Understanding disaster risk: hazard related risk issues

SECTION IV
Technological risk

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Introduction

The risk of technological accidents from man-made and natural hazards is increasing as a result of industrialisation, population growth that leads to more urbanisation and community encroachment on natural-hazard areas, and climate change. The last few years have seen major technological accidents, with significant social, environmental and economic impacts that have had repercussions around the globe. Examples include the explosions at chemicals warehouses at Tianjin Port in 2015, the Fukushima nuclear disaster caused by the 2011 Great East Japan earthquake and tsunami, and the Deep Water Horizon oil spill in 2010.

There is no overarching framework for the reduction of technological risks, and disaster risk reduction initiatives have not commonly addressed this type of risk. With the Sendai Framework for Action, the importance of technological hazards has been recognised and an all-hazards approach to disaster risk reduction is promoted. This includes dangerous situations arising from man-made activities caused by human and organisational error, mechanical failure and natural hazards — so-called Natech risk. Prevention and preparedness for these risks, and for environmental emergencies in general, also has implications for sustainable development.

There are many hazardous industrial activities that provide society with important goods and services (e.g. chemical processing, oil and gas transport and some forms of electricity production). For the purpose of this report, three examples of major technological hazards were selected and the state of play in the management of the associated risks is discussed: (1) chemical accident risks due to the relatively frequent occurrence of accidents, (2) nuclear risks due to the potential for major cross-border consequences, and (3) Natech risks as an example of a multihazard cascading risk.

3.12 Technological risk: chemical releases

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3.12.1 Introduction

In 1921, an explosion of 4 500 tonnes of ammonium nitrate sulphate fertiliser at a BASF site in Oppau, Germany, killed more than 500 people and caused considerable damage to the site and surrounding community. At the time, Carl Bosch, BASF's Nobel Prize-winning engineer said, 'The disaster was caused neither by carelessness nor human failure. Unknown natural factors that we are still unable to explain today have made a mockery of all our efforts. The very substance intended to provide food and life to millions of our countrymen and which we have produced and supplied for years has suddenly become a cruel enemy for reasons we are as yet unable to fathom.' This statement was no doubt true in 1921, when chemical manufacturing was still a new and growing industry. 100 years later, however, thanks to the work of generations of dedicated scientists in industry and academia, 'unknown natural factors' are rarely an underlying cause or chemical accidents today.

Accident reports, investigation results and media reports of recent times give overwhelming evidence that chemical accidents today are mainly caused by a failure to apply what is already known, the 'known knowns'. Improvements in our understanding of chemical accident risks and chemical accident control technologies and systems have not necessarily led directly to advances in a significant reduction in chemical accident disasters. Indeed, according to a famous study by H. W. Heinrich (1931), 98 % of all industrial accidents are preventable. However, technological disasters are by their nature '(hu)manmade' and it can be argued that a reduction in chemical disaster risk is particularly affected by the dependence on humans to manage and use the technology appropriately. Turner and Pidgeon (1997) argue that disasters arise from an absence of knowledge at some point. They occur because we do not understand enough about those forces (i.e. in industrial processes) that we are trying to harness, and, as a result, energy is released at the wrong time or in the wrong place. They are also clear that this is not just an engineering issue and that many disasters arise from social or administrative causes or the combination of technical and administrative causes.

Improvements in our understanding of chemical accident risks and chemical accident control technologies and systems have not necessarily led directly to advances in a significant reduction in chemical accident disasters.

The science of reducing chemical accident risks is now focused on the

underlying causes of human failure to control the risks. Characterising causality in this way adds new dimensions to the study of chemical accident risks. In attributing causality to control, there is a recognition that further progress in reducing chemical accident risks requires strong involvement of the social sciences. Certainly, there is considerable room to examine new engineering solutions, such as the use of artificial intelligence and adapting existing control technologies to new processes. However, these types of solution are industry and even process specific and do not apply to many sectors in which accidents frequently occur. Indeed, the oil and gas industry is one of the world's oldest industries and has been the subject of massive technological investment over many decades; however, globally it is by far the leader in terms of the frequency of severe chemical accidents.

The term 'hazardous industries' comprises numerous substances, processes and equipment, with considerable variation within each category in regard to properties, function and behaviour under different conditions. Petroleum refineries, bulk chemical production (e.g. chlorine and ammonia), the manufacture of specialty chemicals (e.g. paints, dyes, plastics and resins) and pharmaceuticals are examples of industries that comprise a wide range of processes, each with their own unique risk profile and associated risk management implications. While there is less variety, there is still considerable danger in processes involving hazardous substances in the 'non-chemical' industries, such as water and waste treatment, electroplating and food production. In addition, distribution activities, including transport by rail, road and pipeline, as well as explorative and extractive activities both on- and offshore, also are important sources of chemical accident risk. The evaluation of the potential for chemical accidents triggered by natural hazards (so-called Natech accidents, see Chapter 3.14) or other external events, as well as incidents caused by intentional acts, involves additional factors (e.g. natural hazard forecasting, earthquake protection, site security, etc.). These types of incident risks are not specifically addressed in this paper, but it is assumed that standard risk management practices, as here, also help to prevent and mitigate such events.

In societies with mature risk regulation, such production and use of hazardous substances is permitted provided that the risks remain at a level deemed acceptable by the local community and society in general. This paper presents evidence that industrialised countries are still far from achieving an acceptable level of chemical accident risk. It then describes a number of underlying causes common to all industries and societies that are impeding progress in chemical accident risk reduction.

3.12.2 Chemical accidents with serious impacts continue to occur with disturbing regularity

Chemical accidents are still a relatively frequent occurrence in all industrial countries and raise important questions about the adequacy of disaster risk-reduction efforts. Media monitoring over the last several years shows consistently that at least 25-30 chemical accidents with worker or community impacts are reported each month around the world in industrialised countries. Preliminary results of a study by Wood et al. (2016) of accident reports covering all major chemical hazards in fixed facilities and transport over the last 5 years (2012-16) identify 29 national and regional chemical accident disasters and 21 chemical accidents with evident high local impact.

Chemical accidents are still a relatively frequent occurrence in all industrial countries and raise important questions about the adequacy of disaster risk-reduction efforts.

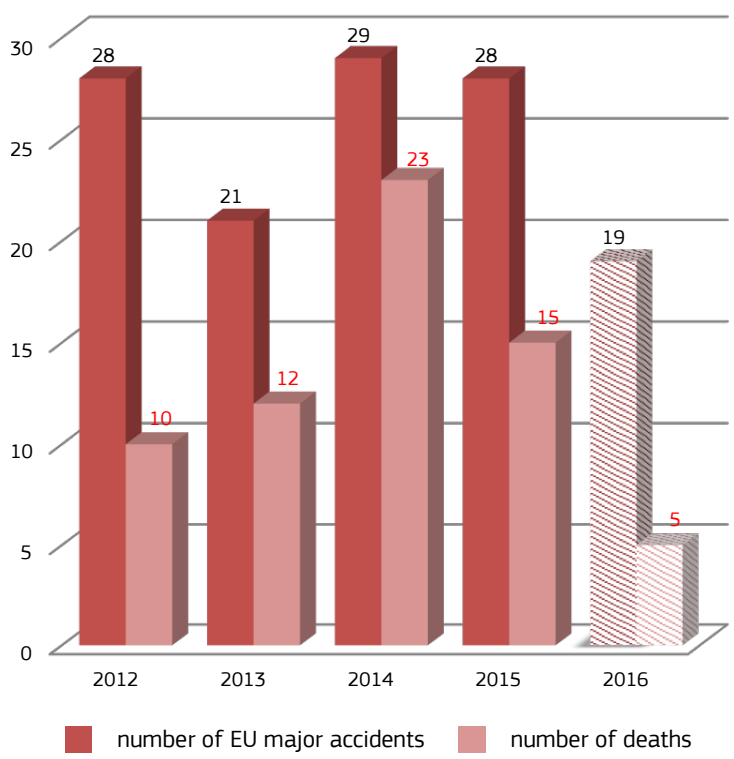
Disasters were classified on the basis of reported impacts on human health, the local community or the environment or on the basis of significant attention at a national level in processing and storage facilities and distribution networks (transport and pipelines). 'Local shocks' were are accidents identified on the basis of important local impacts as reported in the newspapers, corresponding to at least gravity level 3 on the European Gravity Scale for Industrial Accidents (Committee of Competent Authorities for Implementation of the Seveso Directive, 1994). In total, these accidents accounted for

928 deaths, and (where reported) 22 973 injuries. In addition, significant environmental impacts were recorded, with one pipeline disaster reaching USD 257 million (EUR 236 million) in restoration costs (LATimes, 2017). More than 7 000 people were evacuated for several months owing to a slow leak of natural gas that was finally sealed off in February 2016 (October 2015-February 2016, Aliso Canyon, CA, USA). Insurance companies recorded nine accidents resulting in >USD 100 million (EUR 92 million) in damages, including two accidents (Hazardous goods warehouse, Tianjin, China, 12 August 2015 and petroleum refinery fire, 15 June 2014, Achinsk, Russia) costing >USD 1 billion (EUR 0.92 billion). Many other impacts, including job losses, environmental impacts, emergency response costs, damage to nearby buildings and market and production losses were sparsely reported, but businesses in West Virginia were reported to have lost USD 61 000 000 (EUR 56 000 000) in 4 days.

Belke (1998) states:

FIGURE 3.54

European Commission eMARS reporting system.
Source: eMARS (2012)



'From the perspective of the individual facility manager, catastrophic events are so rare that they may appear to be essentially impossible, and the circumstances and causes of an accident at a distant facility in a different industry sector may seem irrelevant. However, from our nationwide perspective at [U.S.] EPA and OSHA, while chemical accidents are not routine, they are a monthly or even weekly occurrence, and there is much to learn from the story behind each accident.'

The frequency of severe chemical accidents is at odds with society's expectations. Societies are becoming increasingly risk averse and failure is less readily tolerated. There are indications that the frequency of serious chemical accidents is higher than expected in many industrialised countries. In 2015 the number of deaths from major accidents on the ≈10 000 EU Seveso sites was estimated to be at least 15 (see Figure 3.54). This statistic, if confirmed, means that the frequency of one fatality on a major hazard site in the European Union was around 1.5×10^{-3}, that is, above acceptable limits for individual risk in EU Member States that use quantitative criteria. (e.g. the criteria established for individual risk (probability of 1 fatality) is $< 1 \times 10^{-6}$ in both the Netherlands and the United Kingdom, although lower probabilities may be accepted in some circumstances, for example, depending on economic costs and benefits (Ham et al., 2006)). In 2013, the President of the United States issued an Executive Order to improve chemical facility safety and security following various high-profile chemical accidents. In recent years, chemical accident frequency and severity in other major industrialised countries, such as China and Brazil, has been approaching, or

has approached, levels that would be generally considered unacceptable in an industrialised economy.

Globalisation and the export of technology have increased chemical accident risk outside the EU.

Similar trends are noted in developing countries (see Figure 3.55). The terms 'developed' and 'developing' are used in this paper to differentiate countries with modern physical and institutional infrastructures from those that are still in the process of establishing such infrastructures. 'Industrialised countries' refers to both developed countries and newly industrialised countries, in which the manufacturing sector has a significant economic presence. China enacted the Emergency Event Response Law of 2007 as a result of an important lesson learned from two major chemical accidents in China: the 2003 gas well blowout in Chongqing that caused 243 deaths mainly from hydrogen sulphide inhalation, and the 2005 release of toxic substances into the Songhua River (Zhao et al., 2014). New legislation in Brazil covering chemical risks stems from broad-based concerns about problems connected with chemical safety that have grown in intensity and extent in the last two decades. Many developing 2014countries have experienced rapid growth in hazardous operations in particular segments of the oil and gas, chemical and petrochemical industries and mining, driven by a combination of factors, including increased demand in emerging economies, access to raw materials and the need to lower production costs, facilitated by a decline in trade barriers and government incentives to attract foreign investors (de Freitas et al., 2001).

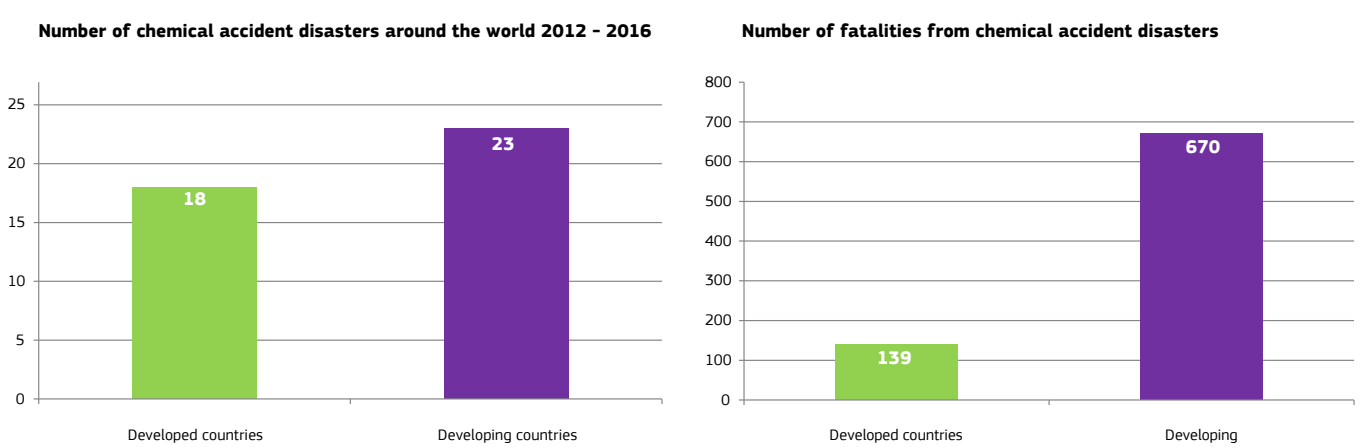
FIGURE 3.55

Chemical accident disasters reported from 2012-16 (N=29), occurring in industries producing, handling or storing dangerous substances, including oil and gas, petrochemical and chemical industries, as well as 'non-chemicals' business, such as power generation, food manufacturing and water treatment.

The frequency of chemical disasters occurring in developing countries in the period 2012-16 was more or less equivalent to that of developed countries, but fatality rates were much higher. It is speculated that risks to humans are less well-managed in developing countries.

Non-human impacts (environment, economic loss, property damage) were often quite severe in both developed and developing regions.

Source: Wood et al. (2016)



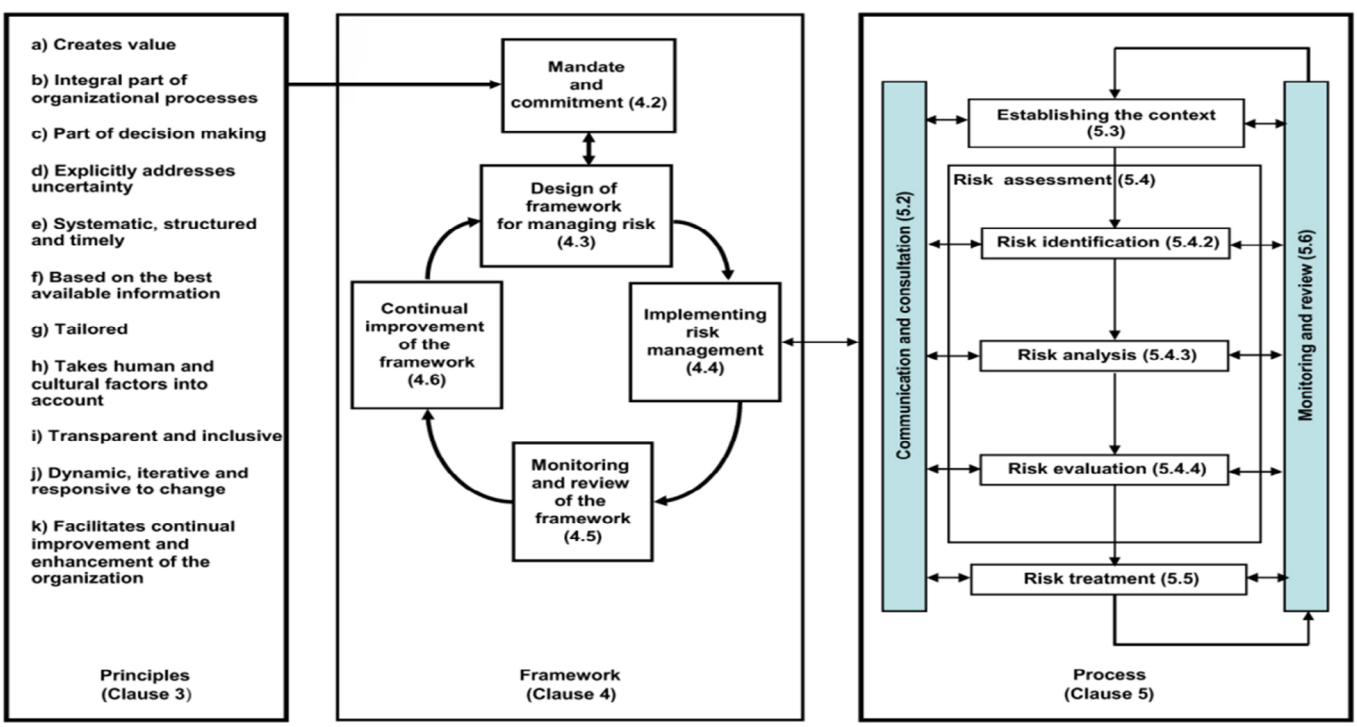
3.12.3 Chemical risk management in modern times: the theory is well-established but implementation lags behind

There is currently considerable agreement on the fundamental principles of process safety management which, if understood and properly applied, would prevent a large majority of chemical accidents that still occur today. These essential principles are then applied in the context of an ISO 31000:2009 risk management process (see Figure 3.56). From an operational perspective, successful risk management comes from applying layers of protection throughout the process life cycle (design to decommissioning), starting with the reduction of the hazard itself, and working outwards to accident prevention, mitigation and response. Above all, it is the organisations and individuals that manage all of these elements. For this reason, hazardous sites are expected to have a safety management system in place, a derivative of the well-known 'management system' concept, to manage the interface of humans with hazardous processes in order to minimise process hazard risks.

The hazardous industries understand in principle how to manage chemical accident risks. Why, then, do these industries continue to repeat failures of the past and have accidents and, sometimes, disasters? A study of accidents of the past few decades and the work of numerous experts on man-made disasters, including chemical accidents, as well as nuclear, space and aviation disasters, suggest that the causes are systemic. Sweeping changes in business philosophy and the explosion of opportunity created by new technology, such as the increasing reliance on the computerisation of business processes, have brought ben-

FIGURE 3.56

Relationship between the risk management principles, framework and processes (ISO 31000:2009 Risk management – Principles and guidelines)
Source: International Organization for Standardization (n.d.)



efits as well as a share of risks. These risks are particularly notable for man-made risks where small changes to complex systems can unwittingly remove barriers to initiation or propagation of a potential hazard event.

It is a fact that technological disasters, past and present, not just chemical disasters, have relevant and timeless lessons for risk managers in all industries, many of which have been recently documented by Gil and Atherton (2008, 2010)). A number of high-profile technological disasters occurring since 2000 have challenged some experienced risk management experts to identify the patterns underlying the repeated failures behind the latest round of technological accidents, building on the work of Perrow (1984) and Rasmussen (1975), among others, on managing risk in complex systems, by means of new approaches. Hollnagel et al. (2008) have introduced the concept of 'resilience engineering' for technologically complex industries. They look at risk management from the organisational perspective of the large multinational and government operators that are the owners and operators of these technologies. In resilient systems, individuals and organisations habitually adjust their performance to match the variability of risk over time, 'prior to or following changes and disturbances so that it can continue its functioning after a disruption or a major mishap, and in the presence of continuous stresses.' Klinke and Renn (2006) suggest that 'risks must be considered as heterogeneous phenomena that preclude standardised evaluation and handling' in their paper describing governments' potential role in managing systemic risks. Le Coze (2013) proposes that new analytical models for safety assessment take into account the dynamic and systemic aspects of safety.

Chemical accidents nowadays are often derived from the failure of industry, government and society to understand the profound effect that their choices have on risk.

Kletz (1993) commented on the pattern of corporate memory loss in United Kingdom companies as far back as 1993. More recently, Baybutt's 2016 review of accidents investigated by the U.S. Chemical Safety Board since 1998 concluded 'Remarkably, all of the reviewed incidents involved some type of deficiency or omission in adhering to established process safety practices. In many cases there were multiple deficiencies and omissions.' Wood et al. (2016) also found that where probable causes of accidents have been ascertained, they are most often associated with predictable circumstances in which control measures were insufficient as a result of poor risk management or, in some cases, a lack of adequate awareness of the risks. This finding is further substantiated in various 'lessons learned' publications, such as the MAHB Lessons Learned Bulletin, where analyses of recent and older accidents are side-by-side, identifying often remarkably similar findings about what went wrong (European Commission Joint Research Centre, 2012-2016).

The research of Taylor et al. (2016) collated and synthesised circumstances and causality associated with 12 significant technological accidents, of which five were chemical accidents, and identified numerous organisational failures associated with leadership, oversight and scrutiny, and communication that were common precursors to the events studied. Their study identified a number of factors, including the general decline of safety departments, oversimplification to upper management through aggregation of indicators and other inputs, poor understanding of operational 'reality', lack of processes and systems that ensure that process safety risks are properly assessed, and the influence of commercial interests, as among the key forces that shaped the events leading to the accidents. Arstad and Aven (2017) point out that 'it is dangerous to assume that system boundaries can be limited to the sharp end of the business … wide and open system boundaries recognise the importance of many more risk sources and safety.' They also remark on the tendency to oversimplify risks ('complexity is incompressible') associated with complex technologies. With petroleum-based industries as a primary candidate, Carnes (2011) outlines a High Reliability Governance model based on multiple engagements between government and industry actors, which continually reinforces common performance expectations and a high-level safety culture.

A large number of scientific studies of technological disasters focus on big, well-resourced organisations. However, it is a fact that many serious accidents around the world originate in small and medium-sized enterprises

(SMEs) that are operating fairly simple processes (e.g. warehouses, fuel distribution) (European Commission Joint Research Centre, 2012-2016; Gil and Atherton, 2010; Howard, 2013; State Administration of Work Safety (China), 2016; U.S. Chemical Safety Board, 2016b). While they are not all 'disasters', the United Nations Development Programme (UNDP)'s 2004 report on reducing disaster risks correctly cites that accidents with local impacts are an important part of understanding the scale and dimensions of particular threats. In addition, there is some evidence that government and society unwittingly, for sometimes for very good reasons, accept more risk in relation to SMEs. These companies often present significant challenges for regulators because they lack adequate expertise or even sufficient hazard awareness to manage their risks within acceptable limits. Typical cases of this type are the small fireworks manufacturers whose premises have been the sites of several accidents with multiple fatalities in the past 5 years within the EU (eMARS, 2012; Wood et al., 2016). Moreover, recent tragedies, such as the disasters of Tianjin, China (2015) (State Administration of Work Safety (China), 2016) and West, Texas (2013) (U.S. Chemical Safety Board, 2016b) indicate that, in these cases, even though the presence of a significant hazard was known, the government failed at many levels to ensure that adequate prevention, mitigation and preparedness measures were in place.

Twelve underlying causes are cited as challenges to controlling chemical accident disaster risk in current times.

The authors of this paper have identified 12 types of underlying causes of chemical accidents based on their own studies of accidents and research of other experts. They are based in part on causal typologies developed by the various experts in man-made risks already cited in this paper. They also reflect the authors' extensive experience in studying and investigating the causes of chemical accidents, bringing in the small business and governmental

BOX 3.3

Distant leadership and optimisation strategies: a recipe for organisational failure.

The accident at a multinational liquefied natural gas plant in South Gippsford, Australia, in 1998, known as the 'Longford accident', is attributed in part to a series of company misjudgements, including relocation of expertise to another site, poor intercompany communication and the insufficient prioritisation of safety over profits . Two people were killed and eight were injured. The state of Victoria was left without its primary gas supply, crippling industry, in particular commercial industry, with an estimated economic loss of at around AUD 1.3 billion (Hopkins, 2014). Similarly, the lack of adequate oversight of operations at a fuel storage terminal, coupled with poor intercompany communication exchange, was considered a leading cause of the devastating Buncefield explosion and fire at the Buncefield fuel terminal, Hemel Hempstead, United Kingdom, in 2005 (U.K Health and Safety Executive, Environment Agency and the Scottish Environmental Protection Agency, 2005). The primary causes were the failure of two-level instruments on the tank that overflowed. The alarm and overfill protection functions did not operate as a result. The analysis of the event indicates that it was the result of a sequence of management failures in addressing known risks and performance uncertainties over a period of months and even years prior to the incident (Howard, 2013).

dimensions that are sometimes not well covered in research.

Causes are not necessarily mutually exclusive, since the presence of one underlying cause can make a site susceptible to other dangerous mentalities and conditions. The 12 underlying causes are as follows:

1. **Lack of visibility.** A paucity of chemical accident data and inconsistent media attention has exacerbated the lack of interest in reducing chemical accident risks in recent decades. The limited public databases on chemical accidents leave society without any performance measures. With the exception of high-cost accidents reported by insurance companies, there are no published statistics on accident frequency. International media picks up only high-profile disasters, which form only a small fraction of the chemical accidents that happen every week. Moreover, as noted by Quarantelli (1997), there is also a misleading tendency to equate disastrous occasions only with casualties and property damage. Hence, there is far less visibility for chemical accidents that cause significant social disruption, such as evacuation, loss of drinking water, severe environmental damage, job loss and elevated and often uncertain exposure to health risks.

2. **Failure to manage risk across boundaries.** The organisations and individuals in charge of chemical accident risks usually define challenges in terms of their own expertise and jurisdictions. There are numerous incidents in the EU eMARS database indicating a failure to communicate information to those who need it, both internally to organisations and externally to other industrial sectors, professional disciplines and international boundaries (eMARS, 2012; European Commission Joint Research Centre, 2012-2016). Chemicals risk management in industry has traditionally been assigned to chemical and mechanical engineers who have little training in human and organisational factors. Government assigns monitoring and enforcement on the basis of who is affected, that is, on-site workers (labour authorities), off-site communities (civil protection authorities) or the environment (environmental authorities). The large multinational industries, such as oil and gas, and chemical manufacturing companies, exchange little information on chemicals risk management with other (and often less-resourced) industrial sectors, such as pyrotechnics production, pharmaceuticals and various non-chemical businesses. Similarly, government oversight and enforcement tends to follow jurisdictional boundaries in the geographic sense. This limitation can lead to

BOX 3.4

When industry and government both fail to learn lessons from past accidents.

Even major disasters are ignored and forgotten. A case in point is the massive explosion involving ammonium nitrate fertilisers that occurred in West, Texas, USA in 2013, which killed 15 people and destroyed 140 nearby homes. This incident was preceded by some well-known disastrous explosions involving ammonium nitrate fertilisers, in particular, Oppau, Germany, 1921 (>500 deaths); Texas City (Texas), USA, 1947 (581 deaths, > 3 000 injuries); and Toulouse, France, 2001 (29 deaths, > 2 500 injuries).

It appears that lessons from prior accidents about handling ammonium nitrate fertilisers had not been taken into account in either industry practices or fire protection laws (BP Refineries Independent Safety Review Panel, 2007). Furthermore, the potential off-site consequences of an ammonium nitrate explosion were ignored by the prevailing environmental regulation that had jurisdiction only over substances with toxic release potential. Emergency and land-use planning measures prior to the accident did not have any special provisions for a school, nursing home or residences in close proximity (U.S. Chemical Safety Board, 2016b).

a lack of regional coordination on chemical accident risk management and may present serious transboundary accident risks. The failure to see beyond one's own boundaries fosters a piecemeal approach to risk management and results in lost opportunities in sharing lessons learned and developing common strategies.

3. **Failure to learn lessons from past accidents and near misses.** There is substantial evidence that neither governments nor public authorities have learned sufficiently from past accidents. Taylor et al. (2015) note that that failure to learn was recurrent in organisations involved in some of the significant man-made disasters of the last 30 years in Europe and elsewhere. According to the study, barriers to learning were related to culture, the poor communication of findings and 'lost' corporate memory, a failure to investigate prior events, a narrow view of what was useful to learn and what constituted an opportunity to learn, and the silo effect, such that information on events does not cross internal organisational boundaries. An effective risk management programme incorporates the systematic study of past accidents occurring both on-site and elsewhere. Learning from one's own accidents (in one's organisation or jurisdiction) is important to diagnose specific weaknesses and trends. Learning from relevant accidents that occur on other sites and in other locations is essential to map all possible pathways that could lead to an accident. Even when problems are recognised, the failure to learn leads to inappropriate solutions. In industry there is a tendency to respond with increasing complexity, in the form of new, but not necessarily better, technology. Similarly, governments will respond with new or stricter, but not necessarily better, regulation.

4. **Social drivers, including economic trends.** Avoiding situations in which judgement is clouded by other considerations is a long-standing challenge of risk management, as evidenced by the accidents at BP Texas

BOX 3.5

Accidents that resulted from a combination of complexity and complacency

Macondo Oil Drilling Platform (Gulf of Mexico, 2010) The Macondo disaster of 20 April 2010, in the Gulf of Mexico, stemmed from the loss of control of an oil well, resulting in a blowout and the uncontrolled release of oil and gas (hydrocarbons) from the well. The accident resulted in the deaths of 11 workers and caused a massive, ongoing oil spill into the Gulf of Mexico (U.S. Chemical Safety Board, 2016a).

BP Texas City (USA, 2005). On 23 March 2005, a series of explosions occurred at the BP Texas City refinery during the restarting of a hydrocarbon isomerisation unit. Fifteen workers were killed and 180 others were injured (BP Refineries Independent Safety Review Panel, 2007).

Experts have noted that these two accidents were caused by severe organisational failures, which had remarkably similar causality, including (1) multiple system operator malfunctions during a critical period in operations, (2) required or accepted operations guidelines not being followed ('casual compliance'), (3) neglected maintenance, (4) instrumentation that either did not work properly or the data interpretation of which gave false positives, (5) inappropriate assessment and management of operations risks, (6) multiple operations conducted at critical times with unanticipated interactions, (7) inadequate communication between members of the operations groups, (8) a lack of awareness of risks, (9) diversion of attention at critical times, (10) a culture with incentives that provided increases in productivity without commensurate increases in protection, (11) inappropriate cost and corner cutting, (12) lack of appropriate selection and training of personnel, and (13) improper management of change (Carnes, 2011).

City (BP Refineries Independent Safety Review Panel, 2007) and the explosion and fire at the Macondo offshore drilling platform (U.S. Chemical Safety Board, 2016a). Both good and bad intentions can interfere with good risk decisions. For example, employees will tolerate bad conditions because they need jobs. Similarly, well-intentioned operators may delay maintenance and repairs on ageing sites to keep costs down and prevent the site from closing. Risk management efforts of some organisations and individuals can also by limited by systemic constraints, including a lack of political will and corruption, affecting both developed and developing countries. Economic and civil instability and a combination of long-standing cultural and structural deficiencies are a particular concern in developing countries. Economic pressure is a particular social driver that can put gains in chemical process safety at risk, particularly in the modern world when business circumstances change at a rapid pace. Instability in management and in business continuity has a knock-on effect on all aspects of risk management. In some situations, poor profit margins impose difficult decisions on various operations in terms of defining safety priorities when resources are stretched. However, there are also various trends in profitable companies, such as optimisation (operational efficiency) and the drive towards increasing shareholder value, that can undermine risk management when they are applied without due consideration of the impacts on risks.

5. **Increasing complexity.** Nowadays, change occurs more and more rapidly in all aspects of daily life. While individually the risks of technologies and associated hazards are generally known, the impacts of multiple and rapid changes in the way humans behave around them are difficult to assess and can to some extent constitute 'unknown unknowns'. As noted by Arstad and Aven (2017) for the Columbia Space Shuttle disaster, 'Always under pressure to accommodate tight launch schedules and budget cuts … certain problems became seen as maintenance issues rather than flight safety risks.' This situation is echoed in a number of the highly visible chemical accident disasters over the last few decades (e.g. BP Texas City (BP Refineries Independent Safety Review Panel, 2007), Buncefield (Howard, 2013), Macondo (U.S. Chemical Safety Board, 2016a)). Risks are not perceived as risk but rather as problems to work around. The prevailing trends are quickly replaced by new trends and existing technologies are quickly replaced by new technologies. Sites change ownership with considerable frequency (Kamakura, 2006), which is often accompanied by significant changes in management policies, work patterns, safety culture or other structures that guide norms of behaviour, and also contributes to an increasing decline in the corporate memory of accident risks (OECD, 2016). In reality, change occurs faster than the knowledge to understand how the change is affecting different aspects of our lives, including habits of living and working,

BOX 3.6

What can happen when governments are complacent.

The disastrous fire and explosion in the port of Tianjin, China, in 2015, is mainly attributed to lax safety procedures and a deliberate lack of government oversight. The owners of the storage and distribution company at the source of the accident somehow managed to persuade numerous authorities to look the other way with regard to permitting inspections and hazard control measures. The site began operations in 2014, handling and storing a variety of dangerous substances, many in volumes much higher than would be considered safe. According to the official investigation report, there was neither evidence that recognised safety standards were applied nor evidence that workers had been trained in handling hazardous goods. In addition to causing 165 deaths and injuries to nearly 800 people, 30 000 people in the surrounding community were evacuated (State Administration of Work Safety (China), 2016).

but also political, commercial and economic dimensions. As noted by Ruifeng et al. (2012), process controls and safeguarding equipment are more complex, thereby increasing newer risk that is often unforeseen. Both Mannan (2005) and Quarantelli (1997) also indicate that a correlation exists between the scale and complexity of process plants and major incidents. However, these and other modern trends are having significant consequences on safety and security, the long-term impacts of which are still not fully understood. Deeper understanding requires a multidisciplinary approach, despite the fact that the job market is exhibiting a tendency for increasing specialisation.

6. **Automation and information technology dependencies.** Twenty years ago, Quarantelli (1997) predicted that technological advances would reduce some hazards but make some old threats more dangerous, and cited computer technology as a kind of technology that represented a distinctly new danger. Indeed, the automation of activities traditionally performed by humans is a frequent adaptation of computer technology but it could in many circumstances create new risks in operations using dangerous chemicals. As pointed out by Lagadec and Topper (2012), society itself is still not clear about the full range of impacts of this innovation or other such 21st phenomena as the internet, the media explosion, social networking and smartphones. Moreover, as Taylor et al. (2016) suggest, an emphasis on interconnectivity and interdependence has become increasingly important, but when a failure occurs in one of the interconnected systems it can lead to major disruption. A further concern has emerged with the vulnerability of information technology systems to hacking or, even more simply, unforeseen potential for errors in the design and operation of automated systems that are increasingly interdependent across sites and accessed and operated by multiple users.

7. **Failure of risk management and risk assessment.** The EU eMARS (2012) and the U.S. Chemical Safety Board (2016a, b), for example, have produced many reports of recent past accidents for which the likelihood of the event occurring or the severity of its impacts could have been reduced with the application of actions within the hierarchy of risk management controls. Many of these reports also indicate a failure in the risk assessment process (e.g. that a risk assessment was not conducted, certain factors were discounted, lessons learned from previous events was ignored or that the risk associated with a change in operations was not considered). Indeed, many accidents also have been known to occur because of lack of follow-up after the monitoring and review of the functionality of the safety management system, such that the risk assessment was not updated after deficiencies in the risk assessment were discovered. Both organisations and individuals can fail to apply risk management principles, even when well established and part of training requirements. There is also often a lack of attention paid to inherent safety in which processes are designed without considering opportunities for risk reduction (chemical substitution, limiting volumes, exposure, etc.). This failure is sometimes attributed to various business and organisational trends cited in this paper, such as business climate and economic trends, organisational change and staff reductions, complexity and, sometimes, a loss of focus (complacency or 'organizational drift' (Taylor et al., 2015)); however, in other industries, particularly non-chemicals businesses and small companies, other factors, such as lack of awareness and education, are stronger influences.

8. **Corporate disconnect from risk management.** The globalisation of hazardous industries has increased both the physical and mental distance between headquarters and the sites they manage. Headquarters staff lose a tacit understanding of how sites experience chemical accident risks. For example, multinational sites can pose particular complexity when the culture and policy of the management is vastly different from that to which the site has been accustomed, especially if it is in a different country (European Commission Joint Research Centre, 2014). Corporate leaders also tend to oversimplify production safety risks (or risks are oversimplified for them) (Arstad and Aven, 2017; Taylor et al., 2015). It is assumed that new communication and automation technologies have universally positive trickledown benefits for all operations. For chemical accident hazards, the opposite is often the case. In particular, the trend towards short-term resource optimisation continues to have disturbing implications for chemical risk management. The tendency to outsource expertise and maintenance operations has already received considerable attention. There is also a preference in some companies to distribute limited expertise across many sites, so that access to critical safety expertise is

proportionately less available to sites. This phenomenon has been considered a significant factor in the Longford accident (Hopkins, 2014) as well as the catastrophic fire that occurred at the Buncefield storage site in 2005 (Howard, 2013).

9. **Insufficient risk communication and awareness.** Hazardous industries are introduced in locations with little attempt to communication and build awareness of the risks, to foster meaningful preparedness and planning, or to ensure that training and expertise are adequate for the responsibilities associated with the risk. This situation is particularly acute in developing countries where the desire for economic growth outweighs other decision factors. In many cases, risks are not so much accepted as ignored, encouraged by a historical lack of transparency in the political classes or society as a whole. When considered in context, the risk of fatal major accidents is also relatively small compared with the risks of poverty, disease and road traffic accidents and, therefore, may not receive the attention it deserves as a risk that is readily mitigated. The Enschede (the Netherlands) fireworks accident of 2000 (The Oosting Commission, 2001) and the accident in West, Texas (USA) (U.S. Chemical Safety Board, 2016b) are notable examples of how a lack of appropriate risk communication and awareness can contribute significantly to disasters.

10. **Resource and infrastructure deficiencies.** Many sites are compelled by a combination of circumstances and poor decisions to operate with less than adequate resources and infrastructure. In particular in developed countries, the physical infrastructures that underpin both public and private services are reaching the end of their normal lifespan (Quarantelli, 1997). A lack of resources generally leads to insufficient competence to manage risks (e.g. no chemical or mechanical engineer on site) or to improve degraded equipment or to apply safety management systems with rigor. Physical infrastructure can also be degraded by age or neglect, the latter of which was a key factor contributing to the catastrophic explosion and fire at the petroleum oil refinery at BP Texas City in 2005 (BP Refineries Independent Safety Review Panel, 2007). In many developing countries, it is common to start operations under less than ideal circumstances. The existing physical infrastructure may be degraded from years of neglect. There may be gaps in the education and risk awareness of local worker populations, as well as a limited availability of university-educated staff. Industries in developed countries also may suffer competency deficiencies due to declines in engineering students seeking career paths in traditional chemical process industries. Moreover, higher education in relevant engineering disciplines still excludes knowledge of chemical accident phenomena or basic principles of risk management.

11. **Deficiencies of the legal infrastructure.** In much of government and industry globally, management of chemical accident risks is focused on emergency preparedness, and strategies aimed at prevention and mitigation are not prioritised. Society as a whole exhibits a high risk tolerance owing to historically poor living and working conditions that consequently predisposes workers to accept and ignore workplace hazards. In many developing countries, there may be no legal framework to require and enforce minimum standards for process safety performance on chemical hazard sites. When a proper legal framework exists, regulators and operators lack the competence and resources to understand or enforce it. These circumstances have implications for developed countries in that companies may have sites in developing countries and their citizens may be customers of their products. However, even in developed countries, there is also a recognised pattern that governments do not often proactively engage in managing chemical accident risks until after a serious accident, or a number of serious accidents, occur. Notably, attention to chemical process safety in Australia gained widespread attention only after the Longford accident in 1998 (Hopkins, 2014), and in New Zealand following the mining accident in 2010 (Royal Commission on the Pike River Coal Mine Tragedy, 2012).

12. **Complacency in government and industry.** The longevity of chemical accident prevention and preparedness regimes in developed countries also leads many politicians and industry leaders to reduce their attention to chemical accident risks, threatening to undermine decades of risk-reduction progress. Sometimes called 'organizational drift' (Taylor et al., 2015), this phenomenon may occur in once-strong organisations and societies that allow their standards to erode over time without noticing their own decline. The perception that chemical accidents are no longer a threat eventually results in dramatic decreases in resources for enforce-

ment and risk management. Notably, there has been a dramatic lack of focus in modern times on process safety as an inherent operating requirement (not just because the legislation requires it). Government complacency can be manifested by lax application of permitting laws, reduced frequency of inspections and insufficient attention to land use and emergency planning. Complacency in industry is often evidenced by greater tolerance of deviations from accepted norms, such as process parameters, safety procedures and maintenance requirements. In developing countries, the problem is arguably worse. The vast majority of owners and operators of hazardous sites, even in large state-owned or multinational subsidiaries, are used to minimal management of chemical hazards on their sites.

3.12.4 Implications for future scientific study

The main topics that emerge as areas for further study and experimentation are listed and described below. Many are already the subject of projects in research institutes and collaborations within the international community.

Experts in all areas should work together on initiatives that promote good risk governance, creating a new paradigm for all society.

However, it is widely recognised that these problems, having proved so resistant to solutions, will require considerable reflection and patience to identify approaches that produce tangible improvements.

Experts in all areas should work together on initiatives that promote good risk governance, creating a new paradigm for all society through the following:

- Motivating corporate and government leadership. New models for the governance of hazardous industries should be explored and tested. These models should apply to corporate leadership and government alike, applying management philosophies supported by rigorous enforcement proportionate to the level and complexity of the risk. New strategies should be based on a mutual expectation between government and industry of overall corporate responsibility for maintaining risk resilience that goes far beyond the current compliance-based paradigm. Enforcement will need new (more evolved) strategies (e.g. nudge, push, force) to drive industrial practice. Concepts such as recovering the profits of illegal/unsafe activity to remove the economic advantage may also be a step forwards. Fears that the process industries could potentially have parallels to the banking crises (2008 onwards) in terms of poorly understood risks have triggered the development of the Organisation for Economic Co-operation and Development (OECD) publication Corporate Governance for Process Safety — Guidance for Senior Leaders in High Hazard Industries, an important new tool for industry and government addressing this topic (OECD, 2012).

- Systematic accident reporting, data collection and exchange. There needs to be a concentrated effort to build national and international chemical accident registers and to promote accident exchange between industries and countries. The availability of reliable chemical accident statistics will allow academics, politicians and the media to understand the magnitude and nature of chemical accident risks and identify appropriate risk-reduction measures.

- Promoting positive safety culture both industry-wide and in society. The chemical processing industries should focus serious attention on developing a positive safety culture industry-wide, such that it is resilient in the face of change, particularly in the economy and site management. Psychologists should work with industry and governments to foster risk awareness and sensitivity among citizens. An informed safety-sensitive society can help to support a broader mandate to insist that companies exercise greater corporate responsibility for reducing the risks associated with their operations.

- Heightened commitment to the Plan–Do–Act cycle in chemical process safety management. After an accident has occurred, a common finding is that a potential risk factor had been identified and ignored. In keeping with improved safety culture, guidance and training on safety management policy and performance indicators need

to put more emphasis on incorporating lessons learned from past events and audit findings on deficiencies in risk management into process hazard assessments and the safety management system as quickly as possible.

- Risk management in SMEs in the chemical business. There are subcategories of SMEs in the chemical business, each of which has elevated risk for different reasons. The most challenging intellectually are the SMEs that know their risks and take care to manage them but still have accidents. More research is needed on why accidents occur in SMEs, including geographic and economic differences that may influence these risks, and on strategies to reduce them.

- Risk management in non-chemical businesses. Similarly to SMEs, studies to develop strategies and guidance to support risk management in many of these industries are still needed. There are a number of examples of this work, such as the U.S. Environmental Protection Agency's Supplemental Risk Management Program Guidance for Ammonia Refrigeration Facilities. More analysis and dissemination of lessons learned from accidents in such locations is also needed.

- Business-sector risk-reduction initiatives on a global scale. Oil and gas, extractive industries, industrial parks and large-scale chemical production should be the focus of a global collaborative effort between industry, government and aid organisations to reduce chemical accidents in these industries.

- Risk assessment models that address new technologies and complexity. Some researchers (e.g. Taylor et al., 2015; Travers, 2016) are already proposing models by which to assess risks associated with complexity. These models need to be tested and developed further. In addition, research is required to characterise and quantify various emerging risks, including those associated with the increasing use of automation and the outsourcing of critical safety functions, ownership change, how culture and competence profiles in different countries can affect chemical accident risk and other emerging concerns mentioned in this paper.

More work is needed on how business practices must change to mitigate the most common violations of safety management principles.

More work is needed on how business practices must change to mitigate the most common violations of safety management principles, in particular in relation to:

- Mechanical integrity. All too often, maintenance and repairs of equipment and infrastructure are considered dispensable when inconvenient for profit or production goals. The underlying causes should be studied and new approaches adopted that provide stronger motivation, including risk assessment requirements and government-operator interfaces (e.g. permits, inspections), for reinforcing mechanical integrity as an operating requirement.

- Management of change. This safety principle is particularly challenging because time pressures and a human preference for expediency undermine its consistent implementation. Finding methods that help companies and individuals to recognise change when a change can elevate risk is an important part of resilience engineering and a significant aspect of the 'resonance' factor described by Leonhardt et al. (2009). Resonance is a quality that explains how disproportionately large consequences can arise from seemingly small variations in performance and conditions.

- Learning lessons from accidents and failures. Industries and sites need to learn from, and remember, past accidents. Corporate memory loss, across-industry, is not an appropriate excuse. A greater investment is needed in projects to develop strategies to learn and remember, with a particular emphasis on collaborations between industry, government and academia. According to Patterson (2009), both industry and government struggle with barriers that tend to undermine systematic extraction and communication and lessons learned and there needs to be a renewed effort to overcome these barriers. As noted by Hailwood (2016), companies operating major hazard facilities should establish systems that not only ensure reporting and learning from their own accidents and near misses, but also make use of databases and re-

ports from the accidents of others. Each country should also make resources available to investigate accident causes and lessons learned, as well as to collect and document this knowledge and make it accessible to third parties.

Renewed effort is needed to ensure that there is adequate competence in our industries and our governments for addressing chemical accident risks now and over the long term.

Renewed effort is needed to ensure that there is adequate competence in our industries and our governments for addressing chemical accident risks now and over the long term, enabled by:

- Greater access to risk management knowledge and tools. Risk management is always specific to a site. Few sites have exactly the same risks, even if they produce the same products, since the physical characteristics of the location, structures and equipment are important elements of the risk. Considerable future mechanisms are needed to ensure good management practice for all kinds of operations and to make equipment available in an easy to read format, taking account of the many different languages in which they might be needed.

- Access to risk assessment competence. Both operators of hazardous sites and regulators need to know the type and severity of accidents that could occur and have a realistic understanding of the control measures needed to ensure that the risk of such accidents is minimised. Cheap and easy access to interactive consequence assessment, risk mapping and quantitative assessment tools is urgently needed in all areas of the world.

- Strategies to combat a labour market deficient in appropriate expertise. Industry and academia need to continue to push for standardised process safety curriculums associated with chemical engineering and chemistry in particular, as well as with environmental management and other related disciplines to some extent. Multinational companies operating in developing countries need to be aware that competence and experience in risk management may be far less available than in Europe or the United States, and process operations need to be adjusted accordingly (Zhao et al., 2014). In all parts of the world, industry and the professional engineering community should do far more to support occupational and process safety education and training to produce more qualified professionals capable of identifying and managing risks in design and daily operations.

European Union industry and government must share responsibility for reducing chemical accident risks in developing countries.

European Union industry and government must share responsibility for reducing chemical accident risks in developing countries, and special emphasis should be placed on the following:

- Building basic awareness of chemical risks and how to manage them to developing countries. Basic training in chemical risks and safe chemicals management is badly needed. The remarkable efforts of numerous international organisations such as UNEP, UNECE (United Nations Economic Commission for Europe), UNEP-OCHA and the WHO, among others, are underfunded and far too fragmented to have significant impacts, despite smart management and promising results from recent initiatives. Meaningful progress is possible only with substantial commitments involving UNDP, United Nations Institute for Training and Research, the World Bank and the European Commission as well as Regional Economic Commissions in the context of a coordinated and comprehensive long-term strategy.

- Resilience and risk awareness building. There has been considerable success with stakeholder involvement approaches such as UNEP APELL to manage risks at a local level within a systemic national and international regional strategy. A number of tools, including those produced by the OECD (2003) and UNEP (2010), already exist to guide developing countries on how to build a comprehensive and effective chemical accident risk prevention and preparedness programme. The clear next step is to identify and deploy mechanisms by which to provide significant and

sustained support to countries that are ready to take steps towards establishing such programmes.

- Fostering regional and international networks and collaborations on chemical accident risk management. A critical mass of policy and technical initiatives at both regional and international level, creating a constant pressure and giving developing countries easy access to expertise and technical support, is a way to establish a new norm. A number of international organisations (e.g. UNECE, 2014)) have reported increasing success with such approaches but they are barely implemented for chemical accident prevention programmes in regions such as Asia and Africa.

- Improving performance measures for interventions. Fund administrators generally lack objective measures by which to evaluate suitable candidates for chemical accident prevention programmes that may target the specific needs of and provide continued support to achieve meaningful results. Further refinement and testing of capacity-building performance indicators, and methods for qualitative assessment (e.g. level of political will, key drivers of change) such as those currently in development by the JRC (Baranzini et al., in progress), can lead to better targeting of such initiatives. These could also be useful for developed countries.

3.12.5 Conclusions and key messages

Recent accident trends provide evidence that the world is nowhere near reducing the risk of industrial accidents to acceptable levels. While developed countries have shown marked improvements, particularly in reducing the average number of fatalities associated with chemical accidents, the overall rate of major accidents with other serious impacts remains high. Throughout the world, accidents continue to stem from violations of well-known safety management principles. Such failures can only sometimes be explained by complexity and a misfortunate combinations of events; very often they may be due, entirely or in part, to incompetence, a lack of awareness or outright negligence. Many experts are exasperated that management practices and attitudes are so vulnerable to other influences and resist improvement.

In conclusion, accepted norms of industry, government and society are undermining good risk management. This finding has a number of important implications for the direction of future research, policy development and the role of government and industry in reducing accident risks.

Partnership

The findings confirm overwhelmingly that the traditional approach in which stakeholders stick to their traditional rules is not going to fix the problems in question. It is no longer possible that industry works alone to define and implement good risk management practice. Policymakers can no longer simply set performance standards and then step aside. Observations from academics, particularly in the social sciences, need to find their way into both industry and government approaches to chemical accident risk.

Knowledge

The control of chemical accident risk is very often undermined by the cultural norms and expectations associated with how government and business are expected to act, and a lack of knowledge and awareness about chemical accident risks in society in general. Combatting these forces requires new thinking about how our businesses and governments are working with these risks. As such, the essence of the change is that all society must recognise part ownership of chemical accident risk, and ownership implies both a certain responsibility for, and power to prevent, such risk. This finding in turn requires that the new approach to controlling chemical accident risks is to change culture with education and awareness.

Innovation

The recommendations in this paper suggest a paradigm change in the way the EU and the developed world in general approach chemical accident risk. Solutions must encompass a broader vision of risk ownership and boundaries of influence, recognising that the role of industry does not end beyond the fence line, that offsite forces can influence onsite risks and that society's responsibility may need to extend beyond traditional geographic boundaries. If the system is the problem, the solutions lie in changing the system.

3.13 Technological risk: nuclear accidents

***Emmanuel Raimond**, Gryffroy Dries, Andrej Prošek*

3.13.1 Introduction

Nuclear accidents, if their consequences are not mitigated, have the potential to initiate a disaster both in the vicinity of and even far away from the damaged nuclear facility. Safety principles, safety objectives and safety rules are internationally promoted and harmonised to reduce such risks as far as possible, but there is always a residual risk, as demonstrated by the recent Fukushima Dai-ichi accident.
This subchapter presents some of the fundamental principles applied in nuclear safety. These fundamentals are introduced with the idea that they can be transposed to other technological or natural risks. It then summarises some important lessons from the three accidents that influenced the nuclear industry significantly: Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011).

The subchapter then explains risk assessment methodologies and describes the current efforts for risk reduction, from plant design to emergency plans.

Nuclear accidents have the potential to initiate a disaster both in the vicinity of and even far away from the damaged nuclear facility.

In conclusion, this subchapter proposes some perspectives on research that can support risk assessment or help in accident management in this area. Understanding the interactions between nuclear facilities and their environment appears to be a crucial and transversal issue.

3.13.2 Nuclear safety framework

In European Member States, Council Directive 2014/87/Euratom of 8 July 2014 (EU, 2014) provides a general framework to be applied in relation to nuclear safety. This framework is consistent with the Safety Fundamentals established by the International Atomic Energy Agency (IAEA) (IAEA, 2006), and the main recommendations provided by the Western European Nuclear Regulators Association (directive for reactors in operation (WENRA, 2014) and new reactors (RHWG, 2013)).

Some important issues are summarised below.

The IAEA (2006) has defined one fundamental safety objective, namely to protect people and the environment from harmful effects of ionising radiation, and 10 fundamental safety principles:

1. The primary responsibility for safety must rest with the person or organisation responsible for the facilities and activities that give rise to radiation risks.

2. An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.

3. Effective leadership and management for safety must be established and sustained in organisations concerned with, and facilities and activities that give rise to, radiation risks.

4. Facilities and activities that give rise to radiation risks must yield an overall benefit.

5. Protection must be optimised to provide the highest level of safety that can reasonably be achieved.

6. Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.

7. People and the environment, present and future, must be protected against radiation risks.

8. All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.

9. Arrangements must be made for emergency preparedness for and response to nuclear or radiation incidents.

10. Actions to reduce existing or unregulated radiation risks must be justified and optimised.

Those safety fundamentals are then expressed in more technical requirements or concepts in each country or at European level (EU, 2014) or in the IAEA Safety Standards.

Some important concepts are summarised below. They can obviously be transposed to other risks induced by human activities.

Safety principles, safety objectives and safety rules are internationally promoted and harmonised to reduce nuclear risks as far as possible.

The safety culture shall be encouraged by the management, at all levels in the licensee organisations: this shall include ensuring that their actions discourage complacency and encourage an open reporting culture as well as a questioning and learning attitude with a readiness to challenge acts or conditions adverse to safety (see WENRA, 2014, for example).

The defence-in-depth approach (INSAG, 1996; IAEA, 2016) is considered a key concept by which to reach an appropriate level of protection from nuclear risk. For example, Council directive 2014/87/Euratom (EU, 2014) includes the following statements:

[…] safety activities are subject to, as far as reasonably practicable, independent layers of provisions, so that in the event that a failure were to occur, it would be detected, compensated or corrected by appropriate measures. The effectiveness of each of the different layers is an essential element of defence-in-depth to prevent accidents and mitigate the consequences should they occur. Defence-in-depth is generally structured in five levels. Should one level fail, the subsequent level comes into play. The objective of the first level of protection is the prevention of abnormal operation and system failures. If the first level fails, abnormal operation is controlled or failures are detected by the second level of protection. Should the second level fail, the third level ensures that safety functions are further performed by activating specific safety systems and other safety features. Should the third level fail, the fourth level limits accident progression through accident management, so as to prevent or mitigate severe accident conditions with external releases of radioactive materials. The last objective (the fifth level of protection) is the mitigation of the radiological consequences of significant external releases through the off-site emergency response.

The design of nuclear power plants (NPPs) is based on a deterministic approach: initiating events (deviations from normal operation, incidents, accidents, hazards) are postulated and used to design all systems, structures and components (SSCs) with design rules that should ensure significant safety margins. Such an approach must be completed by a probabilistic approach that allows considering more exhaustively the combinations of events (initiating events, system and human failures) that could lead to an accident. This is explained below.

The European regulators consider that a continuous improvement of the safety of NPPs is a good practice that should be promoted: this means

that NPPs are submitted to periodic safety reviews, possibly associated to safety objectives enhancement. Such periodic safety reviews shall concern all safety issues, including plant ageing, the modifications of the NPP environment (e.g. climatic changes) and any upgrading or modernisation of the plant. The result of such a process should be such that NPPs become progressively safer.

There are a number of organisations at the international level that share experience and good practices, including:

- the IAEA
- the OECD Nuclear Energy Agency (NEA)
- the European Nuclear Safety Regulators Group (ENSREG)
- the Western European Nuclear Regulators Association (WENRA)
- the European Nuclear Installations Safety Standards Initiative (ENISS)
- the World Association of Nuclear Operators (WANO)
- the European Technical Safety Organisation Network (ETSON)
- the Association of the Heads of the European Radiological protection Competent Authorities (HERCA).

The European Commission also promotes a high level of nuclear safety through its tasks in the preparation of Euratom directives. The European Commission JRC coordinates or participates in several nuclear safety scientific research and technical support projects. The Euratom Framework Programs (now Horizon 2020) also provide financial support to European nuclear research and training projects, including risk assessments and nuclear safety projects. For example, the ASAMPSA_E (Advanced Safety Assessment methodologies: extended PSA) project, on risk assessment practices, which is mentioned in this subchapter, and the European Severe Accident Research Network of Excellence (SARNET) have been supported by European Commission funding. Some projects deal with emergency management (EURANOS, NERIS-TP). Through the EU Instrument for Nuclear Safety Cooperation, European and international safety standards are also promoted in third countries.

3.13.3 Lessons from past events

Lessons learned from Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents influenced the nuclear industry significantly. They led European Union to set out a common European maximum permitted levels of contamination in foodstuffs following a nuclear accident and develop an early warning system ECURIE, while many EU Member States have installed the networks of radiation measurement stations that have been integrated in an EU-wide monitoring system EURDEP.

3.13.3.1 Three Mile Island, 1979

The Three Mile Island accident occurred on 28 March 1979 in Pennsylvania, USA. Although some risk studies had emerged before 1979 (US NRC, 2016), this accident demonstrated the importance of having an awareness of the potential for core melt accidents among NPP designers and operators. The accident was caused by an incident on the reactor steam generator feedwater system, which led to the automatic reactor tripping. Considering all existing safety systems, this event should not have been the cause of an accident, but some maintenance errors (e.g. wrong valve positions), additional equipment failure (one primary circuit safety valve did not respond to a closure signal from the control room), and a misunderstanding of the reactor status by the operators in the control room led to the melting of the reactor core. This led to significant radioactivity release in the reactor containment vessel. The accident progression was stopped when the operators restarted the injection of water into the reactor vessel.

The offsite radiological consequences were very limited thanks to the design features of the reactor containment vessel. Nevertheless, the accident caused extreme anxiety in the population, despite the fact that the recommendation of evacuation by the nuclear authorities was later cancelled by the governor of Pennsylvania.

Many lessons have been learned from this accident (IRSN, 2013) relating to, for example, the following:

- NPP operator procedures (a combination of symptom-based and event-based procedures is now preferred);
- NPP operator training (accident computer simulation training, accident drills, etc.);
- NPP control room design (reliability of information displayed, alarm processing, etc.);
- additional emergency operating procedures are needed for situations that are not anticipated in the

initial design (loss of the main electrical supply, loss of ultimate heat sink, filtered containment venting procedure, etc.);
- the reactor containment vessel is of prime importance and shall be reinforced where possible;
- precursors of accidents (incidents with no serious consequences) shall be analysed systematically to identify possible weaknesses; this may lead to modifications in NPP design or operation;
- emergency preparedness is of prime importance, with local and national emergency response teams able to support control room operators and to coordinate protective actions for the population;
- research to understand accident progression in the case of a severe accident is needed, and appropriate mitigation strategies shall be developed;
- probabilistic safety assessments (PSAs, see below) shall be developed to identify accidents associated with multiple failures or common cause failures, for which safety improvements may be needed.

3.13.3.2 Chernobyl, 1986

On 26 April 1986 at 01:24, the RBMK (Reaktor Bolshoy Moshchnosti Kanalnyy, i.e. high power channel-type reactor that is a class of graphite-moderated nuclear power reactor designed and built by the Soviet Union) type reactor 4 at the Chernobyl NPP, which had been in service since 1983, exploded in an accident during a technical test. The initial design of the RBMK reactors had some significant weaknesses from a safety standpoint. In particular, they were highly unstable at certain power ranges, the emergency shutdown system had too long a response time and there was no containment around the reactor. In addition, the lack of sufficient preparation for the conditions required for the planned test, and the lack of time in which to complete it, meant that operators did not follow all the operating rules. They also violated these rules by suppressing some important safety systems.

The explosion sent radioactive materials contained in the nuclear reactor core into the atmosphere, to altitudes of more than 1 200 metres. The radioactive plume then propagated in the European atmosphere, then worldwide, and caused the contamination of territories at different level. The areas of Belarus, Ukraine and Russia, which received depositions of caesium-137 exceeding 37 000 becquerels per square metre after the accident, cover a surface area of approximately 150 000 km2 with more than 5 million inhabitants. The accident had huge impacts on the environment (contamination of ground, rivers, forest, agriculture products, etc.), the ecosystem (transfer of contamination through the food chain or agricultural cycles), human health (especially for the 'liquidators' who worked to limit the consequences of the accident and for inhabitants of contaminated areas) and the economy and society in general. Many research programmes have been devoted to the study of the impacts of this accident.

A number of lessons have been learned from this accident (IRSN, 2011), including:
- a new perception and understanding of the consequences of such an accident;
- the importance of emergency preparedness to face such events (national emergency response organisations have been reinforced in most countries);
- the importance of transparency and providing information to the public: an EWS, ECURIE (European Community Urgent Radiological Information Exchange), has been elaborated that allows each country to immediately inform all EU Member States in the event of an accident in one of its nuclear facilities; a dedicated European Directive (EU, 1989) defines common requirements on informing the general public in the event of a radiological emergency and some countries have significantly reinforced the legal basis for such transparency (e.g. France; see French Nuclear Safety Authority, 2006); an International Nuclear Event Scale has been defined to ensure clear understanding of the severity of various events;
- the need for common European maximum permitted levels of contamination in foodstuffs following a nuclear accident, which have been set out in a related Council Regulation issued in 1987 (Euratom, 1987);
- for the overall radiological surveillance of the environment, EU Member States have installed radiation measurement stations; these national networks have been integrated in an EU-wide monitoring system EURDEP (European Radiological Data Exchange Platform; a standard data-format and network for exchanging radiological monitoring) which is managed by the European Commission;
- in terms of plant design and operation, the accident has promoted the

safety culture (under an interrogative and prudent approach, the test at the origin of the accident would not have been carried out) and the importance of the appropriate application of the defence-in-depth concept (despite human error, other lines of defence should have prevented such a disaster).

For new reactors, European regulators consider that such accidents with large radioactive release shall be 'practically eliminated' and they require an appropriate demonstration of the various safety features (RHWG, 2013). This requirement has a considerable impact on reactor design features.

3.13.3.3 Fukushima Dai-ichi, 2011

The Fukushima Dai-ichi accident was initiated by the Great East Japan earthquake that occurred on 11 March 2011 with a magnitude of 9. It caused a tsunami that struck the Japanese coasts, with waves exceeding 10 metres. The devastation in Japan was considerable: more than 15 000 people were killed, 6 000 were injured and 2 500 reported missing, and the destruction of buildings and infrastructure was considerable.

Lessons learned from Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents influenced the nuclear industry significantly.

The earthquake did not threaten the Fukushima Dai-ichi NPP's safety functions, but the resulting tsunami submerged the NPP's platform and led to the loss of the ultimate heat sink and most internal electrical supplies. Four out of six reactors stayed in long-term station black-out conditions. The site staff, despite their best efforts and considerable courage, could not prevent core melt at units 1, 2, and 3 and the resulting hydrogen explosions and large radioactive release in the environment. This caused a nuclear catastrophe in addition to the earthquake and tsunami impacts. Although the winds were mostly directed towards the sea during the accident, the ground contamination by the radioactive plume led to the evacuation of 80 000 inhabitants (a number that rose after a 'voluntary' evacuation starting on 25 March) and had huge impacts for agriculture, ecosystems, the economy and society in general in the region of Fukushima. The contamination of the ocean by liquid releases also had impacts on the fishing industry. The IAEA report (2015) provides a description of the accident, its consequences and all remediation efforts.

The accident led European countries and many others to develop a stress test programme to assess the capacity of NPPs to withstand extreme conditions (ENSREG, 2012). The robustness of NPPs has been assessed in terms of three major topics:

- protection against extreme external hazards (earthquake, flooding, etc.);
- NPP controls in the event of a loss of ultimate heat sink or electrical supply;
- severe accident management protocols.

Most NPP operators have decided to implement additional provisions on their utilities to further increase their robustness and the protection of population. The European regulators and the IAEA have also promoted the concept of 'design extension conditions' (IAEA, 2016; WENRA, 2014). The idea is to extend the basic design of NPPs to account for more adverse conditions for which a reactor can still be maintained in a safe state, or for which a severe accident (with core damage or spent fuel damage) can be controlled to recover a stable state without any significant radioactive release into the environment.

After the Fukushima Dai-ichi accident, most countries decided that NPP reinforcements must be able to face extreme conditions. Such reinforcements should enable the following:

- site protection against hazards (extreme flooding, winds, etc.);
- implementation of additional protected (bunkered) safety systems or the reinforcement of some existing structures, systems and components;
- implementation of additional fixed or mobile equipment to allow plant stabilisation in extreme situations;
- implementation of new infrastructure and equipment for emergency response management (reinforced emergency building, reinforced mobile equipment storage, additional communication and transport means, improved protection against radioactivity);
- more staff responsible for emergency actions;
- improvement of severe accident management strategies and, for some NPPs, the implementation of new equipment.

In relation to emergency preparedness and response, existing and reinforced requirements have been integrated into the revision of the European Basic Safety Standards directive (EU, 2013); the directive gives an increased focus on the need for international cooperation. The emergency management plans have been improved or are in revision in many countries (see HERCA-WENRA scheme for severe accidents, change in pre-planning radii for evacuation, sheltering and iodine distribution). Research in this area was promoted via the PREPARE and the recently started CONCERT project.

This has led to post-Fukushima action plans on a national level as well as to enhancements of the safety standards at international (IAEA, WENRA, etc.) or national levels.

Although NPP modifications have been decided, the Fukushima Dai-ichi accident has led to an increased interest in the study of natural and man-made hazards that could threaten a nuclear site and in the development of an on-site and off-site emergency response organisation that is capable of facing any complex situation.

3.13.3.4 High-amplitude external hazards at nuclear power plant sites

Nuclear power plants should be designed to withstand any high-amplitude external hazards that could threaten safety functions. Nevertheless, a number of high-amplitude events have caused problems at some nuclear sites. This is an important challenge for the safe operation of NPPs, and many countries, such as France, include a re-assessment of external hazards at each 10-year periodic safety review. If the safety margins appear to be reduced in light of the most recent knowledge (e.g. on earthquake, flooding risks or more general climatic changes), then NPP reinforcements can be decided. To illustrate this topic, a survey has been carried out by the ASAMPSA_E project (ASAMPSA_E, 2013) on more than 80 high-amplitude external hazards that have been experienced by NPPs or other facilities and high-amplitude external hazards described in the IAEA Incident Reporting System (IRS) database. Table 3.7 provides some external hazards that could be experienced by nuclear facilities identified by ASAMPSA_E.

Meteorological events are the most frequent, followed by biological infestation events. 'Low air temperature' seems to be the most recurrent hazard, followed closely by 'Lightning' hazards. Infestation with marine organisms has been observed more often than infestation with vegetable materials (such infestation may threat the ultimate heat sink of NPPs).
The Fukushima Dai-ichi accident showed the importance of the combinations of hazards. This fact was also identified in France during an event at Le Blayais NPP in 1999 (a combination of a storm, high tide and waves led to the partial submersion of the NPP platform). This event led to the significant reinforcement of certain French NPPs against flooding, but perhaps not to an international awareness of the importance of combinations of hazards in risk assessments.

All the above show the importance of enhanced investigations of all credible external hazards, including all their possible correlations and combinations. This has led to the analysis of the impact of 'rare events', which is a challenging activity for the engineering sector.

3.13.4 Safety assessment methodologies

The design of NPPs follows a set of rules and practices that should ensure a high level of safety. Standards have been developed, then improved, in a number of areas, from high-level considerations (IAEA, 2016; WENRA, 2014; RHWG, 2013) to more technical ones (e.g. rules for mechanical design).

An important step in demonstrating the safety of a NPP design is to identify a set of accident conditions that are applied to design all safety-related SSCs of the NPP. These accident conditions result from initiating events (equipment failure, human errors, internal or external hazards) leading to NPP transients, which are then analysed using specific conservative assumptions to ensure safety margins. The examination of this set of accident conditions using conservative assumptions is the so-called deterministic safety assessment. The methods that are applied must be sufficiently simple for the feasibility of the design and its safety demonstration, and sufficiently robust to ensure that the NPP and its organisation can be resilient to any event during plant operation.

To improve the safety demonstration, and as a complementary approach to the deterministic approach, probabilistic safety assessments (PSAs) are developed. A definition of the three levels of PSA can be found in IAEA Safety Standards SSG-3 (IAEA, 2010a) and SSG-4 (IAEA, 2010b):

'PSA provides a methodological approach to identifying accident sequences that can follow from a broad range of initiating events and it includes a systematic and realistic determination of accident frequencies and consequences. In international practice, three levels of PSA are generally recognised:

1. *In Level 1 PSA, the design and operation of the plant are analysed in order to identify the sequences of events that can lead to core damage and the core damage frequency is estimated. Level 1 PSA provides insights into the strengths and weaknesses of the safety related systems and procedures in place or envisaged as preventing core damage.*
2. *In Level 2 PSA, the chronological progression of core damage sequences identified in Level 1 PSA are evaluated, including a quantitative assessment of phenomena arising from severe damage to reactor fuel. Level 2 PSA identifies*

TABLE 3.7

External hazards that could be experienced by nuclear facilities

Earthquakes Tsunamis Ground subsidence	Flooding High tides Storm surges Wind waves High river levels/flow Spring runoff (from mountains)	High winds Hurricanes Tornados Projectiles driven by high winds Salt storms	Blackout Electrical disturbance transmitted by the external power grid Malware computer programs or computer viruses Electromagnetic interference Disturbance by high-frequency radio signals Oil spills Transport accidents Aircraft crashes External fire due to human activity External explosion Corrosive liquids or gases Toxic liquids or gases Radioactive releases Pandemics/severe epidemics
Biofouling Jellyfish infestation Small fish infestation Mollusc infestation Shell infestation Vegetable material in the heat sink Reeds intrusion Algae Rat infestation	Low water temperature Frazil Ice in cooling water Frost	Lightning Solar flares, solar storms, geomagnetic storms	
Sand deposits Silting Small rocks Sediments	Low air temperature High air temperature Low river levels	Extreme rain Heavy snowfalls Wet snow Atmosphere moisture Hail Freezing rain	Forest fire

ways in which associated releases of radioactive material from fuel can result in releases to the environment. It also estimates the frequency, magnitude, and other relevant characteristics of the release of radioactive material to the environment. This analysis provides additional insights into the relative importance of accident prevention, mitigation measures, and the physical barriers to the release of radioactive material to the environment (e.g. a containment building).

3. *In Level 3 PSA, public health and other societal consequences are estimated, such as the contamination of land or food from the accident sequences that lead to a release of radioactive material to the environment.*

PSAs are also classified according to the range of initiating events (internal and/or external to the plant) and plant operating modes that are to be considered.'

The PSA methodology is based on event tree methodologies, which are conceptually simple but highly complex in detailed applications. This is due to the number of SSCs in a NPP, the variety of initiating events, the possible equipment and human failures, the interdependencies between events, the uncertainties in data (hazards modelling, equipment failure probability, human failure probability, physical phenomena progression, SSCs behaviour in unplanned circumstances, etc.). A PSA modelling exists for almost all NPPs. Their quality is progressively improving, thanks to periodic updates and experience sharing. For example, the OECD-NEA working group risk (WG-Risk) collects and shares international experience in this area.

Although this approach is quite advanced for NPPs, PSA experts recognise in general that these studies still have some weaknesses and continual improvements are performed. One weakness is often the completeness of initiating events and hazards considered, which varies from one PSA to another.

Standards have been developed to design NPPs that should ensure a high level of safety. An important step in demonstrating the safety of a NPP design is to identify a set of accident conditions. To improve the safety demonstration probabilistic safety assessments are developed.

The ASAMPSA_E project was initiated in 2013 to help increase the scope of existing PSAs. For this project:

'An extended PSA (probabilistic safety assessment) applies to a site of one or several Nuclear Power Plant(s) (NPP(s)) and its environment. It intends to calculate the risk induced by the main sources of radioactivity (reactor core and spent fuel storages, other sources) on the site, taking into account all operating states for each main source and all possible relevant accident initiating events (both internal and external) affecting one NPP or the whole site.'

Some general lessons can be identified (Raimond, 2016):

- an extended PSA is still an objective for most PSA teams working on NPPs: no NPP site currently has a PSA that covers:
  - -full-power and all reactor shut down-state initial states
  - -all sources of radioactivity
  - -all relevant types of initiating events (internal and external)
  - -multi-unit accident management
- there is a need to enlarge the analysis scope in terms of the NPP, the neighbouring reactors or other industries, the environment at a medium scale;
- the risk metrics to be used are still a topic for discussion, especially if the objective is to calculate some 'global risk';
- PSA experts have to decide, for each NPP, which initiating events should be included in the PSA. Criteria are applied to identify risk significant events but, for some initiating events (e.g. high-amplitude earthquakes or combined extreme weather conditions), high uncertainties exist in both their frequency and amplitude; in such cases, the PSA approach is questionable;
- the geosciences fail sometimes to calculate both frequencies and features of some rare (extreme) natural events for PSA with reasonable uncertainty bounds; this is, in fact, a societal concern and progress in these areas should be expected;
- the study of the impact beyond design hazards may require additional methodologies (e.g. impact of beyond design lightning strike);
- PSAs have been applied to single NPPs; PSAs for multiple NPP sites have rarely been undertaken; the feasibility and interest of such

studies are ongoing issues;
- the application of PSAs (or extended PSAs) in decision-making processes is still a topic for harmonisation: for example, the recent interest in rare extreme events functions as a reminder of the need to take into account uncertainties in decision-making processes.

3.13.5 Risk reduction, a multiform activity

As explained above, European nuclear stakeholders apply the concept of continual safety improvement. This is done with a risk-reduction perspective. PSA has a role in this process, but many other considerations are taken into account. Risk reduction is in fact a multiform activity that cannot be reduced to a simple list. Some examples are proposed below but they cover only a limited number of risk-reduction possibilities, which are in fact possible at each level of the defence-in-depth approach.

For new reactors, the protection of the population in the event of a severe accident is paramount, as indicated by WENRA (2014):

'reducing potential radioactive releases to the environment from accidents with core melt, in short and long term, by following the qualitative criteria below:
- *accidents with core melt that would lead to early or large releases of radioactive material should be practically eliminated;*
- *in the event that accidents with core melt do occur, design provisions should have been be made so that only limited protective measures in area and time are needed for the public (e.g. no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, no long term restrictions in food consumption) and sufficient time must be available to implement these measures.'*

Several safety authorities request that utilities upgrade existing reactors to meet, as far as possible, the objectives for new reactors. In particular, it shall be postulated that severe accident may happen and that, in such cases, accident mitigation strategies shall be implemented. This obviously contributes to some degree of risk reduction, at least if the other existing safety features are not degraded as a result of ageing.

Risk reduction is a multiform activity that cannot be reduced to a simple list. There are a number of risk-reduction possibilities, which are in fact possible at each level of the defence-in-depth approach.

Research activities are very important to ensure the continued interrogation of existing practices, to develop new knowledge and to promote the application of new knowledge in safety improvements. Some examples are described here but, in fact, there are numerous topics of interest (e.g. see NUGENIA, 2013):
- the reassessment of hazards is an important issue during periodic safety review; as explained above, for natural hazards, there are topics where geosciences provide highly uncertain information due to remaining uncertainties for rare events but, nevertheless, even if the quantification of hazard features is difficult, reinforcement of NPPs can be decided based on the most recent knowledge;
- the analysis of NPPs' responses in the event of an accident using simulation tools capable of providing best-estimate information for the design verification of SSCs or the development of operating procedures;
- the analysis of SSCs' response (fragility analysis) in the event of hazards (earthquake, flooding, fire, lightning, etc.);
- techniques for in-service inspection to check the capability and conformity to safety standards of all key safety equipment (e.g. pipe welding control, risk informed inspection, plant walkdowns);
- research on severe accident progression;
- research on accident precursors;
- research on human factors and organisations: how to evaluate the efficiency of organisations to ensure the efficiency of all human activities (during NPP design, construction, normal operation, modernisation, control, accident management, etc.).

The emergency response is also a crucial factor during accident management. This concerns the site in question (to help manage a complex situation at a local and national level, to ensure the dissemination of trans-

parent information), the public authorities (to decide protective actions for the populations, to disseminate information transparently to the public) and international exchanges (the consequences of a nuclear accident are transnational; rescue solutions can often be found at the international level, and immediate and transparent communication is expected from any country facing a nuclear accident). As mentioned above, many research activities support progress in emergency response capabilities, for example on source term prediction, simulations of radioactivity transfer in environment, rules for the protection of populations, rules for agriculture management and communication during and after the accident (see EURANOS, NERIS-TP and PREPARE projects).

In addition, it is also recognised that the organisation of the control of nuclear activities by official bodies (in general nuclear safety authorities and technical safety organisations) and the relationship between the industry and these official bodies are of primary importance in risk reduction. Relationships with NGOs also have to be considered carefully.

We can mention, as an example, some values generally shared by the safety authorities or the Technical Safety Organisations, namely competence, independence, rigor, transparency impartiality, proactivity or initiative. The efficiency of the control of nuclear activities is another topic for exchanges at the international level.

3.13.6 Conclusions and key messages

Partnership

To conclude, we wish to highlight the importance of the multiform activities conducted to prevent any accident or to limit its consequences should one occur. The fundamental safety principles and the defence-in-depth approach underlie these multiform activities, which intend to enhance the nuclear safety requirements, the design features of nuclear facilities, the quality of construction, all human activities during normal operation and, in response to accidental situations, the continuous safety improvement and the control by appropriate bodies.

Knowledge

The efficiency of the emergency response plans at local, national or international levels and of the related international cooperation remains a challenge for the nuclear industry, and good practices can be shared with other activities. In parallel, research on the resilience of human organisations when facing complex situations can be promoted in the nuclear industry and in many other areas.

Innovation

The nuclear industry has still to face many challenges to maintain and improve the safety of operating and new reactors. Among these challenges are the human and organisational factors (training and education, generation renewal, changes in competences, evolution of requirements and regulation, modernisation programmes, the organisation's efficiency, etc.), the ageing of the nuclear facilities and the financial context.

If some challenges are very specific to nuclear activities, others are fully cross-connected to other human activities. For example, the study of high-amplitude natural hazards has become increasingly important since the Fukushima Dai-ichi accident, and efforts are being made to reinforce nuclear facilities if needed. Understanding and predicting these natural hazards is a societal concern and progress in geosciences is expected. To support safety studies for nuclear facilities, seismic faults identification and modelling, the quantification of correlated natural hazards (typically during extreme weather conditions) or the regional analysis of the consequences of such natural hazards are topics of interest for which knowledge should be improved.

3.14 Technological risk: Natech

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3.14.1 Introduction

The past few years have seen a number of natural disasters accompanied by major damage to industrial facilities and other infrastructures. In March 2011, a tsunami struck a Japanese NPP, causing a nuclear meltdown, and raging fires and explosions at oil refineries in the wake of the massive earthquake that triggered the tsunami also made the global headlines. Other recent examples of major disasters include Hurricane Sandy in 2012, which caused multiple hydrocarbon spills and releases of raw sewage, the damage to industrial parks during the Thai floods in 2011, or Hurricanes Katrina and Rita in 2005, which wreaked havoc on the offshore oil and gas infrastructure in the Gulf of Mexico (Krausmann and Cruz, 2013; Cruz and Krausmann, 2008, 2009).

These events clearly demonstrated the potential for natural hazards to trigger fires, explosions and toxic or radioactive releases at hazardous installations and other infrastructures that process, store or transport dangerous substances. These technological 'secondary effects' caused by natural hazards are known as 'Natech' (Natural-hazard-triggered technological) accidents (Krausmann et al., 2017a). They are a recurring but often overlooked feature of many natural-disaster situations and have repeatedly had significant and long-term social, environmental and economic impacts, including supply-chain disruptions (Figure 3.57). It is important to note that natural-hazard impacts on commercial districts or residential areas where lower quantities of hazardous materials are present are also a safety concern.

Natural hazards can cause multiple and simultaneous releases of hazardous materials over extended areas, damage or destroy safety barriers and systems, and down lifelines often needed for accident prevention and mitigation. These are also the ingredients for cascading disasters. For this reason, successfully controlling a Natech accident has often turned out to be a major challenge, if not impossible, where no prior preparedness planning had taken place.

Natech accidents can have serious consequences, including cascading events. While their risk is increasing, they are not adequately addressed in DRM.

Unfortunately, disaster risk-reduction frameworks do not fully address technological hazards in general or Natech hazards in particular. In addition, chemical accident prevention and preparedness programmes often overlook the specific aspects of Natech risk, which has caused a lack of dedicated risk-assessment methodologies and guidance for industry and

authorities on how to manage these risks both onsite and offsite.

This is aggravated by the expected increase of future Natech risk due to worldwide industrialisation, climate change, population growth and community encroachment in areas subject to natural hazards (Krausmann and Baranzini, 2012).

This subchapter gives an overview of the state of play in Natech risk reduction in the EU and globally; it highlights existing gaps in Natech risk reduction and makes recommendations on how to close these gaps.

While natural-hazard triggered nuclear accidents also qualify as Natech events (see Chapter 3.13), this subchapter focuses on Natech risk in terms of non-nuclear hazardous industrial activities.

3.14.2 Forensic analysis of Natech accidents and lessons learned

Post-accident analysis is a valuable tool to recreate the dynamics of accidents and to draw conclusions on the most prominent damage mechanisms and hazardous materials release paths, particularly vulnerable storage and process equipment types, as well as on the hazardous materials most commonly involved in these types of accidents. For this reason, efforts have been made to systematically collect and analyse information on the causes and dynamics of Natech accidents to support scenario development and the design of better protection options. In order to facilitate this process and to overcome the deficiencies of conventional industrial accident databases with respect to Natech accidents, the European Commission has set up the eNATECH database for the systematic collection and analysis of Natech accident data and near misses. The database exhibits the more sophisticated accident representation required to capture the characteristics of Natech events and is publicly accessible (eNATECH, 2015).

Lessons can be learned in all phases of risk and accident management, from prevention and preparedness to response and recovery. Analyses of single accidents produce immediate lessons specific to the event, while analyses of a set of similar accidents from a broader data pool yields lessons learned that are more widely applicable. The latter type of study facilitates, for example, the identification of commonly occurring causes of accidents involving specific substances or industries, which may not be easily recognisable within a single occurrence. This analysis also lends itself to identifying technical and organisational risk-reduction measures that require improvement or that are missing.

3.14.2.1 General lessons learned

The analysis of Natech accidents across different types of natural hazards showed that there are certain commonalities regardless of the

FIGURE 3.57

Hydrocarbon releases at a refinery during floods in Coffeyville, USA, in 2007.
Source: photograph courtesy of the Kansas Wing of the Civil Air Patrol

natural-hazard trigger. Studies have indicated, for instance, that storage tanks at atmospheric pressure, and in particular those with floating roofs, appear to be particularly vulnerable to earthquake, flood and lightning impacts compared with other types of industrial equipment (Krausmann et al., 2011). While no systematic studies for other types of natural hazards are available, individual case histories seem to support this conclusion in the case of storms or heavy rain (Bailey and Levitan, 2008; Godoy, 2007).

From an industrial safety perspective, the high susceptibility of storage tanks to natural-hazard impacts is problematic, as these plant units often contain large quantities of crude oil, gasoline or other types of flammable liquid hydrocarbons. It is therefore unsurprising that many Natech accidents involve hydrocarbon releases that have ignited and escalated into major fires or explosions (Table 3.8). In addition, with hazardous materials releases possibly occurring from several sources at the same time, an increased ignition probability, coupled with simultaneous damage to safety barriers and systems including the frequent loss of lifelines needed for process control or firefighting, the likelihood of cascading disasters is also higher for Natech events than for conventional industrial accidents.

3.14.2.2 Lessons learned from Natech accidents due to earthquakes, floods and lightning

Most Natech accident analyses have focused on accidents triggered by earthquakes, floods or lightning. Priority was given to these hazards because of the generally greater severity of Natech events caused by earthquakes (Antonioni et al., 2009), and the high frequency of accidents initiated by floods and lightning in EU Member States and OECD Member Countries (Krausmann and Baranzini, 2012). Systematic analyses of the dynamics and consequences of Natech accidents caused by other natural hazards are scarce, although other natural hazards, such as tsunamis, extreme temperature, high winds or landslides have also caused Natech accidents.

Hydrocarbon storage tanks are found to be particularly vulnerable to natural-hazard impact, which increases the cascading risk. Safety barriers are usually also affected by natural hazards and are unavailable for accident mitigation.

The main damage and failure mechanisms of industrial structures and hazardous equipment during earthquakes are direct shaking impact, ground deformation and liquefaction (Figure 3.58). The impact ranges from structural damage without the release of hazardous materials, such as shell buckling, sloshing damage or anchor-bolt stretching, to damage with loss of containment, caused, for instance, by the failure of flanges or pipe connections, shell and roof failures or tank overturning and collapse (Krausmann et al., 2011). The analyses also showed that during earthquakes it is common that several loss-of-containment events occur simultaneously. This increases the likelihood of cascading accidents. The analyses also highlighted the vulnerability of safe-

TABLE 3.8

Substances mainly involved in flood-triggered Natech accidents according to an analysis by Cozzani et al. (2010)

Hazardous substance category	No. of accidents
Oil, diesel fuel, gasoline; liquid hydrocarbons	158
Propane, butane, LPG	12
Fertilisers	11
Acid products	7
Cyanides	5
Oxides	5
Ammonia	5
Chlorine	3
Explosives	3
Calcium carbide	3
Soap and detergents	1

ty barriers (e.g. catch basins around tanks or sprinkler systems) to seismic loading.

In the case of floods, the main damage and failure mechanisms are the displacement of equipment due to buoyancy and water drag, as well as the impact of floating objects. This can break connections between pipework and equipment, cause pipelines to rupture or lead to tank collapse or implosion (Krausmann et al., 2011). Once a hazardous material has been released, the presence of the floodwaters aggravates the accident by acting as a vector for spreading the released toxic or flammable materials over wide areas. This can also increase the likelihood of domino accidents while simultaneously creating further risks in the areas surrounding the damaged facility (Figure 3.57). The analysis of flood-triggered accidents also showed that released substances can react violently with the floodwaters, thereby creating secondary toxic or flammable gases from often less dangerous precursor chemicals (Cozzani et al., 2010).

The analysis of lightning-triggered Natech accidents highlighted two different types of impact mechanisms: (1) direct impacts, causing structural damage to equipment, or the ignition of flammable vapours by the lightning strike (e.g. at the rim seal of atmospheric storage tanks); and (2) indirect impacts, which can trigger loss of containment, e.g. via process upsets due to power outage and power dips and impacts on electrical control and safety systems (Renni et al., 2010).

For a detailed discussion of lessons learned from Natech accidents due to a wide variety of natural hazards, the reader is referred to Krausmann and Salzano (2017).

FIGURE 3.58

Collapse of a dryer and severing of connected pipes at a fertiliser factory hit by the 2008 Wenchuan earthquake in China.
Source: photograph courtesy of E. Krausmann

3.14.3 Status of Natech risk management in European Union Member States and in OECD Member Countries

3.14.3.1 European Union

In the EU, major (chemical) accident risks are regulated by the provisions of the so-called Seveso Directive on the control of major-accident hazards and its amendments (European Union, 2012; see also Chapter 3.12). Following a series of Natech and other major chemical accidents (e.g. the spill of cyanide-laced tailings from a dam breach due to heavy rainfall and rapid snowmelt, or the release of chlorine from a flooded chemical facility), it was decided that an amendment of the Seveso Directive was needed to close remaining gaps. The latest amendment now explicitly addresses Natech risks and requires that environmental hazards, such as floods and earthquakes, be routinely identified and evaluated in an industrial es-

tablishment's safety report (European Union, 2012). Awareness of Natech risks in Europe has been growing ever since.

A recent survey among Seveso regulatory bodies aimed to assess the status of Natech risk management in the EU (Krausmann and Baranzini, 2012). The results of the survey showed an increasing awareness of the potentially disastrous impacts of natural hazards on chemical facilities. However, the survey also highlighted a number of gaps in Natech risk reduction, as well as related research and policy challenges.

Over half of the survey respondents indicated that their countries had experienced one or more Natech accidents in the period 1990-2009. The main accident triggers were lightning, low temperatures and floods. Considering the recurrence of Natech accidents, the survey results suggest that the legal frameworks for chemical-accident prevention have not always been effective. The survey participants expressed their belief that industries in many EU Member States may not consider Natech risks appropriately in their facility risk assessment, with potentially low preparedness levels as a result. The survey also revealed strong differences between the actual Natech accident triggers and the natural hazards perceived to be of concern, highlighting an incongruity between actual causes and risk perception.

The recurrence of Natech accidents has also raised doubts about the adequacy of design codes and standards for hazardous installations with respect to natural-hazard impact, as well as about the associated protection measures in place. The ultimate objective of these codes and standards is the preservation of life safety and, hence, the prevention of building collapse. While in itself an important goal, the preservation of a building's structural integrity is not necessarily sufficient to prevent the release of hazardous materials under natural-event loading.

The survey identified a number of key areas for future work for industry, regulators, and science and engineering. The majority of survey respondents called for the development of guidance on Natech risk assessment for industry with the highest priority, followed by the preparation of Natech risk maps to inform land-use and emergency planning by identifying a region's Natech hotspots.

3.14.3.2 The Organisation for Economic Co-operation and Development (OECD)

Parallel to the survey on the status of Natech risk management in the EU, OECD Member Countries were polled on the same subject. The OECD results showed a similar trend as in the EU and highlighted the same gaps (Krausmann and Baranzini, 2012). The majority of OECD survey respondents expressed their belief that there is a clear need to improve current regulations and fill existing gaps to fully address Natech risk reduction. Similar to the EU survey, they called for the development of natural-hazard and Natech risk maps, methodologies for and guidance on Natech risk assessment for industry and communities, as well as the training of authorities on Natech risk reduction.

Natech accidents continue to happen, which raises doubts about the effectiveness of existing safety legislation, as well as about the adequacy of design codes and standards for natural-hazard impact at hazardous installations.

One of the main international guidelines considering Natech risks are the OECD Guiding Principles for Chemical Accident Prevention, Preparedness and Response (OECD, 2003), the application of which is the subject of an OECD Council Recommendation. Given that the 2003 revision of the Guiding Principles considered only some aspects of Natech risk management, the OECD Working Group on Chemical Accidents decided to address the issue more comprehensively by including a Natech project into its 2009-12 work programme to identify existing gaps and develop targeted recommendations for Natech risk reduction.

As a final outcome of the OECD Natech project, a Natech Addendum to the Guiding Principles was issued (OECD, 2015). This addendum includes numerous recommendations for government and industry that address the inclusion of Natech risks in the drafting of regulations, rules and standards, their enforcement and implementation, and other activities in support of effective Natech risk man-

agement. With pipelines being at risk owing to natural hazards, the Natech Addendum also advocates the consideration of Natech risks in pipeline safety.

As a follow-up to the first Natech project, the OECD included a second Natech project in its 2017-20 work programme, which focuses on the implementation of recommendations from the first project and on improving international cooperation in Natech risk management.

3.14.4 Natech risk assessment

Risk analysis is an important tool by which to estimate the risk level of a hazardous activity. Quantitative risk assessment (QRA) in particular allows the identification of system weaknesses, the prioritisation of safety measures in terms of their importance for risk reduction, or the estimation of a facility's overall risk level, summarised in a risk figure. This risk figure can then be compared with prescribed risk acceptance target levels, where existing, to show that risks are adequately controlled in fulfilment of regulatory requirements (see Chapter 2.1).

3.14.4.1 General methodology

The identification of potentially Natech-prone areas and the determination of the associated risks are the first steps towards managing Natech risks. As Krausmann and Baranzini (2012) note, hardly any Natech risk maps exist in EU Member States and OECD Member Countries, and the development of a Natech risk analysis and mapping capability is considered a high-priority need by authorities to effectively reduce Natech risks.

There is a lack of consolidated Natech risk assessment tools, and extensions to traditional risk analysis need to be made to take into account the characteristics of Natech events.

Regardless of the risk-analysis approach chosen, extensions to both qualitative and quantitative risk analysis need to be made to take into account the characteristics of Natech events. Hence, specific damage models to assess the severity and probability of equipment damage due to a natural event, and a procedure to account for the possibility of simultaneous hazardous materials releases from more than one process or storage unit are needed. Simple damage models are available for a limited number of equipment categories (storage tanks, some types of process equipment) and in particular for earthquake impact. The inclusion of these damage models in QRA case studies has demonstrated the importance of considering earthquake-triggered accident scenarios for ensuring the safety of the facility itself and the surrounding population and environment (Antonioni et al., 2007; Campedel et al., 2008). Therefore, natural hazards can be important risk contributors at hazardous facilities and must be adequately considered in the risk-analysis process.

An in-depth discussion of the individual steps in Natech risk assessment, including the treatment of cascading events, can be found in Krausmann (2017).

3.14.4.2 Methods and tools for Natech risk assessment

The surveys discussed in Chapter 3.14.3 highlighted a lack of methodologies and tools for Natech risk analysis and mapping, which has so far hampered the appropriate inclusion of this type of risk into industrial risk assessment. Following calls by government to close this gap, the European Commission (JRC) developed the RAPID-N framework for rapid Natech risk assessment and mapping, which can be used to quickly identify Natech risk hotspots (Girgin and Krausmann, 2017, 2013). RAPID-N is a unique, semi-quantitative tool that allows the rapid analysis of Natech risks at local (single installation) or regional (multiple installations) level. This web-based tool is freely available via prior user registration and authorisation (RAPID-N, 2017). Figure 3.59 shows an example output of RAPID-N.

RAPID-N supports different natural hazards and industrial equipment types by design. It estimates and maps Natech risk in a web-based environment and can support land use and emergency planning, as well as Natech damage and consequence analysis immediately after a natural event. The latter in particular is fundamental for

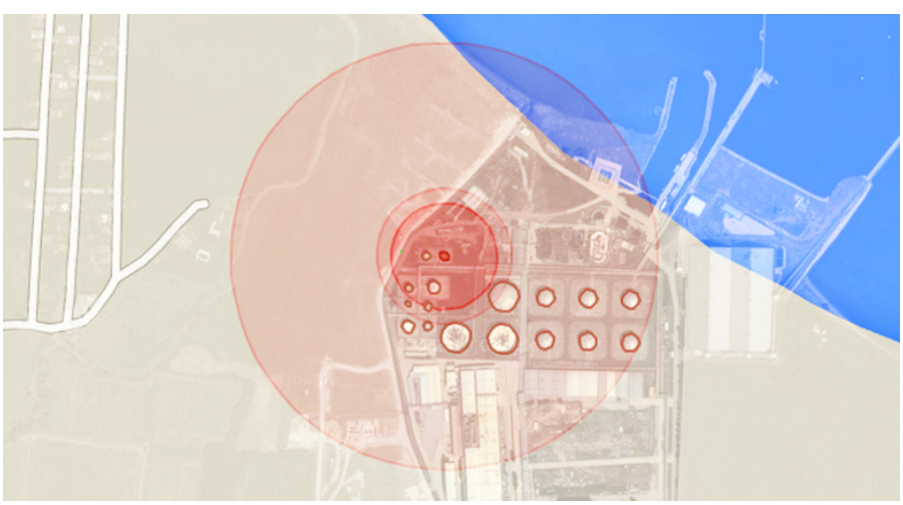
first responders who require an assessment of the dangers of secondary hazards from industrial plants following a natural disaster before dispatching rescue teams. It could also provide a means by which authorities may warn the population in the vicinity of an installation of imminent problems.

The current version of RAPID-N supports earthquake Natech risk analysis and mapping for fixed chemical installations, such as refineries or storage tank farms, and onshore pipeline networks. In the next release of the tool, floods will be included as additional Natech accident triggers. Additional short-term upgrades that are under way are (1) the inclusion of individual and societal risk calculations in addition to impact zones to move towards a more quantitative treatment of the problem, and (2) the implementation of an automated analysis function that will allow Natech risk analysis for facilities in the RAPID-N database immediately following the occurrence of a major natural event. Through this function, competent authorities, first responders and other interested parties can be quickly alerted to potential Natech accidents to ensure that fast protective action is taken if required.

While RAPID-N currently follows a semi-quantitative approach for analysing and mapping Natech risks to ensure a quick assessment with a minimum of data, the University of Bologna has developed a Natech module for its software package ARIPAR-GIS to characterise the Natech risks of single facilities in a quantitative way (Antonioni et al., 2017). This approach is more detailed than that of RAPID-N; however, it requires a significant number of data for the assessment process. The output of ARIPAR-GIS is individual risk and societal risk from Natech accidents caused by earthquakes and floods.

FIGURE 3.59

RAPID-N example output for the release and ignition of a flammable substance caused by a hypothetical Istanbul earthquake scenario. The circle endpoints indicate the point up to which second-degree burns would be received for different release scenarios.
Source: courtesy of European Commission (JRC)



3.14.5 Natech risk reduction

Past near misses have shown that Natech risk reduction generally pays off, and facilities that have benefited from natural-hazard specific design and the implementation of Natech risk-reduction measures have fared better during natural events (e.g. Cruz and Steinberg, 2005). Where these measures were inadequate or totally lacking, damage was more severe or even catastrophic.

Problem areas that stand out in most Natech accidents are related to insufficient prevention and preparedness, often caused by the grossly inadequate design bases of hazardous installations in natural-hazard prone areas due to a failure to acknowledge the specific requirements of process equipment under natural-hazard loads, the absence or weak enforcement of safety regulations, and a lack of guidance on how to address the problem of Natech risks in the industry. In addition, there is the misconception that engineering and organisational protection measures in place to prevent and mitigate conventional industrial accidents would also protect against Natech events. In fact, the very natural event that damages or destroys industrial buildings and equipment can also render inoperable engineered safety barriers (e.g. containment dikes, deluge systems) and lifelines (power, water for firefighting or cooling, communication) needed

to prevent an accident, mitigate its consequences and keep it from escalating. There is, therefore, a need for Natech-specific additional safety measures to accommodate the characteristics of Natech accidents, which require targeted prevention, preparedness and response.

3.14.5.1 Structural prevention and mitigation measures

In general, structural risk-reduction measures for technological risks use engineering solutions, such as safety valves or containment dikes, for accident prevention and mitigation. In this context, prevention refers to passive and active actions or measures put in place to reduce the likelihood of damage and the occurrence of a hazardous materials release, while mitigation refers to actions or measures implemented to lower the impact of hazardous materials releases if they cannot be prevented.

Experience from past Natech accidents and the associated lessons learned have led to the development of recommendations for reducing Natech risks for accident scenarios from a wide variety of natural hazards. For example, in earthquake-prone areas, flexible tank-pipe connections should be used given that the breaking of rigid connections has often led to releases (Figure 3.60). Anchoring or restraining equipment could effectively avoid displacement and keep equipment containing hazardous materials intact. The vulnerability of safety barriers (e.g. catch basins around tanks or sprinkler systems) is particularly apparent during earthquakes. Critical active and passive safety barriers should, therefore, also be designed to withstand the forces of the expected earthquake.

Natech risk reduction requires targeted prevention, preparedness and response, including Natech-specific safety measures, the implementation of which was found to pay off.

The risk of flood-triggered Natech accidents can be minimised, for example, if hazardous equipment is anchored or otherwise restrained to prevent floating and displacement by floodwaters. Indirect flood impacts via short-circuiting of electrical equipment that affects safety-critical systems can be reduced by protecting systems from wave loading and water intrusion. This can be achieved by waterproofing and appropriate design. The lifting of flammable waste oil in plant drainage systems due to flooding can be prevented by segregating the drainage systems for waste flammable substances and surface run-off water.

With respect to reducing the Natech risk from lightning strikes, the rim seal of atmospheric floating-roof tanks is the most likely point of ignition, and the seal should therefore be regularly checked and maintained. Furthermore, partial or total onsite power outage and power dips can lead to process upsets and thereby indirectly to hazardous materials releases. Internal backup systems should provide

FIGURE 3.60

Flexible steel pipe on a large oil tank in an earthquake-prone area. Source: photograph courtesy of A.M. Cruz

emergency power to those processes from which dangerous conditions can result during power loss (Krausmann et al., 2011).

Many more structural Natech prevention and mitigation measures for different natural hazards and equipment types are discussed in detail in Cruz et al. (2017).

3.14.5.2 Organisational prevention and mitigation measures

In contrast to structural measures, which use engineered physical solutions for prevention and mitigation, organisational measures are administrative programmes and controls put in place to reduce risks. Organisational protection measures include staff training, the implementation of safety practices and procedures, including the monitoring of safety performance, educational and awareness-raising campaigns and the establishment of safety policies and laws. Since technical protection measures can never entirely eliminate hazards from a hazardous installation, organisational control is needed to support protection goals.

An in-depth discussion of organisational Natech risk-reduction measures and approaches is provided in Krausmann et al. (2017b). The following sections provide examples of such measures.

3.14.5.3 Natech risk governance

From a Natech point of view, risk governance is becoming exceedingly important in light of increasing industrialisation coupled with emerging hazards, such as climate change. Since natural hazards can impact large areas at the same time, an integrated risk-governance approach involving all stakeholders is needed that addresses the safety of individual industrial installations as well as the potential interactions with neighbouring installations, lifelines and nearby communities. The Great East Japan earthquake and the Thai floods in 2011, for example, highlighted the need to better understand infrastructure-failure interdependencies and the governance of the associated risks.

3.14.5.4 Emergency planning

Natech accidents caused by major natural events pose a tremendous challenge for emergency response owing to:

- possible multiple and simultaneous hazardous materials releases over extended areas, a scenario for which emergency responders are usually not trained and equipped;
- competition for scarce emergency response resources for providing aid in natural disaster areas and for combatting the Natech accident;
- hampering of search and rescue operations as a result of toxic releases, fires and explosions;
- inapplicability of standard civil-protection measures such as evacuation or shelter;
- reliance of industry on external lifelines and emergency-response resources for managing a Natech accident rather than preparing a 'standalone' emergency plan.

In order to increase preparedness for Natech accidents, emergency plans for hazardous industry should consider natural-hazard risks. Plant-internal emergency plans for mitigating hazardous materials releases should assume that safety barriers are absent or non-functional and off-site response resources are not available, requiring backup lifelines to control the Natech accident. Off-site emergency plans need to take into account the eventuality of toxic releases, fires and explosions impacting the population and the rescue operations and the need for evacuation in a situation where transport routes might be com-

TABLE 3.9

Effectiveness of Natech-specific early warning based on the warning time to warn and action time tact. Source: Salzano et al. (2009)

twarn/tact	Characteristics	Effectiveness
<< 1	Short warning time or slow preventive action	Low: little time to implement preventive action
≈ 1	Warning time similar to time needed for preventive action	Medium: some preventive action possible prior to natural-event impact
>> 1	Long warning time or fast preventive action	High: sufficient time for preventive action even if time-consuming

promised. An assessment of the vulnerability of the emergency response resources is also called for in the context of Natech risk reduction.

Emergency plans at both plant and community level should be periodically reviewed and tested to ensure that they remain up to date. This is of particular importance in times of climate change, which might require updates to the assumptions on which the emergency plan is based.

3.14.5.5 Early warning

Early warning is usually not available or practicable for reducing Natech risks, as warning times for some natural hazards are too short for preventive action at hazardous facilities. Salzano et al. (2009) contend that the effectiveness of Natech early warning systems is defined by the ratio of the available warning time and the time needed to implement preventive action (Table 3.9).

For earthquakes, for example, warning times range from fractions of seconds to only a few seconds, which makes early warning for earthquake Natech accidents rather impractical. In this case, the earthquake-resistant design of hazardous installations should be prioritised.

The situation is different for river floods, for which warning times can range from hours to days, leaving ample time and opportunity to mitigate the Natech risk, for example by implementing plant shut-down, depressurising equipment or transferring hazardous substances from predicted on-site inundation zones to safer locations. If tsunamis are generated in the far field, the warning lead time should permit the actuation of prevention actions, as for floods.

Interestingly, Bouquegneau (2007) also suggests that early protective actions, such as disconnecting sensitive equipment or stopping hazardous processes, are possible for lightning hazards by using information from meteorological lightning location systems.

3.14.6 Conclusions and key messages

Past Natech accidents have clearly shown the vulnerability of hazardous industrial activities to natural-hazard impact, with often major consequences on health, the natural environment, and the local, regional or global economy owing to asset damage and the associated business downtime. Some of these accidents have also dramatically demonstrated the increased risk of cascading effects and the challenges faced by emergency responders.
The good news is that awareness of Natech risks is increasing worldwide and first attempts to systematically assess and control this risk are being made. Nevertheless, a number of research and policy gaps related to Natech risk reduction remain that require addressing in a concerted effort of regulators, industry and the research community.

Partnership

In many countries, there is legislation that regulates hazardous industrial activities, and in some cases Natech risks are explicitly addressed. It is important that these regulations be enforced. Where missing, dedicated legislation for reducing Natech risks should be developed and implemented. At the same time, risk communication between industry and all levels of government should be improved to ensure that communication related to Natech risks flows freely and effectively to realistically estimate the risk. Public–private partnerships could facilitate the linking of science, practice and policy in support of Natech risk reduction.

Knowledge

Further awareness-raising efforts are needed to help stakeholders recognise the vulnerability of hazardous installations during natural-hazard impact. In this context, climate change must be a factor in the assessment, as it might change natural-hazard severities and frequencies and thus render the design basis of installations and equipment inadequate. In addition, plant workers, civil protection authorities and those in charge of chemical-accident prevention need to receive targeted training to be able to handle the challenges that are associated with Natech accidents.

Risk assessment is an important tool by which to identify safety gaps and prioritise safety-relevant interventions at a facility. There are no consolidated methodologies for Natech risk assessment, and research should focus on the development of Natech risk assessment methodologies and tools for different natural hazards, as well as related guidance at the industry and community levels. Data on

accidents and near misses crucial for learning lessons and scenario building are often closely guarded by industry for fear of negative repercussions on their activity. Authorities should promote and facilitate the sharing of Natech accident data by companies to support future risk reduction.

Recommendations

The last few years have seen a number of natural disasters that have been accompanied by major damage to industrial facilities. These events have demonstrated the potential for natural hazards, such as earthquakes, floods, storms, etc., to trigger fires, explosions and toxic or radioactive releases at hazardous installations that use or store hazardous substances. These so-called Natech accidents are a recurring but often overlooked feature of many natural-disaster situations. In addition, chemical and nuclear activities are an increasingly important source or risk of such accidents owing to increased industrialisation and urbanisation.

Unfortunately, disaster risk-reduction frameworks have not commonly addressed technological risks. The Sendai Framework for Action recognises the importance of technological hazards and promotes an all-hazards approach to disaster risk reduction. This includes hazardous situations arising from man-made activities due to human error, mechanical failure and natural hazards.

Chemical risk

Chemical accidents continue to occur relatively frequently in industrialised and developing countries alike, which raises questions about the adequacy of current risk-reduction efforts. The causes underlying chemical accidents are largely assumed to be systemic. Most chemical accidents today are caused by violations of well-known principles for chemicals risk management, which have led to insufficient control measures.

From the forensic analysis of chemical accident reports, a number of underlying causes have emerged, one or several of which can affect a chemical installation to create conditions conducive to disaster. These causes include:

- A lack of visibility due to a lack of published statistics on accident frequency and a reporting bias towards high-consequence accidents, which are a mere fraction of the many smaller chemical accidents that occur each week.
- The challenge to manage across boundaries, when chemical and mechanical engineers commonly assigned to chemicals risk management have little training in human or organisational factors.
- A failure to learn lessons from past accidents and near misses.
- Economic pressure and a trend towards optimisation, which can undermine risk management when decisions are made without due consideration of their impacts on safety risks.
- Failure to apply risk-management knowledge by both individuals and organisations due to a lack of awareness and education, or inattention to inherent safety.
- Insufficient risk communication and disconnection from risk management due to the globalisation of hazardous industries, which places a distance between corporate leaders and the sites they manage.

- Outsourcing of critical expertise or distribution of limited expertise over many sites, making it less accessible when needed.
- Governments do commonly not proactively engage in managing chemical-accident risks until after a serious accident, and accident management is focused on emergency preparedness and response rather than prevention.
- Complacency in government and industry due to the incorrect perception that chemical accidents are no longer a threat, thereby causing a decrease in resources for enforcement and risk management.
- Based on the identified accident causes, a number of areas for further study and experimentation to reduce chemical accident risks should be explored, and it is recommended that the following occur:
- Motivation of corporate and government leadership by exploring new models for risk governance, and promotion of a positive safety culture by fostering risk awareness. Enforcement will need a new strategy to drive industrial safety practice.
- Promotion of systematic accident reporting, data collection and exchange to raise awareness of the potential consequences of chemical accidents. These data should be used to learn lessons from accidents and near misses.
- Development of strategies to combat labour market deficiencies related to process-safety expertise.
- Creation of cheap and easy access to risk-management knowledge and tools, including to risk-assessment competence urgently needed in all areas of the world.
- Building of awareness of chemical risks and how to manage them in developing countries.
- Fostering of regional and international networks and collaboration on chemical accident risk management to create pressure and give developing countries easy access to expertise and technical support.

Nuclear risk

Accidents at nuclear facilities, regardless of the accident trigger, have the potential to cause a disaster. In the EU, a nuclear safety framework aims to ensure that people and the environment are protected from the harmful effects of ionising radiation. The basis of this framework is the defence-in-depth approach, a key concept by which to reach an appropriate level of protection from nuclear risks, and an adequate safety culture.

After several major nuclear accidents, safety assessment methodologies have been continuously improved, and the design of a NPP follows a set of rules and practices that ensure a high safety level. At the design stage, a set of accident conditions is identified that can result from different initiating events, and this set is examined using a conservative, deterministic safety assessment. This is complemented by a PSA, which provides a methodological approach to identifying accident sequences that can follow from a wide range of initiating events, as well as to determining accident frequencies and consequences. The challenge is to make certain that the list of considered initiating events is complete.

Many different protective activities form the basis of ensuring the safety of nuclear facilities, both during normal operation and in the case of accidents. However, the nuclear industry still faces a number of challenges that need to be addressed. The following are therefore recommended:

- Further assess the impacts on the safety of nuclear activities of human and organisational factors (e.g. training, management of change, evolution of regulations and associated requirements), of ageing effects on nuclear facilities and of financial concerns.
- Improve knowledge of the identification and modelling of natural hazards to support safety studies for nuclear facilities.
- Share good practice on emergency responses at local, national and international levels between nuclear and non-nuclear industrial activities to increase the efficiency of emergency-response plans.
- Promote research on the resilience of human organisations in the face of complex situations in nuclear industries and other areas with similar requirements.

Natech risk

Natech accidents are a technological 'secondary effect' of natural hazards and have caused many major and long-term social, environmental and economic impacts. National and international initiatives have been launched to examine the specific aspects of Natech risk and to support its reduction.

The forensic analysis of Natech accident records has allowed the preparation of lessons learned across different triggering natural hazards that support the reduction of Natech risks. This includes the setting up of a dedicated Natech accident database to foster the easy and free sharing of accident data. Accident analyses also show that there is an increased risk of cascading effects during Natech accidents. In general, Natech risk reduction pays off, and several structural, as well as organisational, accident prevention and consequence mitigation measures are available.

Studies on the status of Natech risk management in EU Member States and OECD Member Countries have highlighted deficiencies in existing safety legislation and the need to consider this risk more explicitly. Conventional technological risk-assessment methodologies need to be expanded to be applicable to Natech risk assessment and only a very few methodologies and tools are available for this purpose.

With respect to the effective reduction of Natech risks, several research and policy gaps still need to be closed in a collaborative effort between regulators, industry and academia. Public–private partnerships could be helpful in this context. More specifically, it is recommended that:

- Existing legislation that regulates hazardous industrial activities should be enforced. Where missing, legislation for reducing Natech risks should be developed and implemented.
- Risk communication on Natech risks should be improved between industry

and all levels of government to ensure a free and effective flow of information that enables a realistic assessment of the associated risk.

- Government should promote and facilitate the sharing of Natech accident data for future Natech risk reduction.
- An inventory of best practices for Natech risk reduction should be set up and disseminated to all stakeholders.
- Research should focus on the development of Natech risk assessment methodologies and tools, as well as guidance on Natech risk management for industry and at the community level.
- Competent authorities and workers at hazardous installations should receive targeted training to be able to handle the challenges associated with Natech accidents.
- Additional awareness-raising efforts are needed to help stakeholders recognise the vulnerability of hazardous industry to natural-hazard impact. In this context, the effects of climate change on natural-hazard frequencies and/or severities need to be factored in.

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