—Prevention of pollution by harmful liquid substances in bulk: regulates the transport of liquid chemicals and sets standards for their discharge.
3. **Annex III (1992)**—Prevention of pollution by hazardous substances in packaged form: concerns the maritime transport of chemicals in containers or drums.
4. **Annex IV (2003)**—Prevention of pollution by sewage: sets standards for the treatment and discharge of sanitary effluent.
5. **Annex V (1988)**—Prevention of pollution by garbage from ships: prohibits or limits the discharge of plastics, food waste and other solid residues at sea.
6. **Annex VI (1997, amended in 2008 and 2020)**—Prevention of air pollution from ships: regulates emissions of sulphur, nitrogen oxides and greenhouse gases. The introduction of the 'SECA' (Sulphur Emission Control Area) and the entry into force of the global limit of 0.50% sulphur in 2020 are notable examples.

The implementation of MARPOL is the responsibility of the flag States, which must ensure that their ships comply with the technical requirements (certificates, equipment, procedures). In addition, port States exercise effective control through inspections (Port State Control), particularly in the context of regional memoranda such as the Paris MoU in Europe.

Strict enforcement of MARPOL has contributed to a significant reduction in oil spills and better control of chronic (operational) pollution. Nevertheless, the increase in the maritime transport of liquid chemicals and the emergence of new pollutants such as microplastics and atmospheric emissions highlight the need for continuous adaptation of the annexes and increased scientific research to anticipate environmental risks.

Alongside the MARPOL Convention, which regulates pollution prevention, the International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS Convention) is a major instrument of international maritime law. Adopted under the auspices of the International Maritime Organisation in 1996 and amended by a protocol in 2010, this convention aims to establish a comprehensive civil liability and compensation regime for maritime accidents involving chemicals. It covers damage caused by a spill or leak of hazardous substances carried by sea, whether liquid bulk chemicals, liquefied gases, packaged substances or cargo residues. It applies to damage:

- Bodily injury and property damage suffered by third parties,
- environmental damage, including the costs of restoring the affected environments,
- the costs of preventive measures taken to limit or avoid damage.

The Convention establishes a two-tier system:

1. Strict liability of the shipowner, who is required to take out insurance and has a liability limit proportional to the tonnage of the ship,
2. international HNS Fund, financed by companies importing or receiving hazardous substances, which intervenes to supplement compensation beyond the ceiling covered by the shipowner.

This mechanism is directly inspired by the regime established for oil pollution (Civil Liability Convention/International Oil Pollution Compensation), but extends its scope to chemical substances, which are often more diverse and have more complex effects to assess.

The entry into force of the HNS Convention was long delayed due to an insufficient number of ratifications. However, the 2010 protocol simplified certain technical aspects (notably the collection of contributions to the Fund) and relaunched the accession process. Several European States, including France, Spain, Norway and Turkey, have already ratified the text, bringing the Convention closer to its effective entry into force. The HNS Convention provides an essential framework for responding to evolving maritime risks. While the frequency of oil spills is decreasing, the transport of bulk chemicals is growing steadily. The existence of an international compensation mechanism is therefore crucial to.

- Ensure prompt and fair compensation for victims,
- strengthen the liability of economic operators,
- support scientific research and the development of technical capabilities for the management of chemical pollution at sea.

## 5.5 Chemical Behaviour at Sea

In the event of an accidental spill at sea, the fate of HNS will depend closely on their intrinsic chemical nature, which is described, among other things, by parameters such as viscosity, surface tension, vapour pressure and solubility. On this basis, and for each chemical, theoretical behaviour in the environment can be deduced from data obtained in the laboratory, i.e. under standardised test conditions.

The International Maritime Organisation describes the fate of chemicals using 12 categories (Table 5.1) that are presented in the Bonn Agreements and are derived from

the Standard European Behaviour Classification (SEBC) classification (Bonn Agreement 1994). This categorisation ultimately allows all HNSs transported in bulk to be classified into four families (X, Y, Z, OS), also considering their hazardousness according to the MARPOL 73/78 Convention (Annex II). Each new formulation must be assigned a specific behaviour and hazard category before it can be transported by sea (GESAMP 2003).

Floating products (i.e. products designated F according to SEBC) will form a slick that will spread over time to become a very thin layer on the surface of the water (Fig. 5.1).

**Table 5.1** The 12 short-term behaviour groups of chemicals accidentally spilled at sea according to the European classification system

| | SEBC code | Short-term behaviour of the substance | Examples |
|---|---|---|---|
| Gaseous products | G | Gas | Propane, Butane, Vinyl chloride |
| | GD | Gas that dissolves | Ethylene oxide, Ethylamine |
| Products that evaporate | E | Product that evaporates | Benzene, Toluene, Hexane |
| | ED | Product that evaporates and dissolves | Methyl tert-butyl ether, Vinyl acetate, Ethyl acrylate |
| Floating products | F | Floating product | Octanoic acid, Isooctanol |
| | Fp[a] | Floating and persistent product | Vegetable oils (soybean oil) |
| | FE | Floating product that evaporates | Octane, Xylene |
| | FED | Floating product that evaporates and dissolves | Butyl acetate, Butyl acrylate |
| | FD | Floating product that dissolves | Aniline, Dibutyl ether |
| Products that dissolve | DE | Product that dissolves and evaporates | Acetone, Acrylonitrile |
| | D | Product that dissolves | Sulfuric acid, Phosphoric acid |
| Sinking products | SD | Sinking product that dissolves | Benzyl acetate |
| | S | Sinking product | Dichlorobenzene, Phenol |

[a]Behaviour Fp belongs to behaviour F

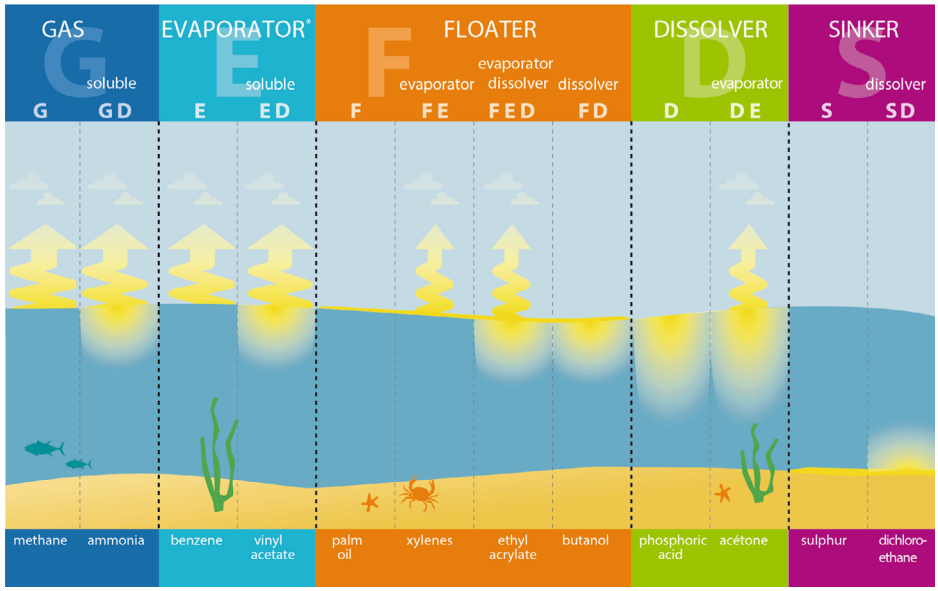



**Fig. 5.1** SEBC European Behaviour Classification groups. Classification of behaviour groups of chemical substances in the marine environment. Short-term behaviours are classified according to the physio-chemical properties of the substance: physical state, solubility, density and vapour pressure *Source* Cedre and Transports Canada (2012) by "© Cedre—illustration hippocampe.com"

This spreading, as well as the fragmentation and drift of the slick, depend on winds and tidal currents.

Products that evaporate (i.e. products designated E according to SEBC) change from a liquid to a gaseous state in a matter of hours or even minutes. The fate of the gas cloud in terms of drift and atmospheric dilution depends on the wind (direction and intensity). Generally, a concentration gradient in the air is observed due to a prolonged evaporation process and because chemical vapours often have a different density than air.

Products that dissolve (i.e. products designated D according to SEBC) pass into the water mass and move with the currents. As with products that evaporate, a concentration gradient is observed, which is also a function of time (intensity of the dissolution process) and the density of the products.

Sinking products (i.e. products designated S according to SEBC) have a density greater than that of seawater. They sediment in the water column and accumulate in crevices, cavities and furrows on the seabed. In all cases, the topography of the seabed determines the final position of the spilled product, but not its ultimate position, as long-term processes will begin (i.e. biodegradation, bioturbation, bioaccumulation, etc.).

This typology is a key tool for the operational framework, as it enables authorities and response teams to anticipate the fate of a substance after a spill, assess environmental and

health threats, and guide the choice of the most appropriate response strategies (satellite monitoring, in situ sampling, containment, dispersion, combustion, etc.). Its value also lies in its integration into databases and simulation models such as HNS-MS European project, which provide decision-makers and responders with rapid access to substance data sheets, dispersion scenarios and recommendations for action. By combining theoretical classification and digital tools, the SEBC strengthens preparedness, inter-agency coordination and the effectiveness of responses to marine pollution involving hazardous chemicals.

However, international regulations are based on classifications that consider the physicochemical properties of products and, therefore, their theoretical fate in the marine environment in the event of an accidental spill. However, past accidents show them to be flawed, and several limitations appear de facto:

- The values of the physicochemical parameters used are derived from laboratory tests, i.e. obtained under standardised conditions (fresh water, temperature and pressure, etc.) that are often far removed from the conditions prevailing in the environment where the accident occurred (seawater composition and temperature, air temperature, presence or absence of wind, etc.). These differences in environmental conditions are a source of error in the characterisation of fate because, for example, the solubility of a product in water is closely linked to the temperature and salinity of the aqueous phase. This divergence between classification and reality in the field is also illustrated by accident scenarios where a given product seeps from the bottom and rises in the water column because its density is lower than that of seawater. In these situations, the solubility of the product alone is not sufficient to assess whether the product will reach the surface and form a slick with all the associated risks, including the formation of a toxic and explosive cloud. Conversely, a fully soluble product with a density greater than that of seawater that is spilled from the surface will not systematically dilute in the water mass, and therefore the risk of stratification cannot be ruled out; that is, the appearance of a phase of pure product at the sediment–water column interface.
- The possibility of a reaction between the spilled product and water or oxygen in the air is not considered, nor is the compatibility between the substances being transported. Although sodium is completely soluble in seawater, this reaction is exothermic and produces dihydrogen, which, in the presence of oxygen in the air, poses a high risk of explosion (see Chap. 3).
- The processes that characterise the fate of a liquid substance once it has been spilled into the sea are simultaneous and, as a result, compete with each other. However, this competition, which often results in a reduction in transfer (i.e. attenuation of evaporation or solubilisation), is not considered in their classification, and thus a theoretically soluble product may be purely evaporating.

- The influence of environmental parameters is never considered, even though it is decisive in determining the fate of a product. Wind and sunlight accentuate the evaporation process, while surface agitation promotes solubilisation.
- In terms of impact on living organisms, similar limitations arise with, for example, eco-toxicity determined in the laboratory on species that are not representative of the environment where the accident occurred, namely freshwater species, copepods with very different resistances to fish, acute eco-toxicity thresholds that are not easily usable in medium- to long-term risk assessment, etc.

Those in charge of response operations must therefore read these classifications critically to assess whether the specific characteristics of the accident and the environment in which it occurred will alter the result. This discussion may lead to a change in the categorisation of the substance, or even to the deployment of response measures designed for a different type of behaviour, i.e. a different category of substance. However, to do so, scientific arguments must be produced which, at present, are often the result of experiments carried out in the emergency situation.

To compensate for this lack of scientific data, it has been necessary to provide answers which, in the long term, can be used in decision support software. To this end, two accident scenarios have been identified, namely cargo leakage from a sunken wreck and surface discharge from a damaged ship.

When a chemical with a density of less than 1 is released from a sunken wreck, the solubility limit alone is not sufficient to determine whether the entire cargo will dissolve in the water column or whether there is a risk of a surface slick forming and, by extension, a potentially toxic and explosive gas cloud forming (Fig. 5.2a).

If this product is released onto the surface of the water, it will immediately form a film that will first spread out before fragmenting, at which point evaporation and dissolution processes will occur. Despite knowing the evaporative nature of a substance via its vapour pressure, and its solubility via its solubility limit, it is not possible to describe precisely which process will prevail over the other, and thus accurately predict whether the product will pass entirely into the atmospheric compartment, or into the aqueous compartment, or be distributed between the two (Fig. 5.2b).

Understanding the fate of anthropogenic products in the aquatic environment is essential to defining the response measures that will be deployed to remove them from the environment. In cases where recovery is not feasible, this understanding will make it possible to estimate the impacts on fauna and flora and to take appropriate precautionary measures (Fig. 5.2c).

Response teams dealing with major spills must therefore have tools at their disposal to assess the consequences of such events on aquatic species. To this end, it has drawn inspiration from methodologies commonly used in marine observation networks (monitoring programmes, ecological surveillance networks, observatories), which respond to the need to understand the impact of chemical contaminants on different time scales (short,

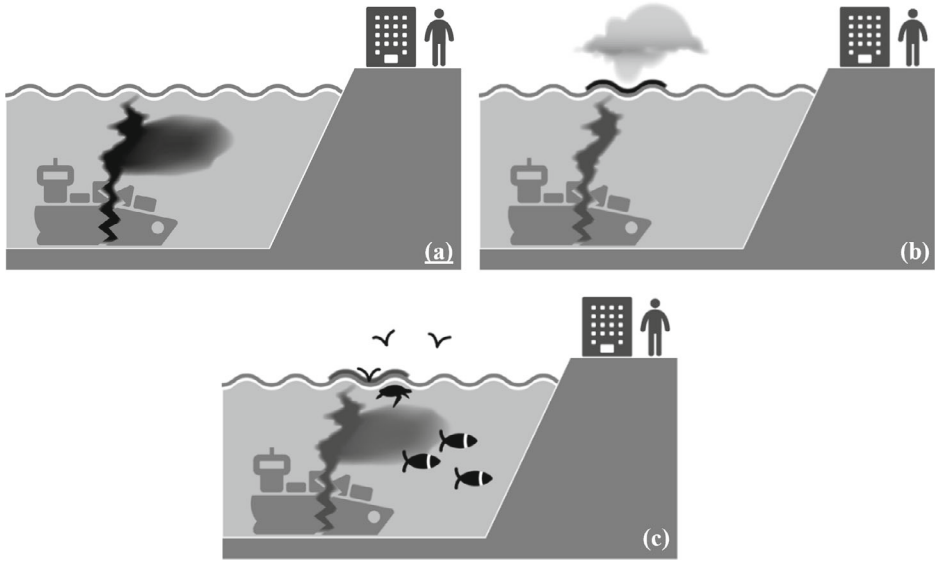



**Fig. 5.2** Schematic representation of the problem of a sunken leaking wreck. **a** Illustration of the solubilisation process in the water column. **b** Illustration of the behaviour of a chemical forming a slick at the sea surface and chemical vapour cloud. **c** Issues surrounding the environmental impact of accidental pollution at sea

medium and long term). These methodologies make it possible to understand the mechanisms of contamination of organisms in their environment, as well as the biological responses and possible tolerances of these organisms to pollutants; they use a range of tools grouped under the generic term 'biomarkers'. Let us recall here the definition of a biomarker: 'any biochemical, cellular or physiological change that can be measured in a tissue, biological fluid or whole organism, which indicates exposure to (and/or the effect of) one or more pollutants' (Depledge, 1994). While such tools are very useful for obtaining initial information on the effect of pollutants at the molecular or individual level, they have limitations when it comes to predicting the long-term impact of pollution or at higher organisational levels (population, community).

The use of biomarkers must therefore be complemented by approaches that are less directly related to exposure to the contaminant under study, but better able to assess long-term effects at a higher level of biological organisation. This is particularly the case for behavioural studies, which can be used to describe the effects of pollution on organism-ecosystem interactions.

The analysis of past accidents clearly shows that most accidents that released volatile, flammable or explosive products took place in Europe. Of the total incidents selected, some did not present major hazards and the solutions chosen to deal with the dispersion were to let the chemicals disperse into the sea. Moreover, some measures are often taken

to decrease or eliminate human risks such as distance boats from the coastline, evacuate the crew and people at risk (Elgin, Montara). Another initiative is to put in place an exclusion zone, as for Alesandro Primo and Anna Broere where a 10 km exclusion zone was imposed for safety (Alcaro et al., 2021). Finally, it is also possible to recover dangerous substances, either by pumping directly chemicals on the boat or trying to recover them once already spilled into the ocean. The response also often involves intensifying fires and stopping leaks. In these cases, the substances did not have a significant impact on the marine environment, and the population or crew was not endangered or had already been evacuated. However, the main hazards identified during these spill incidents were related to the formation of a potentially flammable or explosive vapour cloud. Regarding the impact on human health, most of the substances spilled have consequences such as skin and eye irritation or can damage the respiratory tract.

## 5.6 Focus on the Use of New Energies in Maritime Transport

The marine industry is on the cusp of a major energy revolution with the introduction of new propulsion fuels for ships. These innovative fuels offer a cleaner, more sustainable alternative to traditional fuel oils, in response to growing environmental concerns and increasingly stringent international regulations. The maritime sector is responsible for around 2.5% of global greenhouse gas (GHG) emissions. To reduce these GHG emissions, the International Maritime Organization (IMO) has set targets to reduce the carbon impact of ships by 40% by 2030 and 70% by 2040, compared with 2008 levels. These drastic reductions are driving the development of new alternative technologies to use more environmentally friendly fuels. The development of alternative fuels for ship propulsion, such as ammonia, methanol and hydrogen, offers promising prospects for reducing these greenhouse gas emissions. However, the use of these new ship propulsion fuels is not without risks. Ammonia is considered a promising fuel because it is carbon-free, which means it does not produce $CO_2$ during combustion. However, ammonia is extremely toxic to humans and marine organisms. A leak or spill could lead to serious health consequences and significant environmental damage (EMSA, 2023). Regarding the risks associated with handling and storage, ammonia is stored under high pressure or at low temperature, which requires specific infrastructures with a high probability of explosion and fire. Methanol is another interesting alternative fuel, but it is also a highly flammable and explosive product, which poses safety risks on board ships. Although less toxic than ammonia, methanol is nonetheless toxic to humans and marine life. Prolonged exposure or major spills can have harmful effects on health and the environment. As for hydrogen, this fuel is often presented as the ultimate solution because of its clean combustion, producing only water. However, its use in the marine sector is complex and involves storage issues. Hydrogen is a compressed gas at very high pressure or in liquid form at extremely low temperatures; it is also extremely flammable and can form explosive mixtures with air (EMSA, 2024).

Within this context, the European projects MANIFESTS and MANIFESTS Genius (MANIFESTS Genius, 2025) play a central role in advancing knowledge, preparedness and response strategies regarding these new marine fuels. These research projects have focused on understanding the behaviour and impact of alternative fuels in the event of accidental releases at sea. Through experimental campaigns, modelling activities and the development of decision-support tools, the project has improved the capability of first responders and maritime authorities to assess and manage emerging risks. Together, these projects have significantly contributed to bridging the gap between scientific research and operational risk management in the marine domain, supporting a safer and more sustainable transition towards low-carbon shipping.

Attention to the environment and the impact of shipping on climate change has encouraged the development of alternative solutions for ship propulsion fuels. While the previously cited products are promising, Liquified Natural Gas (LNG) stands out as a fuel that is already being used by ships (Chen et al., 2018). However, the widespread use of LNG raises significant concerns about the risks and consequences of potential spills into the marine environment. Low-temperature storage conditions coupled with a limited understanding of the physicochemical models that describe the behaviour of these substances when released into the environment, and the likelihood of unconventional accidental scenarios, inevitably lead to considerable concern among authorities and response services (Aursand & Hammer, 2018). In the event of an accidental release of LNG or other low temperature refrigerated substances into water (e.g. ammonia, hydrogen, etc.), the mixing between the two fluids and the temperature difference between the nucleation point of the mixture and ambient temperature can lead to very rapid evaporation rates. This rapid phase change (from liquid to vapour) is known as a Rapid Phase transition (RPT) and can lead to vapour cloud explosions and potentially the formation of shock waves (Bariha et al., 2017; Bubbico & Salzano, 2009). Several examples of industrial accidents and large-scale tests have been reported in the literature (Cleaver et al., 2007; Sun et al., 2017).

Such scenarios raise significant concerns, particularly in onshore or port facilities, where congested areas may increase local turbulence phenomena that potentially lead to catastrophic explosions, as in Zhoushan Port in the eastern Chinese city of Ningbo where a huge explosion occurred on 9 August 2024, on a container ship carrying dangerous goods on the vessel.

## 5.7 Conclusion

The analysis of past maritime accidents demonstrates a dual dynamic: while major oil spills have significantly decreased, the transport of hazardous and noxious substances continues to grow, creating new and complex risks for marine ecosystems and human safety. The SEBC classification, combined with operational tools such as the HNS-MS

database, offers a valuable framework for anticipating the behaviour of chemicals at sea and guiding response measures. However, limitations remain, particularly in translating laboratory-based parameters into real-world accident conditions. To ensure effective preparedness and response, it is essential to integrate scientific knowledge with operational practices, strengthen international regulations (MARPOL, HNS Convention) and maintain specialised response capacities. Emerging alternative fuels for ship propulsion add another layer of complexity, requiring proactive adaptation of monitoring, modelling and emergency plans. In this context, enhancing collaboration between scientific research, maritime authorities and response services is a key factor in reducing the impacts of future pollution events at sea.

## 5.8 Perspectives

The maritime sector is entering a new era of complexity in terms of pollution preparedness and response. While the frequency of major oil spills has decreased significantly thanks to regulatory advances and improved practices, the diversification of transported substances, particularly hazardous and noxious substances (HNS) and alternative marine fuels, is creating emerging risks that are less visible but potentially more serious.

The global transition to low-carbon shipping is reshaping the chemical landscape of marine pollution. Fuels such as liquefied natural gas, ammonia, methanol and hydrogen introduce new accident scenarios involving toxicity, flammability and rapid phase transitions. Understanding their environmental behaviour and combustion characteristics at sea is now a major research priority for safe maritime decarbonisation.

Bridging the gap between laboratory data and real-world conditions remains a major challenge. Models such as SEBC and HNS-MS provide valuable frameworks, but need to evolve to better reflect environmental variability, coupled processes and the influence of temperature, salinity and turbulence. Future decision support tools will increasingly rely on experimental validation, hybrid modelling and real-time data from sensors and satellites.

At the same time, the effective implementation of international frameworks such as MARPOL and the HNS Convention must be supported by scientific innovation, joint exercises and stronger coordination between research institutions, maritime authorities and response services, representing an important step forward in collective responsibility and compensation. Ongoing training and joint exercises between coastal states remain essential to ensure operational preparedness.

Scientific advances in ecotoxicology, biomarkers and behavioural studies of marine species will improve the assessment of long-term impacts and the restoration of ecosystems after chemical spills. Digital technologies (remote sensing, AI-based modelling and predictive analytics) will play a central role in early detection and optimisation of interventions.

In summary, marine pollution preparedness and response are evolving towards a more integrated, adaptive and knowledge-based paradigm. The combination of regulatory vigilance, technological innovation and scientific collaboration is essential to protect marine environments and coastal communities in the face of accelerating maritime and energy transitions.

**Key Sentences**

- Marine oil spills have decreased, but HNS transport is rising, creating less visible and mediatic yet potentially more severe risks for people and ecosystems.
- SEBC classification and crisis management tools like HNS-MS and MANIFESTS support short term spill prediction, though real accidents highlight the limits of chemical laboratory-based parameters.
- Maritime Chemical spill management preparedness requires strong regulations and science-based response capabilities, integrating monitoring, modelling and coordinated operational action.
- New alternative fuels (LNG, ammonia, methanol, hydrogen) introduce emerging hazards, requiring adapted emergency planning and improved understanding of rapid phase-change phenomena.

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# NaTech Hazards: The Case of Wildfire Events on Industrial Assets

6

Frédéric Heymes and Dylan Bernard

**Abstract**

The chapter examines NaTech events (technological accidents triggered by natural disasters) with a focus on wildfires impacting industrial assets. Such events pose rising global risks as climate change intensifies heatwaves, droughts and fire seasons. The text first outlines wildfire behaviour, emphasising the roles of fuel characteristics, moisture content and meteorological and topographical factors. It then addresses the complexity of fire spread modelling used to predict parameters such as rate of spread (ROS), fireline intensity (FLI), flame length and heat flux. The chapter then discusses prevention measures, which include creating defensible spaces, using fire-resistant materials, applying chemical retardants and installing sprinkler systems or water curtains. A detailed case study on LPG tanks shows that exposure to heat fluxes can lead to tank rupture and possible BLEVE explosions. The chapter concludes with emerging research on natural gas pipelines emphasising that continued integration of experimental data, modelling and prevention strategies is essential for mitigating NaTech wildfire risks in an era of accelerating climate change.

**Keywords**

Wildfire • NaTech • Wildland industry interface • Domino effect

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## 6.1 Introduction

NaTech scenarios (Natural Hazard Triggering Technological Accidents) occur when natural events like earthquakes, floods, hurricanes, wildfires or lightning strikes cause failures in industrial or technological systems. These failures can result in the release of hazardous materials, fires, explosions or structural collapses. Such events compound the damage and complexity of the original natural disaster, often overwhelming emergency response systems.

Common NaTech targets include chemical plants, oil refineries, nuclear facilities, gas or oil pipelines and storage tanks. The risks are higher in areas with poor infrastructure, outdated safety systems or lack of disaster preparedness. Climate change is increasing the frequency and intensity of natural hazards, raising the potential for NaTech events. Understanding these scenarios requires combining knowledge from natural hazard science and technological risk analysis. Mitigation involves risk assessments, improved design standards, land-use planning and integrated emergency response strategies.

Wildfire events are considered a major threat to industrial facilities in the future. Forest fires, and more particularly extreme wildfires and megafires, are a growing problem across the world. Over the past few years, wildfires have raged with large intensity across many world regions, as never seen before:

- Australia (18 600 000 ha burnt, 2020)
- California (390 000 ha burnt, 2021)
- Russia (3 200 000 ha burnt, 2019)
- Spain (250 000 ha burnt, 2022)
- Portugal (75 000 ha burnt, 2022)
- Romania (150 000 ha burnt, 2022)
- France (73 000 ha burnt, 2023).

Another evolution is that wildfires are now occurring in zones previously spared from this risk:

- *Boreal Forests* (Siberia, Canada and Alaska). In 2023, Canada experienced an unprecedented wildfire season, burning a record 18 million hectares.
- *Northern Europe* (Scandinavia): Countries like Sweden and Finland have also faced increasing wildfire threats. Historically less impacted, these regions are seeing hotter and drier summers that make them more susceptible to fires.
- *United States* (Eastern and Northern regions): New regions, such as the Pacific Northwest, the Great Lakes region and even parts of the Northeastern US, are seeing more fire activity due to shifting weather patterns.
- *South America* (Chile and Argentina): The dry season in Chile and Argentina has grown longer, and with it, the risk of wildfires.

- *South Asia* (India, Bangladesh, Nepal): These areas have traditionally faced some wildfire risks but are now experiencing more significant fires, especially in forested areas.

Climate change is a major driver in the increasing frequency, intensity and duration of wildfires. Here's how it influences wildfire events:

- Hotter Temperatures. Global warming leads to longer and more intense heatwaves, drying out vegetation and making it more flammable. This increases both the likelihood and severity of wildfires.
- Drier Conditions and Droughts. Climate change alters precipitation patterns, causing prolonged droughts in many regions. Dry soils and vegetation act as fuel, making fires start more easily and spread faster.
- Longer Fire Seasons. Warmer temperatures extend the fire season by weeks or even months in many regions, particularly in Mediterranean, North American and Australian climates.
- Ecosystem Changes. Warming alters ecosystems and species distribution. Forests stressed by heat, pests and disease (also climate-related) become more flammable and prone to severe burns.
- Feedback Loop. Wildfires release massive amounts of carbon dioxide and other greenhouse gases, which further drive climate change—creating a dangerous feedback cycle.

The direct impacts of wildfires on industrial facilities are (see Chaps. 3 and 4).

- Structural Damage. High temperatures can destroy buildings, pipelines, storage tanks and electrical systems, especially if materials are flammable or not designed for heat resistance.
- Combustion of Hazardous Substances. Wildfires can ignite flammable chemicals, fuels, leading to explosions, toxic releases or secondary fires.
- Power Outages and Equipment Failures. Fires often damage power lines or cause grid shutdowns, which can disrupt safety systems like cooling units, alarms and containment controls.
- Smoke and Soot Contamination. Even without direct flame contact, smoke and soot can contaminate products, machinery and control systems, especially in food, pharmaceutical and semiconductor industries.

This chapter describes how wildfires impact industrial assets. The zone in which a forested area may impact an industry during a wildfire event is called the wildland urban interface (WUI). A first part gives some core knowledge about wildfire physics; the modelling of the impact of fire on structures in the wildland–industrial interface is presented. The

vulnerability of industrial assets is presented. The case study of LPG tanks will be considered, and research perspectives on natural gas pipelines. Finally, a section addressing prevention and protection measures concludes the chapter.

## 6.2 Wildfire Risk

### 6.2.1 Characteristics of the Wildland Fuel

Characteristics of the wildland fuel are important. When fuels are abundant, a fire can be uncontrollable and destructive. But when fuels are scarce, a fire cannot build intensity, which makes it much easier to control. The denser and more continuous the fuels, the bigger the threat they pose to homes.

The measure of fuel hazard refers to its continuity, both horizontal and vertical. Horizontal continuity refers to fuels across the ground, while vertical continuity refers to fuels extending from the ground up into the crowns of trees and shrubs. Fuels with a high degree of both vertical and horizontal continuity are the most hazardous, particularly when they occur on slopes.

Heavier fuels, such as brush and trees, produce a more intense fire than light fuels, such as grass. However, grass-fuelled fires travel much faster than heavy-fuelled fires. Some heavier surface fuels, such as logs and wood chips, are potentially hazardous heavy fuels and should be addressed.

#### 6.2.1.1 Surface Fuels

Surface fuels consist of logs, branches, slash, pine needles and grass. Woody material on the ground and debris occur naturally from cutting down trees (also known as slash). Due to decades of fire suppression, decomposing layers of pine needles are deeper under many large trees today than they would have been a century ago. Grasses are perhaps the most pervasive and abundant surface fuel. This is critical in summer and fall, when grasses dry out and in the spring in cold areas, after the snow is gone but before plants green-up. All these surface fuels may increase the intensity of fires. Increased fire intensity makes a fire harder to control and increases the likelihood of surface fires transitioning to crown fires.

#### 6.2.1.2 Ladder Fuels

Ladder fuels are defined as smaller trees and brush in the understory that provide vertical continuity, allowing a fire to spread from the ground up into the branches and crowns of larger trees. Lower branches on large trees also can act as ladder fuels. These fuels are potentially very hazardous but are easy to mitigate. The hazards from ladder fuels near homes are especially important to address. Therefore, it is recommended to remove ladder fuels in defensible spaces.

#### 6.2.1.3 Crown Fuels

Crown fuels consist of the live and dead branches, foliage and other biomass found in the overstory (upper canopy of trees). These fuels are located above the ground and are often interconnected, allowing fire to spread rapidly through the tree crowns once ignition occurs. The structure and density of the canopy, as well as the species composition, greatly influence crown fire behaviour. When crown fuels ignite, they can produce extremely intense and fast-moving fires that are difficult or impossible to control. Crown fires often generate strong convection columns and can create spotting, where embers are carried long distances and ignite new fires ahead of the main front. Managing crown fuels typically involves thinning dense stands, pruning lower branches and reducing ladder fuels to break the vertical continuity between surface and crown layers. Proper management of crown fuels is essential for reducing the risk of high-intensity crown fires and for maintaining forest health.

## 6.3 Wildland Fire Modelling

Wildland fire modelling, considered in its entirety, is a very challenging task. The challenge arises from the range of physical processes and the temporal and spatial scales over which they operate. These processes range from the small scale (1 mm) to a large scale (1 km) and involve complex phenomena. Wildfire depends strongly on meteorological conditions (wind, humidity, temperature, sun) and the topographic parameters of the considered zone.

Different types of modelling are proposed in the literature. Simple models are those that do not attempt to model the physical processes. Instead, they use formulas for the spread rate, and other quantities, derived from measurements (empirical-based) or from observation and experience (rule based). Complex, physics-based models do attempt to capture the physical processes through the numerical solution of equations governing the physical processes in question. Of special importance is the fact that physics-based models include the interaction and coupling of the driving processes (wind, buoyancy-induced flow, combustion, thermal radiation, thermal degradation of vegetation). As a result, the same model can be used to investigate the relevance of wind, fuel structure, fuel moisture, terrain on fire behaviour over a range of environmental variables. This is not possible with empirical or rule-based models of fire behaviour. Each environmental scenario requires sufficient, repeatable, measurements (or observations) to form a legitimate basis for developing the model or formula.

Simple models have the advantage that they can provide faster-than-real-time predictions. However, their application to complex environments and unusual conditions is not justified. Physics-based models would not have this limitation. The governing equations would capture the basic physical processes regardless of the scale of the process. But the equations require empirically derived information, such as the radiation coefficient or the

convective heat transfer coefficient. The key points for modelling the propagation of a wildland fire are:

- To characterise the fuel.
- To evaluate the moisture content of the fuel.
- To model the intensity of fire and rate of spread.

The last point involves two factors that are linked and depend on wind and land configuration such as spatial and altimetry data of the land. Spatial information technologies such as remote sensing and geographic information systems (GIS) offer great potential for the effective modelling of wildland fire behaviour. To calculate the effects of fire on targets in the wildland–industrial interface, it is necessary to achieve the supplementary calculations:

- Evaluation of the temperature and emissivity of fire
- Modelling the height of flames.
- Modelling the effects of the convective and radiative heat transfer.
- Modelling the effects of flying embers on targets.

### 6.3.1 Fuel Characterisation

A fuel model is a set of numerical values that describes a fuel type for the mathematical model that predicts spread rate and intensity. The parameters that can be varied in a fuel model are:

- The loading for each fuel particle diameter size class ($kg.m^{-2}$).
- The surface-area-to-volume ratio for each size class ($m^2.m^{-3}$).
- The fuel bed depth (m).
- The heat content of fuel ($kJ.m^{-1}$).
- The moisture content, percent.

There has essentially been a choice of 13 stylised fire behaviour fuel models (Anderson, 1982). For each type of fuel, a range of previously cited parameters for modelling is given. The use of the (Rothermel, 1972) fire spread model and the desire for more options in selecting a fuel model led to the development of a set of 40 standard fire behaviour fuel models (Scott & Burgan, 2005).

Fuel models in the set of 40 are grouped by fire-carrying fuel type. The number of fuel models within each fuel type varies. Each fuel type has been assigned a mnemonic two-letter code. Non-burnable fuel models, even though not really a ‘fuel’, were included in the set to facilitate consistent mapping of these areas on a fuel model map.

Fuel types were ordered in a way like the original 13, with hybrid fuel types (such as timber-understory) generally between the two types that comprise the hybrid. Fuel types are as follows:

- (NB) Non-burnable
- (GR) Grass
- (GS) Grass-shrub
- (SH) Shrub
- (TU) Timber-understory
- (TL) Timber litter
- (SB) Slash-blowdown.

### 6.3.2 Fuel Moisture Content

Fuel Moisture is a critical variable predicting fire behaviour. There are many classes of fuel moisture, depending on whether the fuel is dead or alive and according to the nature of the fuel. A live fuel may be herbaceous or woody and may be partially considered dead fuel. This point is a result of physiological changes in the plant, which are mainly due to the time of the season, precipitation events, the temperature trend and the species. The moisture content of live and dead fuel particles is an important factor affecting wildfire behaviour. Significant variability in fuel moisture content occurs within the period of fire behaviour simulations. Fine dead fuel moisture content, for example, varies significantly within a single day and from day to day. Live woody moisture content typically varies from week to week throughout the course of a season.

For use in fire modelling systems, fuel moisture is measured as the mass moisture content on a dry-mass basis. The moisture mass represents a heat sink (the heat required to evaporate that moisture) and the oven-dry mass represents the heat source available for combustion.

### 6.3.3 Rate of Spread and Fireline Intensity

The key parameters in modelling the fire are quantitative fire behaviour characteristics: flaming front rate of spread (ROS), heat released per unit area (HPA), fireline intensity (FLI). These characteristics affect other important fire characteristics and fire-level fire characteristics (fire size and magnitude).

#### 6.3.3.1 Flaming Front Rate of Spread (ROS)

The flaming front of a wildfire is its leading edge, dominated by flaming combustion and spreading into previously unburnt fuel. The flaming front is located at all positions

around the fire perimeter: head, hank, flank, rear and points in between. Flaming front rate of spread is a function of slope and wind velocity. Flaming front spread rate of free-burning wildfires varies over more than three orders of magnitude. A backing fire in a compact timber litter fuel bed may spread at less than 0.2 m/min; a fully active crown fire can spread faster than 100 m/min; and rate of spread in cured grass fuels can reach nearly 170 m/min under the influence of strong winds.

Spread rate of surface fires may be predicted using Rothermel's surface fire spread model (Rothermel, 1972). The Rothermel (1983) crown fire spread model is used to predict crown fire spread rate. Other models can be found in the literature (Mell et al., 2006; Morvan et al., 2000).

Rate of spread is an important fire behaviour characteristic for two reasons. First, it contributes to how large wildfires can become during a specified period, and that in turn influences the likelihood that wildfire will reach certain places of concern on a landscape. Second, rate of spread is a significant factor affecting fireline intensity and flame size, which are important for determining fire effects.

#### 6.3.3.2 Heat Per Unit Area (HPA)

Heat per unit area (HPA) is the amount of heat released per unit area ($kJ.m^{-2}$) during the short period of continuous flaming. Flaming front residence time is typically on the order of seconds (for very fine fuel particles, such as grass) to a few minutes (for coarser woody fuel particles). Post-frontal flaming and smouldering can continue for many hours or days after the flaming front has passed, but the heat released during that time is not included in HPA.

HPA can be thought of as the product of fuel particle heat content (HC, $kJ.kg^{-1}$) and the fuel load consumed during passage of the flaming front (FLC, $kg.m^{-2}$). HC is functionally constant for most fire modelling simulations. Charts giving the heat per unit area for each type of vegetation can be found in (Andrews & Rothermel, 1982). Values range up to 45 $MW.m^{-2}$ (4000 BTU per square feet).

For crown fires, *HPA* includes the combined load of surface and canopy fuel consumed during passage of the flaming front. An active crown fire consumes nearly all the available canopy fuel, while a passive or intermittent crown fire consumes only a portion. At low wind speeds, where only surface fire is possible, overall *HPA* is equal to the surface fuel *HPA*. Overall *HPA* increases during the period of passive crowning as the fraction of canopy fuel consumed increases. By the time active crowning is possible, at a wind speed of 33 $km.h^{-1}$, all the possible canopy fuel contribution is included in overall *HPA*.

The Rothermel model does not estimate surface fuel *HPA* directly; only by combining reaction intensity, an intermediate parameter in the model, with a model of residence time (Anderson, 1982). Nonetheless, the Rothermel surface fire spread model is the best choice currently available for surface fuel *HPA*.

#### 6.3.3.3 Fireline Intensity (FLI)

Fireline intensity (also called Byram's fire intensity) is the rate of heat release per unit length of the fire front ($kW.m^{-1}$). As with HPA, the heat released during post-frontal flaming and smouldering combustion is not included in the calculation of fireline intensity. Byram (1959) defined the fireline intensity as (Eq. 6.1).

$$FLI = HC \times FLC \times ROS \tag{6.1}$$

where HC is the heat content ($kJ.kg^{-1}$), FLC is the fuel load consumed in the flaming front ($kg.m^{-2}$) and ROS is the rate of spread ($m.s^{-1}$) of the wildfire event. This equation shows clearly that the intensity of a wildfire is driven by the speed at which a fuel load is consumed by the propagating fire.

### 6.3.4 Flame Length and Height

Flames are the visible manifestation of rapid combustion. Flame size is a measure of the physical dimensions of such flames. Two measures of flame size are available: flame height and flame length (Fig. 6.1). Flame height is used to calculate the effects of fire on targets such as houses, but flame length has been more closely related to fireline intensity and is therefore more commonly used.

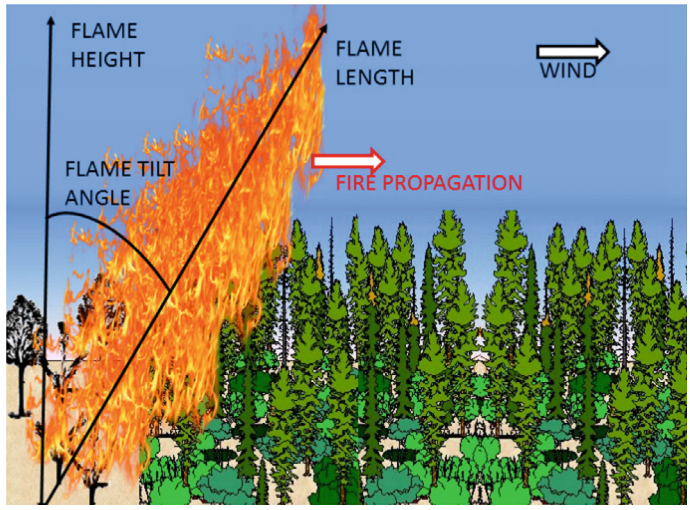



**Fig. 6.1** Flame dimensions for a wind-driven fire

A variety of mathematical models have been constructed for relating flame length to fireline intensity as defined above, such as the Byram (1959) and Thomas (1963) models. Flame length is presented as a fire behaviour characteristic because it is so readily apparent to personnel on the ground, whereas fireline intensity is not.

Calculating flame length is problematic for passive or intermittent crown fires. A passive crown fire is the burning of a single tree or simultaneous burning of a small group of trees. For most of the time that a passive crown fire is spreading, surface fire behavior would be observed, with flame lengths represented by what the surface fuel alone can produce. During the short period when trees are torching out, flames briefly increase in length by more than an order of magnitude. An intermittent crown fire (one that frequently alternates between surface fire and active crown fire) exhibits the same bimodal flame length distribution. Which of these observed flame lengths is the flame length of a passive or intermittent crown fire? Fireline intensity is a scientifically better measure of fire intensity, even if it cannot be readily observed in the field.

Figure 6.2 helps to calculate the flame length from fireline intensity. Thomas' model (Thomas, 1963) is most commonly used for estimating crown fire flame length, whereas Byram's model (Byram, 1959) is used for surface fires.

Deep fuel beds also present a problem for interpreting flame length values. Flame length is defined as the distance from the base of the flames, the mid-height of the fuel bed, to the tip of the continuous flame. When flames are quite long in comparison to the fuel bed depth, there is little concern for making an adjustment for the mid-height of the fuel bed. When the fuel bed is deep, however, as in crown fires, this adjustment is critical. For crown fires, Byram suggested adding one-half of the fuel bed height (stand height) to the flame length values calculated using his model to obtain a better estimate of what might be observed. No such correction is suggested or needed when using Thomas'

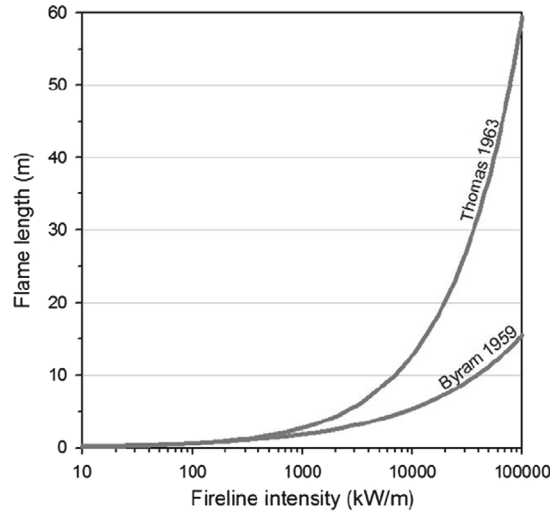



**Fig. 6.2** Flame length as a function of fireline intensity

flame length model. For that reason, Byram's model is generally applied to surface fires (shallow fuel beds) and Thomas' model to crown fires (deep fuel beds).

### 6.3.5 Heat Flux Emitted by a Wildland Fire

Fire transfers heat to the surroundings in three ways: conduction, convection and radiation. Conduction is in most cases negligible in wildfires. Convection is a short-range heat transfer. The flame just above the vegetal stratum (the continuous flame region) forms a strong ascending heat flow, the inertia of which stops the upwind flow from crossing the flame. The consequence is that there is no heating transport due to the wind flowing through the front of the flame. Finally, the convective heat transport above the flame just acts in the close neighbourhood of the flame (Balbi et al., 2009). Thermal radiation comes from hot gases and particles in the flames and entails long-range effects.

The intensity of thermal radiation from fire depends on the temperature, thickness and size of fire. A popular approach to the estimation of the radiation flux from wildland fires is the use of the solid flame model (SFM). In this model, the visible flame is idealised as a solid body, with a simple geometrical shape and with thermal radiation emitted from its surface. The flame is considered as behaving like a grey body, whose surface emissive power (SEP) depends on flame thickness and the emissivity of gases and soot. The contribution of non-visible zones of the fire plume to the radiative heat flux is usually not considered. Although several authors (Parent et al., 2010) suggest that this model may be questionable for wildland fires, the SFM model is easy to use and gives results in acceptable agreement with experimental data (Butler & Cohen, 2000).

Data about SEP values can be found in the literature, the most valuable of them was measured during the International Crown Fire Modelling Experiments (ICFME) (Butler et al., 2004a, b). These authors measured SEP on large crown fires of Jack pine and black spruce trees (average height 13 m) in forest squares ($1 \times 75$ / $1 \times 100$ m / 8–150 m side lengths). SEP measurements were taken at different heights: 3.1, 6.2, 9.2, 12.3 and 13.8 m. By averaging the data measured at these heights in 6 experiments, the maximum peak radiative flux was nominally 190 $kW.m^{-2}$ throughout the entire stand, with a standard deviation of 90 $kW.m^{-2}$. However, these values are only valid during the maximum fire intensity, which lasts a few seconds.

When averaging Butler data over the time during which the fire is significant (SEP > 20 $kW.m^{-2}$), it appears that the average heat flux is reduced to 70 $kW.m^{-2}$. Others SEP values can be found in the literature, such as 57 $kW.m^{-2}$ (Billaud et al., 2011), 118 $kW.m^{-2}$ (Zárate et al., 2008), 90 $kW.m^{-2}$, 60 $kW.m^{-2}$ and 59 $kW.m^{-2}$ (Heymes et al., 2013a, b).

The international crown fire modelling experiments (ICFME) presented spatially and temporally resolved measurements of air temperatures and radiant energy fluxes in a

boreal forest crown fire (Butler et al., 2004a, b). Measurements were collected at different heights above the ground surface (from 3.1 to 13.8 m). Peak smoke temperatures exceeded 1330 °C, and maximum radiant energy fluxes occurred in the upper third of the forest stand and reached 290 $kW.m^{-2}$. Average radiant flux from the flames across all experiments was found to be approximately 200 $kW.m^{-2}$. Measured temperatures showed some variation with vertical height in the canopy. Equivalent radiometric temperatures calculated from radiant heat flux measurements exceeded thermocouple-based temperatures for all but the 10-m height, indicating that fire intensity estimates based on thermocouple measurements alone may result in underestimation of actual radiant intensity. The data indicate that the radiative energy penetration distance is significantly longer in the forest canopy than in the lower levels of the forest stand.

### 6.3.6 The Flying Embers and Firebrand Showers

Flying embers and firebrands ignite most flammable targets, such as homes or woodpiles. There were few, if any, reports of homes burnt because of direct contact with flames from wildland fuels. Very few works focused on how firebrands ignite structures in WUI. A better knowledge is required to establish building codes and standards. These documents are needed to guide construction of new structures in areas known to be prone to these fires to reduce the risk of structural ignition in the event of a firebrand attack.

Authors such as Manzello et al., (2010, 2012) and Meerpoel-Pietri et al. (2021) performed an extended research effort to quantify structure vulnerabilities to wind-driven firebrand showers. Ignition regime maps were determined as a function of feed rate (related to firebrand generation rate) for fixed wind tunnel speed (6 $m.s^{-1}$) and two different cedar crevice moisture contents.

Several results have laid the foundation for this important research direction. But more knowledge is required to design mitigation tools intended to reduce structure losses in these fires. A new model for firebrand's transport could be incorporated in fire simulators such as FDS.

## 6.4 Industrial Assets Vulnerability to Fire

Industrial assets are composed of buildings, technical structures and storages. Buildings are most frequently made by metallic or concrete parts and include classical elements such as windows, doors and ventilation. Technical structures cover a very large and variable field of elements, especially in the case of chemical factories:

- Process units: reactors, distillation columns, heat exchangers, absorbers, strippers, pipes, pumps, ventilators, compressors, chimneys, boilers, condensers, etc. These parts are filled with liquids, gases.
- Control and command equipment: sensors, actuators, valves, etc.
- Electric structures: high-voltage lines, transformers, power stations, etc.
- Steel structures to maintain all parts together: beams, walkways, floors, stairs, etc.
- Safety systems: fire detection and suppression systems, gas and leak detection systems, pressure relief devices.
- Control Rooms, with a very high level of resistance to hazards.

Storages may be open and bulk storage (coal, for example), atmospheric liquid storages, pressurised liquid storages, compressed gas storages, cryogenic storages. The impact of fire on these elements is done in different ways:

- Ignition of materials, leading to in situ fire and worsening the fire scenario.
- Loss of resistance, leading in the worst case to collapse and loss of containment, with major consequences (explosion, fire, toxic cloud release, soil and water pollution).
- Loss of control, leading to major breakdowns and failures that can be dramatic; that can entail or not hazardous consequences
- Loss of operability: operators are evacuated, circulation may be stopped, electricity may be shut down, etc.
- Loss of reliability: no problem is observed, but some elements may have been deteriorated.

The subject is vast and cannot be covered in this chapter. Nevertheless, regarding physical impacts, it can be said that there are two approaches to assessing consequences:

- The threshold approach: resistance values for damage to structures may be found in the literature. Table 6.1 summarises data from literature (Babrauskas, 2003).
- The dynamic approach: most thermal effects are difficult to predict with a single threshold value and require a dynamic modelling. For example, the pressure increase of a pressure vessel exposed to fire requires a dynamic model to estimate the risk of failure. The Time to Failure (TTF) is a classical approach, investigated by Landucci et al. (2009). According to various incident fluxes, the exposure time required to lead to explosion is calculated.

The threshold values are not sufficient to predict the ignition and failure. Structure ignitions (given an exposed flammable surface) from radiation heat transfer depend on two aspects of the flame: the radiant heat flux incident to a surface and the duration of the radiant flux. The incident radiant heat flux refers to the rate of radiant energy per unit

**Table 6.1** Critical heat flux for construction material

| Type of material | | Critical heat flux ($kW.m^{-2}$) |
|---|---|---|
| Certain polymers can ignite | | 10 |
| Thin steel (partly insulated) can lose mechanical integrity | | 11.7 |
| Thin steel (insulated) can lose mechanical integrity | | 25.0 |
| Damage to process equipment and collapse of mechanical structures | | 37.5 |
| Glass | *Type of glass* | |
| | Single glazing | 9 |
| | Double glazing | 25 |
| | Heat-tempered glass | 43 |

*Source* Adapted from Babrauskas et al. (2003)

area that is striking the surface from the flame zone and can be calculated according to the previous part equations. The duration, or length of time of the radiant flux, relates to the flame source burning time, i.e. the amount of exposure time.

The duration of the radiant heat flux also influences ignition. For any radiant heat transfer rate above the minimum required for ignition, a time to ignition depends on the magnitude of the radiant flux. As the radiant heat transfer rate to a surface increases, the time required for ignition decreases. Generally, for wildland vegetative fuels, flame zone burning time depends on the fuel particle size. Grasses, twigs, leaves and conifer needles represent fine fuels that have flame durations of approximately 1 min or less. By contrast, a firewood pile or a neighbouring structure might support a significant flame zone for tens of minutes.

Supplementary elements increase the complexity of modelling:

- Fire exposure time requires a good knowledge of fire propagation and trajectory.
- Flames' location changes with time due to propagation and modifying the view factor between fire and the structure; the incident heat flux cannot be considered as constant.
- The view between fire and the target may be obstructed at certain times during fire propagation, changing the incident heat flux.

## 6.5 Modelling the Impact of Wildfire on Industrial Targets

This part considers the radiative heat transfer from a wildfire to targets located in the WUI. The first section details the modelling strategy to calculate the heat flux impacting a target located at a distance from fire, while the second and third sections describe two case studies.

### 6.5.1 Radiative Heat Transfer Modelling

Considering fire as a solid flame, the heat flux transferred from fire to targets can be computed thanks to the view factor (Fig. 6.3). The view factor F 1 > 2 (dimensionless) is defined as the fraction of the radiation leaving a surface A1 ($m^2$) at fire that is intercepted by a surface A2 ($m^2$) on the target. Oriented elemental areas dA1 and dA2 ($m^2$) are connected by a line of length R (m), which forms the polar angles $q_1$ and $q_2$ (radians), respectively, with the surface normal vectors n1 and n2. The values of R, $\theta_1$ and $\theta_2$ vary with the position of the elemental areas on A1 and A2. Assuming that both surfaces emit and reflect diffusely, and that the radiant emitted power is uniform, the view factor can be defined as (Eq. 6.2).

$$F_{1>2} = \frac{1}{A_1} \int_{A1} \int_{A2} \frac{cos\theta_1 cos\theta_2}{\pi R^2} dA_1 dA_2 \tag{6.2}$$

The heat flux emitted by surface $A_1$ and received by surface $A_2$ is then calculated from equation (Eq. 6.3).

$$Q_2 = F_{1>2}.\tau.SEP \tag{6.3}$$

where $Q_2$ is the heat flux received by surface $A_2$ ($kW.m^{-2}$), $\tau$ is the atmospheric transmittivity of radiative heat and SEP is the surface emissive power of surface $A_1$ which is fire ($kW.m^{-2}$). The fire surface $A_1$ will be considered as flat, straight or curved, with a height Hf and a length L. The distance between each cell $dA_1$ and $dA_2$ depends on the distance X between the fire and the target, corrected by trigonometric equations derived from location of element $dA_i$ on the surface $A_i$ (Fig. 6.3)

So, for each couple (dA1; dA2), there is a distance R and angles ($\theta_1$, $\theta_2$) that must be calculated by integrating on both surfaces (A1, A2). This double integration is time-consuming; specific attention must be paid to radiation directions that are impossible due to shading (for example, at the back of the vessel in Fig. 6.4). X and R are different: X is the global distance between fire and target, whereas R is a local distance depending on the position of both surfaces and the distance X.

Three different types of methods can be used to calculate or approximate the double integral equation to calculate $F_{1>2}$. The first one is the exact or approximate analytical

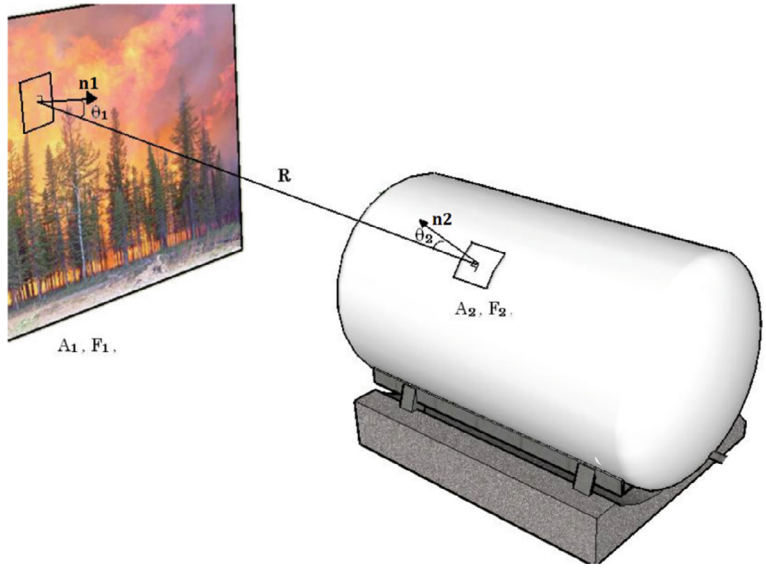



**Fig. 6.3** Geometric parameters for radiative heat transfer calculation

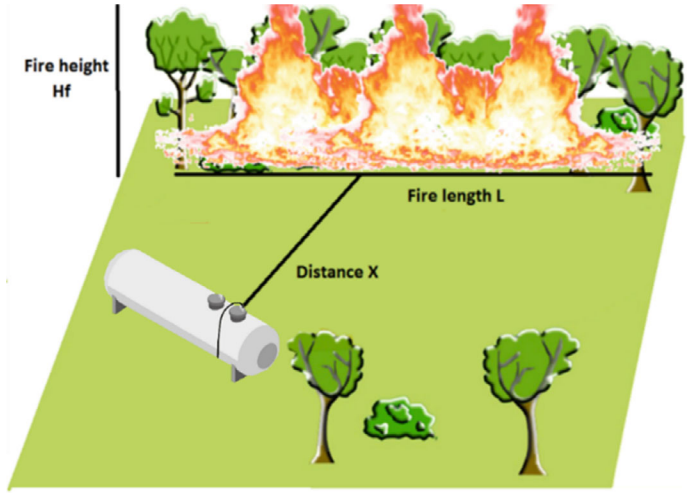



**Fig. 6.4** Scenario geometric parameters

solution of the equation. This is the easiest way to proceed, but analytical solutions were only proposed in simple configurations. The second method is a finite element method (FE method), the accuracy of which depends mainly on the mesh size. This method of computing is time-consuming since the total number of calculation steps corresponds to the multiplication of the number of cells of $A_1$ by $A_2$. The last approach relies on the Monte Carlo method (MC), which reduces the computational time by reducing stochastically the number of calculations to approximate the double integral. The last two methods are compromises between accuracy and computation time. The full computation method can be reduced when one of the two surfaces is very small. The Ondracek method simplifies the computation of the view factor by integrating only over the larger surface.

A set of calculations was performed by the FE method to calculate the view factor $F_{1>2}$ in a simple case of a target located in front of a flat and straight firewall (Fig. 6.5).

This figure shows that the view factor increases when the flame height increases. For a given surface emissive power (e.g. SEP = 90 kW.m$^{-2}$), at a distance of 40 m, the received heat flux will be 11.7 kW.m$^{-2}$ for 40-m-high flames; 6.3 kW.m$^{-2}$ for 20-m-high flames, 3.6 kW.m$^{-2}$ for 10-m-high flames and only 1.8 kW.m$^{-2}$ for 5-m-high flames.

On another consideration, for a fire with 20-m-high flames (SEP = 90 kW.m$^{-2}$), the received heat flux will be 21.6 kW.m$^{-2}$ at 20 m from fire; 50.4 kW.m$^{-2}$ at 10 m from fire and 75.6 kW.m$^{-2}$ at 5 m from fire. For the latter case, heat transferred by convection should also be considered.

These equations can be used to evaluate the heat flux received by a target located in the WUI. As detailed previously, the heat flux impacting a target depends on the fire properties but also on geometric considerations such as the distance between the fire and the target. At the WUI, the configuration is complex, and a large set of various cases may

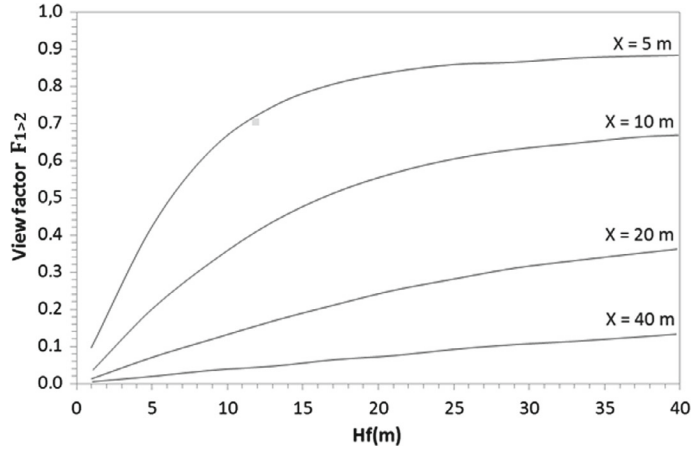



**Fig. 6.5** View factor $F_{1>2}$ for a target located in front of a straight and flat surface of flames (length 40 m) at various distances and various flame heights

occur. An isolated target may be impacted from all sides by an intense fire, whereas in the case of a complex industrial facility the forest edge will be reduced to a single exposition side.

The incident radiant flux to a structure depends on an unobstructed view. Any obstacles between the structure and the flame zone will block part or all the radiation and thus reduce or eliminate the incident radiation flux. Unburnt vegetation, walls and terrain can effectively block radiation. For example, a structure set back from the top edge of a steep slope might not see the flame until it reaches the top of the slope. Thus, if a flame stops before reaching the level of a structure, a steep slope will shield the structure from radiation exposure in that direction. The opposite can occur on the uphill side of a structure. A steep slope uphill from a structure can possibly radiate its entire flame area. For rapidly spreading flames, a structure can be exposed to the increased radiant exposure of an extensive flaming area on its uphill side.

### 6.5.2 Case Study: Effect of Wildfire on an LPG Tank

Few papers focused on possible LPG tanks located near houses (Fig. 6.6). Liquefied Petroleum Gas (LPG) is a common fuel widely used in industry as well as in domestic applications. It can be stored at large scale in industry (up to 5000 $m^3$) or at small scale in residential areas. In this case, this fuel is usually stored out of the house in pressurised cylindrical tanks of medium capacity (1 or 2 $m^3$). These tanks are not protected by a passive protection layer against fire but are prevented from excessive pressure by a relief valve. However, when such a tank is exposed to external fire, there is a chance that the tank will fail despite the action of the pressure relief valve. If the failure mode is catastrophic then this could lead to a boiling liquid expanding vapour explosion (BLEVE). The immediate hazards from a BLEVE are blast and projectiles. Since LPG is flammable, it can be ignited, and a fireball is possible with the associated hazards of fire engulfment and thermal radiation. If the flammable commodity is not ignited immediately, then delayed ignition may lead to widespread fires or in some cases explosion (VCE vapour cloud explosion). These hazards may hurt or kill firemen fighting against wildfire in a residential area if an LPG tank fails, especially if firemen are not aware of the presence of the LPG tank in the surroundings.

The impact of a heat flux on an LPG tank leads to an increase in wall temperatures and therefore material weakening. Heat is also transferred to the liquid phase, which increases the liquid temperature and the vapour pressure. This internal pressure increase leads to creep and thinning in the hot wall area, and this may eventually lead to the formation of a tear or fissure in the tank wall. If the tear propagates the entire length of the tank, then a BLEVE takes place. If the fissure stops short, then a transient jet release takes place. Modelling the thermo-hydraulic behaviour of an LPG tank requires a comprehensive study of the heat and mass transfer processes involved within the tank.



**Fig. 6.6** LPG tank close to a house. *Source* Author's own photograph

Many works were undertaken to model that thermo-hydraulic system with more or less success. Time rupture can be modelled by these models, but a safety margin must be considered since LPG tanks can be old and can present weaknesses.

The American Petroleum Institute recommended critical values for safety studies (American Petroleum Institute 1986). According to this document, the critical value for an LPG tank equipped with a pressure relief valve is 7000 British thermal units per hour per square foot (~22 $kW.m^{-2}$). A vessel shell surface receiving more than this value will require cooling to prevent overheating and loss of strength. This is a very strict safety limit that should prevent BLEVE for a long duration of fire (>30 min). All scenarios leading to an impacting heat flux below the API criteria will be considered as no risk to the LPG tank.

Few works considered the vulnerability of an LPG tank to wildfires. Heymes et al. (2013a, b) performed theoretical and experimental work to assess the effect of a wildfire on the tanks (Fig. 6.7). The authors calculated the maximum heat flux impacting the tank (MHF) which must be compared with the safety criterion from API. Two configurations for the fire wall were considered: a straight and a circular flame front (Fig. 6.8).

#### 6.5.2.1 Influence of the Fire Height, the Distance to the Tank and the Burning Edge Geometry

A parametric study was done to compute the MHF impacting the tank at different distances and for different fire heights. Figure 6.9 represents the MHF impacting the tank for different fire heights Hf = 40 m, Hf = 30 m, Hf = 20 m, located at three distances X = 50 m, X = 30 m and X = 25 m from the tank. In a first consideration, the fire

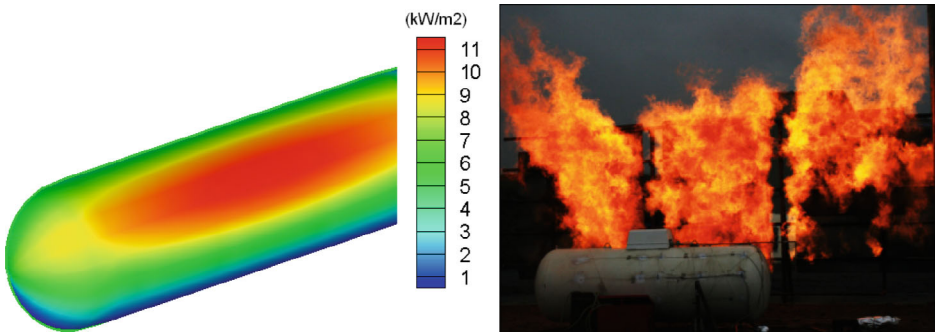



**Fig. 6.7** Modelling and experimental work of fire impacting an LPG tank




**Fig. 6.8** Straight (left) and circular (right) configuration of forest edge. *Source* Heymes et al. (2013a, b)

is considered as straight (Fig. 6.8). A strong influence of the fire length is observed, the MHF can be multiplied by a factor 4 between burning sections of 20 m to 100 m. The study was limited to 100 m since any supplementary length of burning wall will quite not increase the received heat flux for view factor considerations.

Certain authors consider that a burning edge should not be wider than 20 m. This hypothesis seems relevant because in many real fire scenarios the fire propagates along the edge and doesn't reach the whole length of the edge simultaneously. One or several burning strips will propagate along the edge and in the same way increase the exposure time to radiant heat flux. With that consideration (L = 20 m), all safety distances are sufficient for the LPG tank safety since no MHF exceeds 22 $kW.m^{-2}$. On the same figure is represented the configuration in circular edge (dashed lines), following observance of the safety distance in either direction (Fig. 6.8). The circular configuration was limited to a half circle; the authors assumed that the tank would be located close to a house hiding the other half space. The MHF received by the tank are higher in comparison with the straight burning edge. This is due to the higher view factor in that configuration. For a

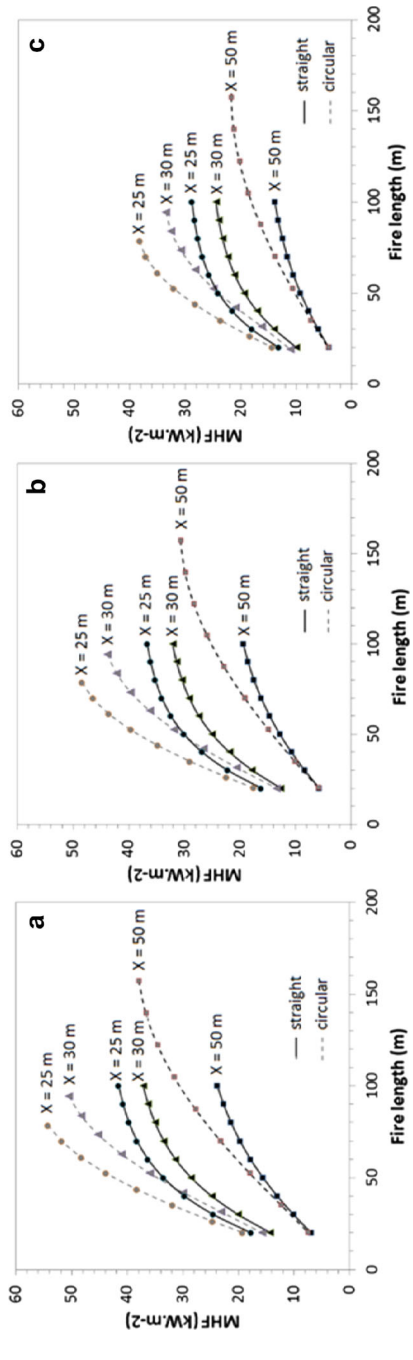



**Fig. 6.9** Impact on the LPG tank as a function of the fire length, for different distances X: **a** fire height Hf = 40 m; **b** fire height Hf = 30 m; **c** fire height Hf = 20 m

short wall (20 m), the circular shape is limited and the behaviour is close to that of a straight fire.

When comparing the different fire heights, the MHF received by the tank decreases according to the fire height. It can be noticed that for a 20-m-high fire, a safety distance of 50 m is sufficient in the considered scenarios.

#### 6.5.2.2 Influence of the Flames Tilt

Another point to consider is wind. The wind increases the fire intensity but also will provoke a tilt of the flames. This tilt will change the view factor between the tank and the fire. A parametric study was undertaken to check this point. Figure 6.10 shows the MHF impacting a tank for a straight fire (100 m) with different tilt angles and with different flame lengths. Results show that a tilt of 20° represents the worst case, but the MHF will only increase by 4 $kW.m^{-2}$. When considering a fire closer to the tank, the worst case occurs with a tilt of 30°; the MHF is increased by 8 $kW.m^{-2}$.

Iso-flux parametric curves were calculated. For each (distance; fire length) couple, the height of fire was sought to get 22 $kW.m^{-2}$ at the LPG tank (Fig. 6.11).

Results of the FE model confirm that a safety distance of 50 m prevents BLEVE with a conservative approach in any fire scenario, even if the crown fire is exceptional (height 40 m, length 100 m). However, several authors consider that the maximum fire height is only 20 m. In that assumption, a safety distance of 30 m is sufficient to prevent any BLEVE risk. Reducing this distance to 25 m could be considered not safe.

But one should not forget many assumptions of this work:

- The entire firewall burns along its entire length and height during the time required to lead to a BLEVE. This time is longer than the few minutes of intense combustion of the wildfire.
- The safety zone will probably not be totally free of trees, and a screen effect must be considered.

On the other hand, when the fire is as close as 3 m from the tank (frequent mandatory distance between a tank and its combustible surroundings), results show that a small fire of 2 m high and 5 m long (for example, a house or a hedge fire) can entail a heat flux higher than 22 $kW.m^{-2}$. This is evidence that even if a safety zone is respected between the forest and the tank, the BLEVE could occur if firebrands ignite combustibles located close to the tank or the house itself.

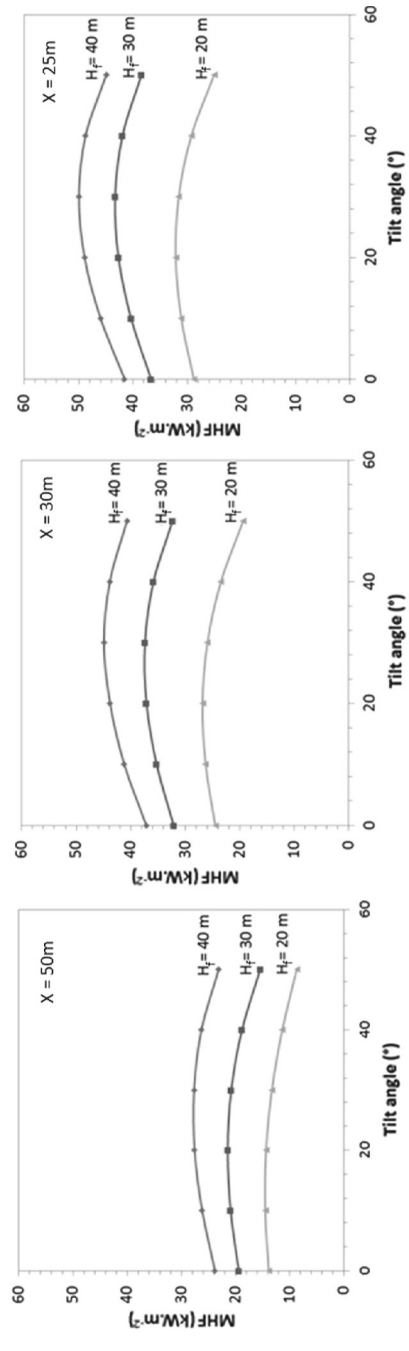



**Fig. 6.10** Influence of the fire tilt angle at different distances (X = 50 m; X = 30 m; X = 25 m) from fire

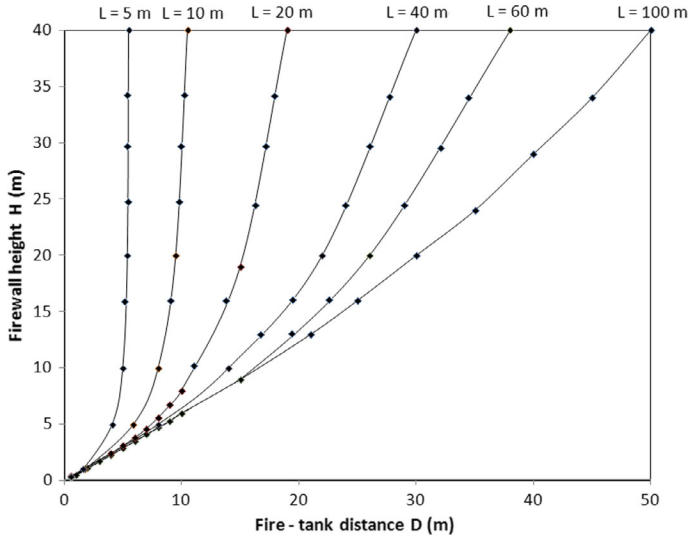



**Fig. 6.11** Safety distance as a function of firewall height and length

## 6.6 Prevention and Protection

### 6.6.1 Defensible Space

A defensible space is the area around an asset that has been modified to reduce fire hazard. In this area, natural and man-made fuels are treated, cleared or reduced to slow the spread of wildfire. Creating defensible space also works in the reverse threat (from industry to wildland) and reduces the chance of a structure fire spreading to other targets or the surrounding forest.

Defensible space provides another important advantage during a fire: increased firefighter safety. Firefighters are trained to protect structures only when the situation is relatively safe for them to do so. They use a process called 'structural triage' to determine if it is safe to defend a home from an approaching wildfire. The presence or absence of defensible space around a structure is a significant determining factor used in the structural triage process, as defensible space gives firefighters an opportunity to do their job more safely. If firefighters are unable to directly protect a target during a wildfire, having an effective defensible space will still increase the house's chance of survival.

Creating an effective defensible space involves a series of management zones in which different treatment techniques are used. These zones must be developed around each building, including detached garages, storage buildings, barns, LPG tanks and other structures. The size of the defensible space depends on the country/state and varies in a 30–50-m range.

### 6.6.2 Protecting Structures

Although defensible space can reduce the risk from surface and crown fires, it cannot prevent firebrands from igniting targets or entering an opening and igniting a structure. Using fire-resistant materials, which inhibit ignition, and screening exterior vents and other openings can help protect against firebrands and provide another important level of protection.

#### 6.6.2.1 Fire-Resistant Building Materials

Fire-resistant building materials play an important role in protecting structures by helping to prevent ignition. During a wildland fire, flames or firebrands may meet a structure, or intense heat may either ignite the exterior of a structure or melt it, thus exposing the structure's interior to the fire. Elements made of fire-resistant building materials, such as fibre-cement, bricks, stone, metal and stucco, help structures resist such damage and destruction.

#### 6.6.2.2 Fire-Resistant Windows and Windows Shutters

Fire-resistant windows help protect a structure from wildland fire by reducing the risk a window will break and allow fire to enter a structure. Windows constructed of double-paned glass, glass block or tempered glass can help resist breakage. The materials used for shutters are also a crucial factor during wildfire. Depending on the material, the fire may reach the window more easily.

### 6.6.3 Chemical Agents

Firefighting chemical agents, such as foams and gels, are temporary protective measures that can be applied as an exterior coating shortly before a wildland fire reaches a structure. Foams, typically based on detergent, are combined with water or forced air. Gels are polymers that can hold many times their weight in water. Both are designed to be sprayed onto a structure, coating it with a protective outer shield against ignition. These kinds of agents have helped during the Cedar Fire in San Diego County (US) in 2003 and saved more than 75 homes from fire. The disadvantages of using foams and gels are that they need to be applied to a structure by a homeowner or firefighter. Chemical agents may also need to be periodically reapplied or sprayed with water to remain effective, and they can be difficult to clean up.

### 6.6.4 Sprinkler and Water Curtain Systems

Sprinkler systems, which can be installed inside or outside a structure, lower the risk of ignition or damage. Sprinklers, however, require reliable sources of water and, in some cases, electricity to be effective. Several firefighting officials in the US claim that during wildland fires, power and water services may not be adequate for sprinklers to function properly.

A water curtain is a device which used to be used by firefighters (probably last used extensively in the early 70 s) to prevent fires from spreading from one building to the next. It is connected to a water hose and sprays water vertically. The droplets of the water curtain stop radiant heat by reflection and absorption mechanisms. The water curtain also decreases the convective heat flux by evaporation of water and mixing of the hot gases with ambient air. However, water curtains aren't as effective at absorbing heat from fire than direct application of water to the exposed house. Thus, the water curtain needs to be sprayed directly on the exposure. Placing it between the burning structure and the exposure does no good. It must be of sufficient size and capacity to continuously wet the entire face of the exposure facing the burning building now this includes the roof if the flames are above the structure.

## 6.7 Perspective: Research About Natural Gas Pipelines Impacted by Wildfire

Few studies have investigated the vulnerability of natural gas transport infrastructures located near areas prone to wildfire (Fig. 6.12). Natural gas is transported over long distances through buried or above-ground steel pipelines operating under high pressure. Along these pipelines, surface installations such as compressor stations or pressure reduction stations are necessary to maintain gas flow and regulate delivery conditions. These facilities are often located in semi-rural or forested areas, where they may be exposed to wildfires.

Although buried pipelines are generally well protected from direct flame contact, heat conduction through the surrounding soil can still affect their structural integrity. In contrast, above-ground equipment such as valves and other surface installations remains vulnerable to thermal radiation and flame engulfment. Under prolonged fire exposure, the resulting heat flux can weaken steel components and other materials, potentially leading to loss of containment. Such failures can result in jet fires, fireballs or explosions, depending on whether ignition occurs immediately or after a delay.

The associated hazards—including intense thermal radiation, blast waves and projectiles—can endanger nearby personnel, firefighters and infrastructures. Furthermore, undetected leaks or delayed ignition of released natural gas can produce large vapour clouds, increasing the risk of a Vapour Cloud Explosion (VCE) (see Chap. 3). These



**Fig. 6.12** Surface installation of a natural gas transport system near a forest. *Source* Author's own photograph

risks highlight the importance of assessing wildfire exposure scenarios for gas transport facilities located within or near areas prone to wildfire.

The Alliance Pipeline, a Canadian-U.S. natural gas transmission pipeline system, has recommended critical values for safety studies (Robinson et al., 2018). According to this study, the critical heat flux for a pipe with 1 m/s flow ranges from 95 to 191 $kW.m^{-2}$, while for a pipe with no flow it ranges from 21 to 54 $kW.m^{-2}$. These ranges depend on the steel grade and the pipeline diameter, which are directly related to the wall thickness. For structural steel, the critical value is 32 $kW.m^{-2}$. According to a report from NaTran (2017) a major operator of high-pressure natural gas transport in France, the critical heat flux for thermal exposure is at 25 $kW.m^{-2}$ for a total exposure duration of 1 h. These values represent safety limits intended to prevent domino effects due to potential failures under a constant external heat flux.

Few studies have focused specifically on wildfire impacts on natural gas facilities. Robinson et al. (2018) conducted a theoretical study to evaluate the effects of wildfires on above-ground installations. The authors recalculated the radiative heat flux emitted by the May 2016 wildfire near real facilities and then estimated the heat flux received by various targets. The results were compared with field observations of actual damage, showing good agreement between modelling and observed impacts. The wildfire model was computed using the previously presented methods, including Byram's formula and the solid flame model.

### 6.7.1 CFD-Based Method for Estimating Emitted and Received Heat Fluxes

To better quantify the thermal exposure of pipelines and surface equipment, CFD-based approaches have been developed. The solid flame model (SFM) is widely used to estimate the heat flux emitted by a wildfire. However, due to its theoretical simplifications, SFM has several limitations: only the radiant component of the heat flux is considered, and the real dynamics of a wildfire is not accounted for. Computational Fluid Dynamics (CFD) provides an alternative by numerically solving the fundamental equations governing fluid motion, heat transfer and related physical processes. CFD allows detailed simulation of complex flows, including fire–atmosphere interactions, through discretisation of space and time. While general-purpose CFD tools such as OpenFOAM, STAR-CCM+, ANSYS Fluent or COMSOL exist, few are specifically adapted for wildfire studies. The Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST), is a large-eddy simulation (LES) code for low-speed flows, with an emphasis on smoke and heat transport from fires, including extensions suitable for wildland fire modelling. Adaptation of FDS to wildland fire spread began in the early 2000s: Mell et al. (2009) simulated fire propagation over grasslands and Douglas fir stands, while Perez-Ramirez et al. (2017) performed small-scale laboratory fire spread experiments. These studies used a specialised variant known as Wildland-FDS (WFDS), now integrated into FDS. Wadhwani et al. (2022) developed a device to generate controlled firebrands, validating FDS predictions of firebrand transport against experimental observations.

To apply FDS to natural gas pipelines, results from the International Crown Fire Modelling Experiment (ICFME) were used for validation. Alexander et al. (2004) provided extensive pre-fire and post-fire vegetation data, including crown bulk density ($kW \cdot m^{-3}$) of overstory and understory, number of cells, crown base height, tree diameter and tree height. Data from Butler et al., (2004a, b) and Cohen (2004) were also used for the emitted heat flux in vegetation and the incident heat flux measured at 10, 20 and 30 m from the forest edge (Fig. 6.13).

The initial results (Fig. 6.14) indicate that FDS overestimates the heat flux near the forest edge (10 m) and underestimates it farther from the forest (30 m) compared with experimental data from Plot 9 and the average of four plots. These discrepancies are attributed to model parameter choices, highlighting the importance of conducting parametric studies for this type of simulation.

### 6.7.2 Thermal Effects of Wildfires on Buried Pipelines

Buried pipelines, although generally protected from direct flame contact, remain vulnerable to heat conduction through the surrounding soil. These pipelines are often installed

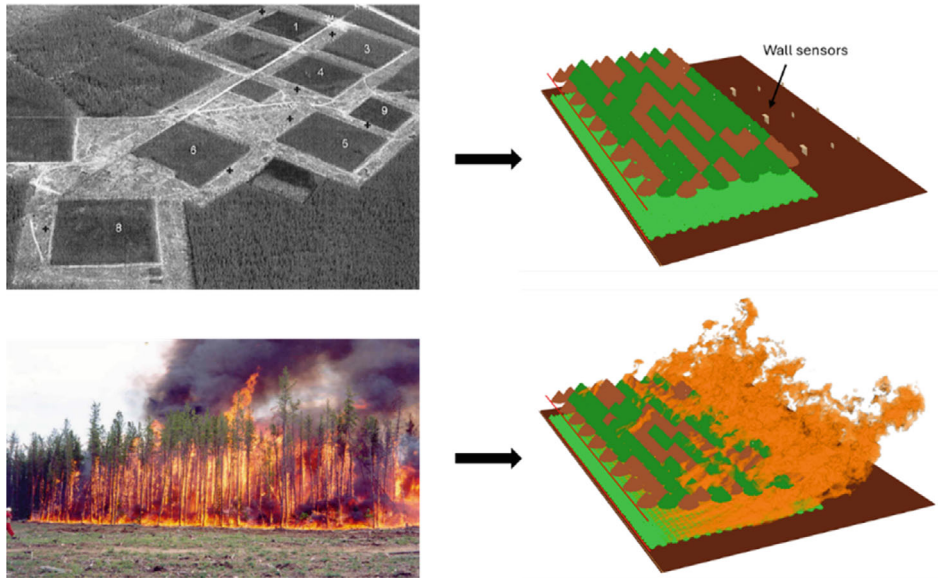



**Fig. 6.13** Experimental set up of the ICFME (Cohen2004) and corresponding FDS simulation of Plot 9. *Source* Adapted from Butler et al., (2004a, 2004b)

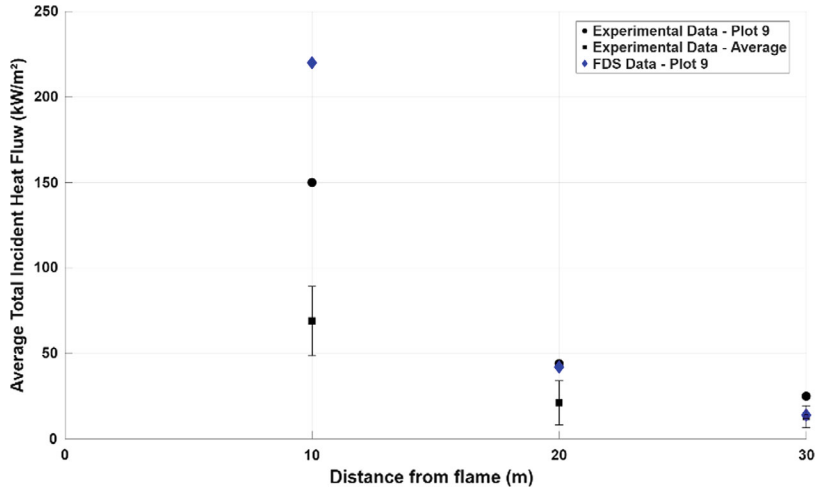



**Fig. 6.14** Average total incident heat flux at 10, 20 and 30 m from the forest edge for ICFME Plot 9. *Source* Cohen (2004)

within rights-of-way, where vegetation is managed or pruned. However, in some cases, maintenance is insufficient, allowing vegetation to accumulate above buried pipelines.

Few studies have investigated the impact of wildfires on buried pipelines. Richter et al. (2022) conducted a theoretical study on thermoplastic water pipes, which was later extended by Janssens (2025) through a more detailed analysis of soil thermal parameters and heat transfer mechanisms. Bernard et al. (2025) analysed buried natural gas pipelines with a clear right-of-way exposed to a nearby crown fire. Their results showed that, under the authors' assumptions, for a burial depth of 0.8 m—the minimum depth required in France—even an intense 4-h crown fire caused no significant temperature to increase within the pipe.

These studies solve the one-dimensional transient heat conduction equation (Eq. 6.4).

$$\frac{\partial T(z,t)}{\partial t} = \alpha \cdot \frac{\partial^2 T(z,t)}{\partial z^2} \tag{6.4}$$

where α is the soil thermal diffusivity ($m^2.s^{-1}$), T the soil temperature (°C) and z the depth below ground (m). Boundary and initial conditions are applied, with the soil surface continuously exposed to the incident heat flux. The surface heat flux is modelled using a Neumann boundary condition, accounting for the soil thermal conductivity λ ($W.m^{-1}.K^{-1}$) (Eq. 6.5).

$$-\lambda \cdot \frac{\partial T(0,t)}{\partial t} = Q \tag{6.5}$$

Soil emissivity ($\varepsilon \approx 0.97$) is integrated into the boundary condition, approximating a black-body response (Qin et al., 2006). Convection and potential evaporative cooling are also considered at the surface.

To validate further modelling using a two-dimensional transient heat equation, experimental investigations were conducted. The soil surface was exposed to a radiant panel with a nominal power of 60 kW, producing incident fluxes up to 110 $kW.m^{-2}$, consistent with previously defined SEP values for crown fires. The results, shown in Fig. 6.15, present the experimental set up and the temperature evolution with depth over a 1-h exposure to an incident heat flux of 95 $kW.m^{-2}$ on a dry clay–limestone soil.

### 6.7.3 Study on Above-Ground Gas Facilities

Unlike buried pipelines, above-ground installations are directly exposed to wildfire hazards and remain vulnerable to thermal radiation and flame impingement. To assess this vulnerability, a combined approach using experimental investigations and coupled CFD tools—FDS and ANSYS Fluent—can be applied.

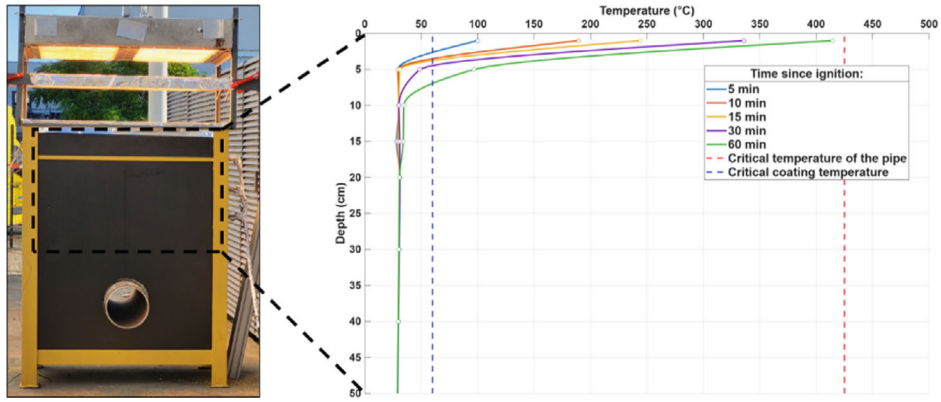



**Fig. 6.15** Experimental set up and temperature evolution with depth for a dry clay–limestone soil exposed to an incident heat flux of 95 kW·m$^{-2}$ for 1 h

In this coupling strategy, FDS is used to simulate the wildfire and determine the heat flux emitted and received by the target equipment. The resulting incident heat flux distribution on the surface of the component is then mapped and imported as boundary conditions into ANSYS Fluent (Fig. 6.16). Fluent allows detailed modelling of the equipment, including complex geometries, high-pressure internal gas flow and precise thermal conduction, under the imposed thermal loads.

Complementary experimental tests are conducted to validate the simulations and provide additional data on critical temperatures. These experiments involve exposing representative targets (e.g. valves, seals and piping) to a radiant panel simulating the fire, with dimensions of 1.5 m in length and 1 m in height, reproducing realistic heat flux conditions from surface fires to crown fires.

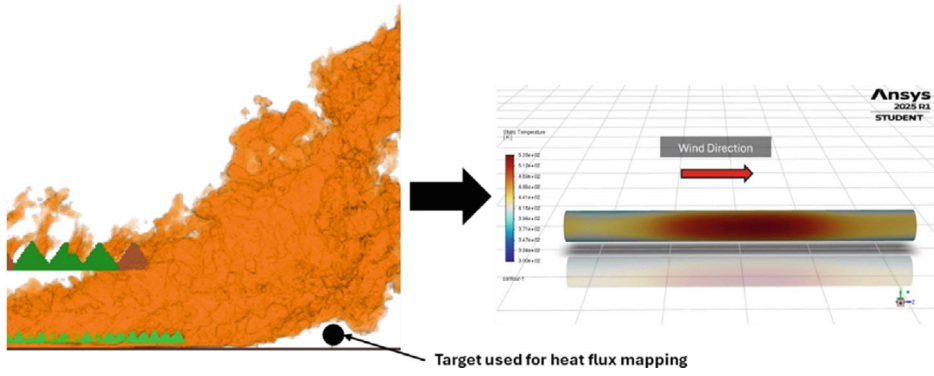



**Fig. 6.16** CFD coupling strategy: FDS to fluent

The main objective of this study is to determine the 'Time to Failure' (TTF) of the equipment, i.e. the time until rupture occurs under fire exposure. This information is crucial to evaluate potential domino effects and implement effective mitigation strategies for above-ground gas facilities.

**Key Sentences**

- Wildfires represent an increasing NaTech hazard, with their behaviour governed by fuel characteristics, moisture dynamics, terrain and the accelerating influence of climate-driven extreme events.
- Industrial assets located in the wildland–industrial interface are exposed to multiple failure mechanisms, including ignition, thermal degradation, loss of containment and firebrand-induced damage.
- Assessing wildfire impacts requires coupling fire behaviour models with radiative heat transfer calculations, accounting for flame geometry, view factors, exposure duration and environmental variability.
- Risk reduction relies on defensible space, fire-resistant design and robust safety distances, while advanced CFD-based methods enhance understanding of vulnerabilities for LPG tanks and natural gas facilities.

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# Conclusion and Outlook

7

Ingrid Canovas and Aurélia Bony-Dandrieux

**Abstract**

This concluding chapter highlights the growing systemic nature of technological risks in increasingly interconnected industrial, digital and territorial environments. It underscores how cascading failures, NaTech interactions and evolving climate-related hazards challenge traditional prevention and protection approaches. Advances in modelling, monitoring and data-driven analysis offer new opportunities for anticipating complex scenarios, yet they also introduce novel vulnerabilities, particularly in cyber-physical systems. Effective risk management therefore requires integrating scientific, operational and organisational knowledge while reinforcing weak-signal detection and feedback mechanisms. The chapter calls for more coherent, multi-level governance linking industrial safety, environmental protection, land-use planning and climate adaptation. Long-term resilience will depend on the capacity to coordinate across sectors, combine innovation with precaution and align technological progress with sustainability and societal expectations.

**Keywords**

Systemic risks • Territorial resilience • NaTech • Technological innovation • Integrated governance

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## 7.1 Systemic Risks and the Need for Robust Understanding

In modern industrial societies, risks are no longer confined to isolated facilities or single processes; they have become systemic, global and multi-scalar. The increasing coupling of production systems, the densification of urban–industrial interfaces and the acceleration of global flows of energy and materials have expanded both the scope and magnitude of potential consequences. Dependence on digital infrastructures further amplifies these interconnections, exposing critical systems to cascading failures and cyber-physical disruptions. Understanding these risks is therefore essential for developing effective prevention and protection measures that limit impacts on populations, ecosystems and property. This requires the rigorous application of risk analysis methods to identify potential accident scenarios, along with a solid grasp of accidental phenomena—such as toxic gas dispersion, explosions, fires or releases at sea—and their propagation mechanisms and consequences. While explosions, fires and toxic releases follow universal physical laws, each industrial configuration has its own dynamics of escalation and impact. Advances in modelling have improved the ability to anticipate consequences and design appropriate safety barriers, yet events such as AZF (2001) and Beirut (2020) show that even the best models must contend with the unexpected, underscoring the need for operational vigilance, maintenance and effective emergency response.

The analysis of pollution by hazardous substances, whether at sea, in rivers or in the atmosphere—as illustrated by the Rouen fire in 2019—adds a cross-border dimension to technological hazards. Managing such events requires coordination across multiple scientific fields, including chemistry, physics, environmental science and public health. Beyond the scientific aspects, crisis management mobilises diverse forms of expertise (emergency responders, authorities, operators, industrial risk specialists, medical services, communication professionals). Issues of liability and legal responsibility may also arise. When pollution crosses borders, governance becomes even more complex due to differing organisational structures, response mechanisms and communication protocols across countries, which must nonetheless be coordinated to ensure a rapid and effective response.

This book provides an initial basis for understanding the complexity of these issues and encourages readers to explore further. The integration of scientific, empirical and experiential knowledge is essential for addressing systemic challenges related to NaTech hazards, interconnected infrastructures, innovation in prevention, modelling, protection, crisis management and remediation technologies.

Feedback mechanisms and near-miss analysis should also be reinforced. Systematic reporting, investigation and analysis of weak signals, deviations and near-miss events are among the most effective ways to prevent major accidents. Such mechanisms promote continuous learning, highlight underlying organisational weaknesses and help adjust preventive measures before incidents escalate. Embedding these processes into everyday operations contributes significantly to building adaptive capacity and improving long-term safety performance.

## 7.2 Emerging Challenges

Climate change further increases the exposure of existing facilities to extreme weather events. The growing importance of NaTech risks illustrates this interdependence: forest fires affecting storage tanks, floods inundating chemical plants or earthquakes damaging pipelines show how environmental forces can amplify technological vulnerabilities. As climate change alters hazard patterns globally, such scenarios are becoming more frequent and severe. Industrial safety can no longer be separated from climate adaptation. The resilience of facilities, supply chains and territories must be assessed considering future climate conditions. Addressing these combined risks requires integrating natural hazard assessment into technological risk management, developing new cascade-effect models and rethinking land-use planning.

Innovation in monitoring and analysis can support this evolution. Sensors, drones, real-time data collection, predictive maintenance and digital twins offer advanced monitoring and modelling capabilities. Artificial intelligence and machine learning can improve the detection of anomalies and weak signals. Yet these developments introduce new challenges: reliance on digital infrastructures creates cyber-security vulnerabilities and the abundance of data can complicate rather than clarify decision-making if not critically interpreted. Future risk management will depend on achieving a balance between technological assistance and human oversight.

Climate change and energy transition are also reshaping technological risk governance. The shift to renewable and low-carbon energy sources introduces new materials and processes—hydrogen, ammonia, lithium-ion batteries—with associated hazards. The restructuring of industrial landscapes, the emergence of distributed energy systems and the conversion of legacy infrastructures are creating new interfaces between technological, human and environmental systems.

## 7.3 Evolving Governance and Long-Term Perspectives

Economic, environmental and social imperatives must be reconciled within frameworks that ensure transparency and coherent communication. As technological systems become increasingly interconnected, governance depends on the ability to coordinate across multiple scales and sectors, prepare for uncertainty and surprises and adapt to extreme events. The challenge is therefore not only technical but also organisational and strategic. It requires embedding resilience—understood as the ability to anticipate, absorb, recover and adapt—into design, operation, land-use planning, safety culture and crisis management.

At a strategic level, policy and institutional frameworks must continue to evolve towards greater coherence and integration. International standards such as the Seveso III Directive (2012/18/EU), the RCE Directive (2022/20257), the OECD Guidelines for Chemical Accident Prevention (OECD, 2023) and the Sendai Framework for Disaster

Risk Reduction already provide a foundation for harmonising practices. However, their effective implementation often remains fragmented across sectors and territories. Future progress will depend on cross-sectoral coordination—linking industrial safety with environmental protection, urban planning, climate policy and civil security. Territorial risk governance—supported by digital platforms and open data—can facilitate collaboration among stakeholders and enhance preparedness. Achieving this integration requires consistent objectives, institutional innovation and a shared vision of sustainable safety.

In conclusion, the management of technological risks stands at a crossroads shaped by increasing complexity and rapidly evolving capabilities. Advances in science and data analysis offer powerful tools for anticipating and mitigating hazards, while global interdependence and environmental change continually generate new challenges. The integration of climate science, technological innovation and systemic approaches is becoming essential. The future of technological risk management will depend on the ability to integrate diverse knowledge, foster cooperation across domains and maintain a thoughtful balance between innovation and precaution. By combining methodological robustness, interdisciplinary insight and long-term vision, societies can strengthen their resilience and ensure that technological progress remains compatible with safety, environmental integrity and sustainable development.

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