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Natech risk management

Guidance for operators of hazardous industrial sites and for national authorities

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Abstract

Natural hazards, such as earthquakes, floods or storms, can trigger the release of toxic substances, fires and explosions when impacting industrial installations that process, store or transport hazardous materials. This type of event is called Natech (natural hazard triggered technological) accident. Impacts on industrial operations and hazardous infrastructure are a recurring but often overlooked feature in many natural disaster situations. With climate change affecting the intensity and frequency of some natural events, Natech risk has become a topic of concern for disaster risk management at local, national and international levels.

Following a number of important accidents, awareness of Natech risk has increased in the European Union, and the risk has been acknowledged in legal acts on chemical accident prevention. In 2012, an amendment of the EU Seveso Directive on the control of major accident hazards involving dangerous substances explicitly introduced Natech risk as an issue of concern that is required to be addressed.

To date the implementation of effective Natech risk management has been hampered by a general lack of guidance on how to conduct Natech risk assessment. In order to facilitate compliance with the requirements of the Seveso III Directive or similar legislation, this document aims to provide technical guidance on Natech risk management for operators of hazardous installations and national authorities. It outlines the necessary steps in the Natech risk management process and discusses the main challenges that hamper its proper implementation. While emphasising the identification and modeling of specific scenarios for Natech risk assessment, the document also provides solutions for addressing existing gaps in Natech risk assessment and the control of Natech risk.

Although this guidance focuses on Seveso requirements, the Natech risk management principles discussed herein can also be adopted in other industry sectors that handle hazardous materials.

1 Introduction

Natural hazards can trigger the release of toxic substances, fires and explosions when impacting industrial installations that process, store or transport hazardous materials. This type of event is called Natech (natural hazard triggered technological) accident (Krausmann et al., 2017). Natech accidents are therefore technological accidents, and the management of the associated risk is within the purview of the operator of a hazardous site. With climate change affecting some natural hazard triggers and with increasing human development (booming urbanization, rapid industrialization), Natech risk is expected to increase in the future.

Experience shows that a large number of past Natech accidents could have been prevented if only better awareness and understanding of the risk had existed. Following a number of important Natech accidents, awareness of Natech risk has increased in the European Union (EU), and the risk is acknowledged in legal acts on chemical accident prevention. The EU Seveso III Directive (2012/18/EC)[1] requires that national authorities oversee the implementation of effective safety policies for the control of major accident hazards at industrial installations involving dangerous substances. In this framework, operators of upper-tier establishments are obliged to present a safety report to their national authorities to demonstrate that they have evaluated all risks, including those due to natural hazard impacts, and that they have taken all measures to prevent major accidents. The safety measures implemented at hazardous establishments should be based on the risks identified and assessed in the safety report. The Directive explicitly states that safety reports must include "*a description of the possible major accident scenarios and their probability […], the causes being internal or external to the installation; including in particular: […] natural causes, for example earthquakes and floods*" (Annex II of the Seveso III Directive).

A study by Krausmann and Baranzini (2012) on the status of Natech risk management in the EU found that the implementation of effective Natech risk management is hampered by a general lack of guidance on Natech risk assessment, in the absence of which the measures taken by operators to reduce the risk may be incomplete or inadequate. Since then, national and international initiatives have been launched which have resulted in the preparation of natural hazard-specific or high-level guidance to raise awareness of and better manage Natech risks (e.g., INERIS, 2014; OECD 2015; UNI, 2021; TRAS 310,320, 2022; DSB, 2022). This document complements these initiatives by providing the first comprehensive technical guidance for operators that describes the process of Natech risk analysis in a systematic way and which is applicable to all natural hazard triggers.

In order to facilitate compliance with the requirements of the Seveso III Directive, this document introduces the main characteristics of Natech accidents, collected during years of observation and study, and provides clear guidance on how to identify, analyse and treat Natech risks at industrial sites. In this context, particular emphasis is given to the identification and modelling of specific scenarios for Natech risk assessment. Using practical examples, the guidance also suggests solutions for better control of the Natech risk.

While Natech risk management should be implemented both at local and territorial level, this guidance focuses on the site level and addresses with priority the operators and inspectors of Seveso III establishments. The information provided is, however, also directed at national authorities responsible for ensuring compliance with major accident prevention legislation.

Although this guidance is centred on Seveso requirements, the Natech risk management principles discussed herein can also be adopted in other sectors, such as in industry that handles quantities of hazardous materials below the Seveso qualifying criteria, offshore oil extraction, critical infrastructure, defence facilities, and the transport of hazardous materials.

[1] https://ec.europa.eu/environment/seveso/legislation.htm

2 Characteristics of Natech events and associated challenges

Natech accidents are a class of cascading events that manifest when technological systems are affected by the impact of natural hazards which in turn results in the release of hazardous materials. Natech events have occurred during many past natural disasters and have often had significant impacts on public health, the natural and built environment, and the economy (Krausmann et al., 2017). Contrary to common belief, Natech events can also be triggered by "minor" natural hazards. For example, in a study reviewing Natech risk management in the European Union, Krausmann and Baranzini (2012) found that in contrast to risk perception the number of accidents caused by lightning and low temperature was significantly higher than the number of accidents triggered by windstorms and earthquakes.

The characteristics of Natech events differ from those of other types of technological accidents. A lack of awareness and low preparedness levels can limit greatly the effectiveness of existing risk management approaches against Natech accidents. Some recurrent characteristics that need to be taken into consideration in Natech risk management are:

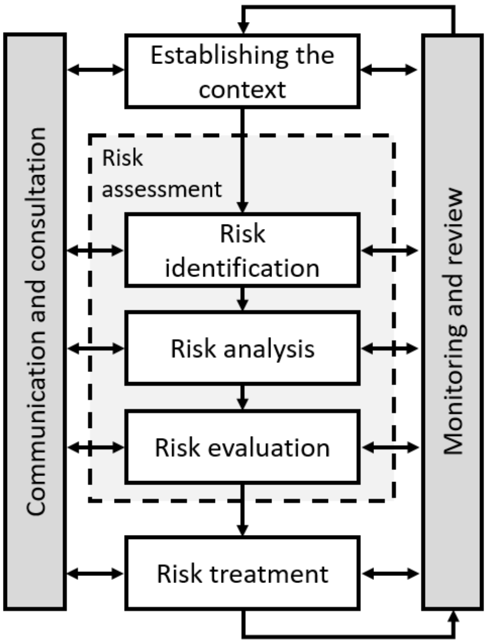
1. **Some natural hazards can affect large areas, hitting several hazardous industrial sites and installations at the same time** (e.g., earthquakes, floods, storms). They can trigger multiple Natech accidents simultaneously, possibly leading to situations where the consequences of multiple accidents overlap, thereby challenging limited emergency response resources and hitting the affected area harder than any one accident alone would have done.
2. **Natural events can affect engineered protection barriers** (e.g., containment dikes, gas detectors, alarms, backup power generators, water sprinkler systems) that are meant to handle hazardous situations, preventing their evolution into full-scale accidents. Similar to impacts on installations, natural hazards can disrupt or destroy many safety barriers at the same time, effectively thwarting any effort to improve the reliability of safety systems via redundancy.
3. **Natural events can disrupt auxiliary systems and utilities** (e.g., power, water, communication lines), thereby triggering or aggravating an accident. In a process plant, the loss of utilities may result in a wide range of unwanted events, e.g., loss of control of an industrial process, inoperability of safety equipment, or the inability to contact the local civil protection authorities and to implement emergency plans correctly.
4. **Standard emergency response measures may not be functional or appropriate during an accident caused by a major natural event**. Procedures commonly used during conventional technological accidents, like shelter in place or evacuation, may not be feasible. In the wake of a natural disaster, roads are often impassable, e.g. due to flooding or fallen trees. Emergency responders may not be able to access the site, thereby increasing the response time, while people at risk, including the pant personnel, would be unable to evacuate (Steinberg et al., 2008). In addition, protection from chemical releases by staying indoors ("shelter-in-place") may not be a viable option when the structural integrity of a building is compromised by, e.g., an earthquake.
5. **Natural hazards can aggravate the consequences of Natech accidents** by creating secondary hazards or by expanding the accident's impact zone. For example, releases into floodwaters can spread hazardous materials over wide areas and therefore increase the pollution or fire risk. Also, some otherwise innocuous chemicals can change characteristics upon contact with water (floodwaters, rain), creating toxic or flammable vapours that pose new hazards to the population and to emergency responders.
6. Compared to other types of technological accidents, **Natech accidents feature a higher likelihood of domino effects** (the process of the propagation of an accident to nearby units or to other plants that produces an escalation of the consequence of the initial accident) (Krausmann et al., 2017, p. 4). This is mainly due to limitations in the mitigation of the consequences of Natech accidents already mentioned in the previous bullets.
7. **Natural hazards can trigger cascading effects** that may cause a secondary natural hazard to affect the industrial site (e.g., heavy rain causing a landslide; earthquake triggering a tsunami). Natural hazards and their cascading effects can cause damage and disruption separately, but also due to their combined effects, which needs to be taken into account in the Natech risk assessment. For instance, in the case of the 2011 Tohoku earthquake, the tsunami was the main source of damage to several industries and contributed to spreading hazardous materials in the environment (BARPI, 2013).

8. **Natural hazards are changing in time and location** due to climate change, and anticipation of and adaptation to such changes are needed for effective Natech risk management. If there are new insights into a specific natural hazard, previous Natech risk assessments and the risk management measures implemented as a consequence need to be reviewed and revised if necessary. Adaptation of risk management strategies to changing boundary conditions which themselves may be subject to uncertainty is challenging.

3 Introduction to Natech risk management

"Risk management" is composed of all coordinated activities to direct and control an organisation with regard to risk. Risk management covers the whole process of identifying and assessing risks, setting goals, and creating and operating systems for their control. Risk is generally defined as the likelihood of a specific effect occurring within a specified period or in specified circumstances. **In the context of process safety, risk is a measure of the combination of the extent of consequences of an accident and their likelihood**. Generally, organisations use risk management to deal with internal and external factors that create uncertainties in the achievement of the organisation's objectives. One of the main applications of risk management at hazardous process plants is major accident risk control. The hazards with which risk management is concerned include those from natural events and those from man-made systems that give rise to a range of physical, financial, legal, and societal risks (Mannan, 2005). The risk management process is composed of a number of generic steps (Figure 1). This chapter discusses these steps based on ISO-31000[2] in the context of a framework for Natech risk management with a focus on risk assessment and treatment.

Figure 1. The process of risk management.



Source: ISO 31000:2009(E)

3.1 Communication and consultation

Communication and consultation with internal and external stakeholders should take place during all stages of the risk management process. These activities should address all risks, including their causes and consequences, and measures to treat the risks. Consultation ensures that all interests related to a risk are taken into account. This helps to establish the risk management context correctly and that the plans for risk treatment are endorsed. It is worth noting that perceptions of risks can vary among stakeholders due to differences in values, interests, needs, assumptions, concepts, and concerns.

3.2 Establishing the context

In this step, the organisation articulates its objectives, defines the internal and external parameters to be taken into account when managing risk, and sets the scope and risk criteria for the remaining process. In this regard, for all European chemical enterprises with major accident risk, the main objective is to control the risk to workers on site, to the nearby population and to the environment due to the presence

[2] ISO 31000:2009(E) Risk management - Principles and guidelines, 1st ed., 2009, International Organization for Standardization, Switzerland.

of hazardous materials in areas with natural hazards, in compliance with national rules that transpose the requirements of the EU Seveso III Directive.

In the Seveso framework, operators are obliged to take action to prevent major accidents on site, including Natech accidents, and to mitigate their consequences. To achieve this goal, the risks associated with the release of dangerous substances must be identified, assessed and managed. To this end, the operator should draw up a major accident prevention policy (MAPP) implemented by the appropriate means, structures and a safety management system (SMS). The information generated in the context of Natech risk management is, i.a., used to draw up the site's internal emergency plan which is then also submitted to the competent authority to enable it to prepare the external emergency plan.

Land use planning (LUP) is a key component for accident risk management, as it aims to identify whether the risks posed by a hazardous industrial site are compatible with the surrounding territory. In Seveso III, this evaluation must take account of the presence of residential areas, commercial activities, locations of public use (e.g., hospitals and schools), transport routes, other industries, agricultural areas, and environmentally protected areas. Each of these entities may be impacted differently in case of an accident, therefore it is important to consider each risk receiver individually. For Natech risk management, LUP is also relevant to determine if a hazardous site is or would be located in an area subject to natural hazards. In this case, it may be decided to relocate a new plant project elsewhere or to implement additional protection measures. When several hazardous sites are located in the same natural hazard-prone area, they should cooperate in order to control risk due to possible domino effects when accidents propagate from one site to the other.

Each operator should develop their own policy to ensure safety by controlling major accidents, in compliance with regulations, the strategic view of the organisation, and its business objectives. Since the goals are manifold, the risk criteria and methodologies used by different businesses could differ significantly. Also, within the same site, different methodologies may be applied when evaluating different types of risk (for example, when calculating the risk to the environment or the risk to the business). When defining risk criteria, the following factors should be taken into consideration (ISO 31000:2009(E)):

- The nature and types of causes and consequences that can occur and how they will be measured;
- How likelihood will be defined;
- The timeframe(s) of the consequence(s);
- How the level of risk is to be determined;
- The views of stakeholders;
- The level at which risk becomes acceptable or tolerable; and
- Whether combinations of multiple risks should be taken into account and, if so, how and which combinations should be considered.

3.3 Risk assessment

Risk assessment is a complex process composed of risk identification, risk analysis and risk evaluation. Natech risk assessment, which requires extensions compared to conventional industrial risk assessment, is discussed in detail in Chapter 4.

3.3.1 Risk identification

The organisation should identify sources of risk (hazards), areas of impacts, and events that can lead to risks (e.g., occurrence, causes and consequences of process upsets). The aim of this step is to generate a comprehensive list of risks present at a hazardous site based on those events that might create, enhance, prevent, degrade, accelerate or delay a risk. All significant event causes and consequences should be identified. Identification should include risks whether or not their source is under the control of the industrial site, even though the source of risk may not be evident. It should also consider a wide range of event consequences.

NB: Risk and hazard identification are often used interchangeably in process safety. A hazard is a generic source of risk (e.g., the presence of a flammable substance) while specific risks can be generated from the hazard (e.g., presence of a flammable substance in the vicinity of a risk receptor). The risk identification step does not assess the identified risks but should ascertain that all relevant risks are captured before proceeding with their analysis. For the purpose of this guidance we use the term hazard identification.

For Natech accidents, the risk source is two-fold: On the one hand, there are natural hazards that can threaten a site; on the other hand, there are the hazards due to the presence of hazardous materials and processes.

3.3.2 Risk analysis

Risk analysis is aimed at determining the risk, i.e., evaluating the severity and likelihood, associated with the main accident scenarios. The risk analysis uses various techniques to estimate these two elements for each scenario. These methods can be qualitative, semi-quantitative or quantitative, depending on a number of factors, such as data, time and resource availability, or scope of the analysis. In this step, factors that affect consequences and likelihood must be analysed, in particular the causes and sources of risk, and their positive and negative effects on both likelihood and consequences. The results of the risk analysis should be framed in the context of uncertainties and assumptions that may affect the robustness and credibility of the conclusions from the analysis.

Risk analysis provides the input to the risk evaluation and risk treatment steps. The decision to reduce a risk is based on the results of the risk analysis. Risk analysis can also provide an input to decision-making where choices must be made about the relevance of different types of risk or the prioritisation of different risk reduction measures. Risk mitigation strategies and their effectiveness should also be taken into account in risk analysis.

For Natech risk analysis both the risks due to natural hazards and technological hazards must be analysed and combined.

3.3.3 Risk evaluation

The purpose of risk evaluation is to assist in making decisions, based on the outcome of risk analysis, about which risks need treatment and the priority for treatment implementation. In the evaluation, the level of risk obtained during the analysis is compared with risk criteria established during the context-setting step. Based on this comparison, the need for risk treatment may be identified. Occasionally, the risk evaluation can lead to a decision to undertake further analysis.

3.4 Risk treatment

Risk treatment consists of the selection and implementation of one or more actions for reducing risks. Risk treatment involves an iterative process of implementation, monitoring, and review that repeats until a target goal is reached.

Some examples of risk treatment are:

- Avoiding the risk by deciding to stop (or not to start) the activity that gives rise to the risk;
- Removing the risk source;
- Reducing the likelihood;
- Mitigating the consequences;
- Sharing the risk with another party or parties (e.g., partnership, insurance);
- Making an informed decision to retain the risk.

Selection and implementation of a risk treatment option requires evaluating the benefits versus costs. For example, some risk treatment options may be prohibitive on economic grounds, e.g., when high costs would result in only a minimum reduction of the level of risk. Alternatively, some options, or combinations of options, may have a low cost but have a greater impact on risk reduction than other more expensive options.

Options for treating Natech risk are discussed in Chapter 5.

3.5 Monitoring and review

Both monitoring and review steps are an integral part of the risk management process. Monitoring and review covers all aspects of the risk management process and can be periodic or ad hoc. This activity, implemented, e.g., via inspections or audits, ensures that controls are effective while helping to obtain additional information for risk assessment. It supports the analysis and learning of lessons from events, successes and failures, and it facilitates the identification of changes in the established context of the risk assessment, or in the nature of risk, which would then translate into an adaptation of the risk treatment. This step also helps to measure the performance of the whole risk management process.

4 Elements of Natech risk assessment

Natech risk combines risks due to natural hazards and those due to hazardous human activities. Natural hazards can affect man-made risks in a particular area either by increasing the frequency (likelihood) of major accidents in hazardous installations or by producing an array of accidents that would not occur without the impact of an external force (e.g., displacement of a tank due to storm surge and release into the floodwaters). In addition, when a natural disaster hits a region with industrial sites and technological hazards, the Natech accidents triggered may increase the severity of the impacts associated with the natural disaster and hamper natural disaster response activities due to hazardous materials releases (Necci et al., 2018b).

Natech risk assessment requires the adaptation of conventional industrial risk analysis approaches to account for the specific characteristics of Natech risk (natural hazard trigger, potential for multiple and simultaneous loss of containment events). It also requires the identification of Natech scenarios that are representative of the impact of specific natural hazards on a specific site. Natech accident scenarios feature a natural hazard scenario, a scenario of the potential effects on the installations (e.g., damage, disruption) that lead to a critical event (e.g., loss of containment), and a consequence scenario to assess the extent of the damage. This chapter discusses the steps required to analyse (Steps 1-6) and evaluate (Step 7) Natech risks at an industrial site. These are:

1. Natural hazard identification and characterization;
2. Identification of critical equipment;
3. Analysis of natural hazard damage to critical equipment;
4. Natech hazard identification;
5. Natech consequence analysis;
6. Assessment of Natech event likelihood;
7. Evaluation of Natech risk.

Natech risk assessment requires a significant amount of input data, such as information on the natural hazard, the vulnerable equipment, damage models and data linking damage to releases, consequence analysis models, likelihood estimates and information on the risk receptors (Krausmann, 2017).

Box 1. Uncertainties and lack of data

Risk analysis invariably contains uncertainties introduced during the steps of the analysis process. These uncertainties stem from uncertainties in models, input data and general analysis quality (CCPS, 2000). Natech risk analysis usually contains a larger number of uncertainties compared to the analysis of other types of technological risks. This is due to a frequent lack of detailed data on the natural hazard trigger (especially for very rare events), missing fragility data for certain types of equipment and specific natural hazards, or the absence of consolidated models for Natech risk analysis. The analyst may resort to using expert judgement that is - by nature - subjective to complete the missing information, adding further uncertainty to the analysis. Transparency about the assumptions that went into the risk analysis and the associated uncertainties helps the users of the analysis to apply its results cautiously.

4.1 Natural hazard identification and characterisation

This step consists of gathering and analysing data on the natural hazards (CCPS, 2019). Natech accidents can be triggered by all types of natural hazards, including rapid-onset (e.g., earthquakes, hydro-meteorological events) or slow-onset ones (e.g., sea-level rise, drought). It is important that **all types of natural hazard that have the potential to trigger an accident at an industrial site are identified**. At least one natural hazard scenario should be described for each site-relevant natural hazard. Different criteria for the selection of the natural hazard scenarios can be used (most likely, worst case, etc.); they are all viable provided that the choice is reasonable and can be justified.

The natural hazard description can be either probabilistic or deterministic. In the deterministic approach, experts identify a reference natural hazard scenario (e.g., credible worst case, most likely) that is described through its intensity (e.g., peak ground acceleration, flood depth). In the probabilistic approach, the hazard description includes an estimate of its frequency based on historical records in addition to an intensity measure.

The natural hazard information can be described in two ways:

1. **As a discrete event (a scenario)**, or as a set of discrete events (scenarios) with a specific intensity (e.g., wind speed, peak ground acceleration). Each such event (e.g., river flood, earthquake scenario) can occur with a given probability in a reference time interval. A typical way to describe the probability of a scenario in a way that is easy to understand is assigning a “return period” to the scenario. A return period describes the average time between two occurrences of the same event. A return period is high for events that are unlikely to occur and vice versa.
2. **Associated with a variable (the intensity parameter) that has a range of values**. The probability that a given value of the intensity parameter will be equalled or exceeded in a reference time interval is described by the use of continuous probability distribution functions, also known as **hazard curves**. For some hazards like earthquakes, volcanoes and tsunamis, this information is typically displayed in hazard maps.

Analysts with adequate information at their disposal can adapt the approach they prefer to use. From a set of scenarios with associated probabilities, hazard curves can be derived. Alternatively, from a hazard curve one or more discrete events (scenarios) can be selected using values of the intensity parameter chosen at specific points of the distribution (e.g., the median value, quartiles, percentiles).

Figure 2 shows an example of a single scenario with a 100-year return period in the form of a flood hazard map, while Figure 3 shows an example of a hazard curve built to represent the relationship between ground shaking and probability at a specific location.

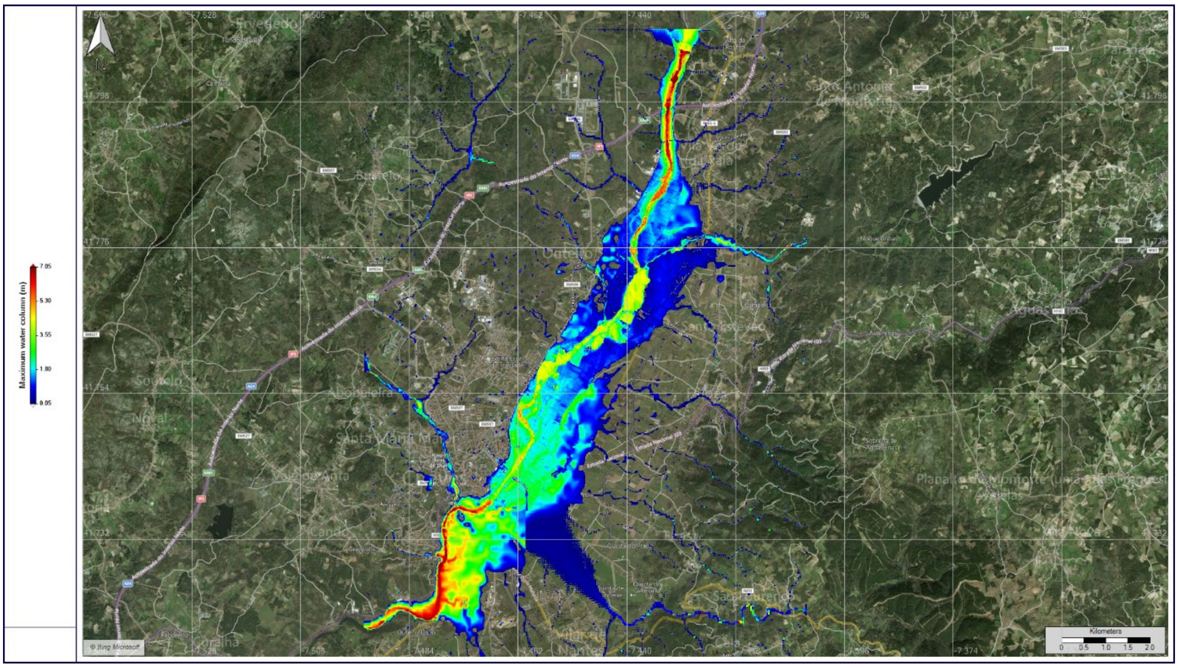
Location-specific data at the site of the industrial plant should be used for the description of the intensity parameters of the natural hazards (e.g., mapping natural hazard scenarios, or using hazard maps), allowing the identification of the exposed installations in the plant. Some natural hazard scenarios may not affect just one part of the site, but several installations at once (or even all of them), although some parts may be more vulnerable to natural hazard impact.

Once the natural hazard scenario, or its relevant intensity parameter, is known, the effects of the natural hazard on the site’s surroundings should be briefly evaluated, as well. In particular, macroscopic effects on nearby electricity infrastructure and roads should be identified and used later in the assessment of the Natech scenarios and the associated emergency response plans.

For each scenario, the natural hazard description should adhere to the following principles:

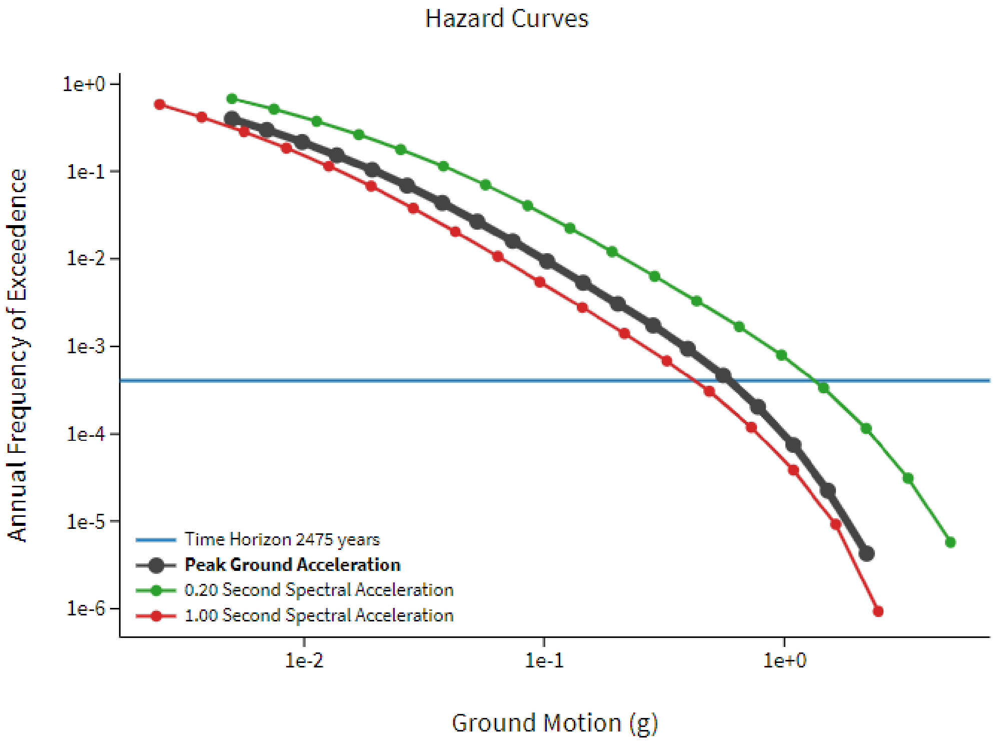
- The **type and characteristics of the natural hazard should be indicated**.
- **Natural hazard scenarios should be detailed and complete** and should be described according to best practices.
- The level of detail of the **natural hazard information should be adequate for the analysis of major accident risks**.
- **The person, or agency,** carrying out the assessment of the natural hazards at the industrial site **should have the appropriate expert knowledge and competence**.
- **The source documentation should be readily available** for subsequent assessments.
- **The natural hazard description should be based on reliable and trusted sources**. The preferred sources of information are generally government authorities (e.g., civil protection, Met office, geological survey) at the national, regional, or local level.
- **The natural hazard information should be as up-to-date as possible**.
- **It should take into consideration** the increasing frequency and intensity of some natural hazards due to **climate change**.
- **It should also take into consideration** other influencing factors, such as **changes in land-use over time** and **in the natural hazard management of the territory.**
- **A list of the installations exposed to the harmful effects of the natural hazard should be created**.
- The natural hazard **information should be useful for assessing the potential damage to industrial equipment** (including auxiliary systems and safety barriers) and/or utility disruption (i.e., potential **accident initiators**).
- **This information should include references to historical natural hazard events that occurred at the site** or in its vicinity.

Figure 2. Example of a water depth map associated to a 100-year return period flood.



Source: Fernandes et al., 2022

Figure 3. Example of an earthquake hazard curve showing the probability of exceedance of the peak ground acceleration at a given location.



Source: USGS, Unified Hazard Tool, 2022, https://earthquake.usgs.gov/hazards/interactive/

Box 2. Climate Change

The management of Natech risk requires anticipation of future changes of the climate and adaptation to the foreseen new conditions. In fact, climate change has been linked to an increase of both frequency and intensity of extreme hydro-meteorological events. Moreover, climate change is responsible for a number of phenomena that can be a hazard for industrial plants located in certain regions. These are:

- Sea level rise
- Snowmelt
- Desertification
- Wildfires
- Permafrost thawing

Operators should acknowledge the hazards posed by climate change and the possibility of an increase of the severity of some natural hazards. Several actions can help to cope with risks due to climate change, for example:

1. Development of a climate adaptation strategy.
2. Analysis natural hazards that are specifically caused by climate change or worsened by it.
3. Acknowledgement that past natural hazard information is insufficient, on its own, to give an accurate estimate of the natural hazards of a future that covers the whole operative lifetime of the site.
4. Keeping risk assessments updated and adaptation of preparedness measures as new natural hazard information becomes available.
5. In the absence of a clear estimate of the effect of climate change on the expected severity of future natural hazards, representation of this additional uncertainty by applying corrective factors that increase the expected severity of future natural hazards. This principle has been implemented in the German Technical Rules for process safety TRAS 310 (2022) and TRAS 320 (2022). The adapted values should be used for both Natech risk assessment and equipment design.

4.2 Identification of critical equipment

For every industrial site exposed to a natural hazard, **potential damage to all installations that contain hazardous materials** should be assessed. It is therefore important to identify all the critical equipment that could lead to Natech accidents. The analysis should focus on **equipment whose sudden failure may result in a foreseeable chain of events that leads to hazardous situations**[3]. For example, storage tanks have proven to be vulnerable to many natural hazards. In addition, the consequences of accidents at large storage tanks can be very severe due to the large quantity of hazardous materials they contain.

Past studies provide pragmatic methods for a preliminary ranking of different types of equipment, based on their Natech consequence potential. The preliminary criteria use operating conditions, volume, and physical state of hazardous materials for the ranking. In fact, Natech accidents can be all the more severe depending on the amount of hazardous materials involved, and on their storage or process conditions.

Storage and process conditions that affect the accident consequences are:

- **Temperature:** At high temperature, even combustible substances classified as non-flammable can reach their flash point and pose the same fire hazard as flammable substances would do. When the temperature is sufficiently high, the self-ignition temperature can be reached. Also, a liquid stored at high temperature is more volatile than a liquid at low temperature (affecting both flammable and toxic substances). As a result, a cloud formed from evaporation (or boiling) at high temperature contains more hazardous material than a cloud formed at low temperature. A superheated liquid may “flash” upon release, generating a vapour cloud much faster than it would do through evaporation. High temperature also directly translates into high storage

[3] A hazardous situation is a circumstance that exposes people, property or the environment to one or more hazards (ISO 14971).

pressure for pressurised gas (the pressure increase is almost proportional to temperature and follows the equation of state) or gas liquefied under pressure (the pressure increase is almost exponential with temperature and follows the Antoine equation).

- **Pressure:** High pressure produces a driving force that translates into a high release rate of hazardous material in case of rupture or leak of the container. For a gas, higher pressure also means more material in the storage. Pressurised vessels also produce a blast when ruptured and are likely to project fragments of the broken vessel in all directions.
- **State of matter:** State of matter influences the quantity of hazardous material and the operative conditions. Liquids contain a larger quantity of hazardous material per unit of volume compared to gases, but they take time to evaporate. However, gases have other properties that make them dangerous. They are usually stored and processed under high pressure (see *Pressure*) and upon release they become immediately airborne. Gases liquefied under pressure have hazardous properties of both liquids and gases. They have high density, comparable to those of liquids, are stored under pressure, and flash immediately upon release. Superheated liquids behave similarly to gas liquefied under pressure. Gases liquefied at very low temperature have the same behaviour as liquids and they typically do not flash upon release. However, they evaporate much more quickly than most liquids.
- **Volume:** Some processes are inherently larger than others, meaning that they contain higher amounts of hazardous materials. Storage vessels are usually the largest vessels and are designed to contain high substance quantities. Pipelines and piping can also contain a large amount of substance. Similarly, separators and columns also contain a large amount of hazardous material although they are usually smaller than a storage unit and are typically only partially filled. Reactors are usually the smallest process units. Other units that may contain a considerable amount of hazardous material are heat exchangers, furnaces, ovens, and boilers.

Table 1 shows an example of the application of this approach to obtain a preliminary ranking of critical equipment units. The method that was applied by Antonioni et al. (2009) takes into account the maximum damage distances (calculated taking into account lethal effects for humans) expected for different unit types and substances, with similar release scenarios (equal hole diameters through which the release occurs).

It is important to note that the ranking of equipment in terms of their criticality may have different outcomes depending on the type of risks considered. In fact, the results of the ranking may change when the target of the assessment changes. Likewise, some units that may have a high score for one type of risk may not be considered critical at all for a different risk. For instance, storage vessels of liquid lubricant may rank high when the damage distances are calculated taking into account the impact on the environment, particularly on water bodies. However, the same unit is not critical at all when considering the risk to people or assets since lubricant oil is neither flammable nor toxic for humans.

Table 1. Example criteria for the identification and ranking of critical equipment items (Antonioni et al., 2009).

	Storage vessels	Large-diameter pipes	Columns	Reactors, heat exchangers
Pressurized liquefied gas	4	4	3	3
Superheated liquid	3	3	2	2
Gas (compressed)	3	2	2	1
Cryogenic liquid	2	2	2	1
Liquid	1	1	1	1

4.3 Natural hazard damage to critical equipment

For every natural hazard, it is important that the main damage modes of each critical equipment belonging to an exposed plant are identified. Damage modes that could lead to hazardous situations or loss of containment (LOC) should be considered (e.g. storage tank rupture with leakage). The main damage modes for the most common types of equipment units are described below.

Buckling damage: Deformation of metal enclosures is typical for many types of natural hazards when a sudden load affects the structure. Buckling alone does not typically cause loss of containment. However, it may cause structural instability and may be accompanied by other damage types, such as the rupture of pipes and connections, tearing of metal plates or detachment of the shell-to-bottom connection. Buckling damage is often observed in the lower part of atmospheric storage tanks following strong earthquakes, and manifests as “elephant foot” buckling or “diamond” buckling of the tank wall (Eidinger et al., 2001; Cooper, 1997). Buckling damage can also occur due to debris impact, e.g. during flooding, landslides or high winds, or due to wind buckling in empty tanks. Figure 4 shows an example of buckling damage due to earthquake.

Rupture of pipes and fittings: Damage to piping typically results in loss of containment. Earthquakes and floods have been responsible for deformation and rupture of pipe networks especially at flanges and other types of connections by displacement of units connected to the network (see *Displacement and overturning*). Rupture often occurs because the pipe network is usually not designed to allow for plastic deformation when the natural event causes large displacements. Lightning strikes have punctured pipes both on the ground and underground. Strong winds have caused tall objects (like stacks or chimneys) to fall onto pipes and pipe racks, severing them (Necci et al., 2018a). Low temperatures have triggered several accidents due to solidification (freezing) of content inside the pipes, thereby choking the flow. Figure 5 shows an example of a pipe break at a flange connection during an earthquake.

Figure 4. Buckling damage due to an earthquake at silos.

Photo credit: E. Krausmann

Figure 5. Pipe break at flange connection during an earthquake.

Photo credit: A.M. Cruz

Tearing of metal shell: When the deformation is sufficiently large, the metal sheets that compose the shell of a vessel may fall apart and cause a LOC. This phenomenon is more frequent for equipment whose shell plates have been riveted or bolted together (Eidinger et al., 2001; Cooper, 1997).

Detachment of the shell-to-bottom connection: In most atmospheric storage tanks the shell walls and bottom can be composed of two separate metal sheets. When buckling affects the lower part of a vessel, the annular connection between the wall and the bottom is heavily stressed. Tearing of the vessel at this location can cause loss of containment of hazardous materials. This damage mode is often associated with elephant foot buckling of atmospheric storage tanks in earthquakes (Eidinger et al., 2001; Cooper, 1997). Figure 6 shows an example of shell-to-bottom detachment during a hurricane, likely due to storm surge and wind action (including possible debris impact).

Support leg failure: Many equipment units have support legs to sustain their weight. These legs are typically designed to sustain the equipment's own weight including its content and some horizontal excitation. In the case of earthquakes, lateral loads can exceed the design specification of support legs and cause their failure, resulting in the entire equipment to collapse on the ground (Eidinger et al., 2001; Cooper, 1997).This damage mode can cause loss of containment. Figure 7 shows an example of support leg failure in the wake of an earthquake.

Rupture of fixed tank roof: When a storage tank has a fixed roof, it can be vulnerable to the impact of a natural hazard, being the part of the equipment with the lowest weight and thickness. Strong winds can cause the roof to buckle (Godoy, 2007) without loss of containment. Liquid sloshing caused by earthquakes may cause the roof to buckle and portions of the liquid to spill outside the tank through vents and through newly created tears on the roof (Eidinger et al., 2001; Cooper, 1997). Figure 8 shows an example of wind damage to a storage tank's fixed roof.

Figure 6. Shell-to-bottom detachment of an atmospheric storage tank during a hurricane. The insulation of the tank was also stripped away.

Photo credit: M. Nauman, FEMA

Figure 7. Support leg failure of a spherical storage tank due to earthquake.

Photo credit: H. Nishi

Figure 8. Damage to the fixed roof of an atmospheric storage tank caused by strong wind.

Source: NOAA

Floating roof failure: Some of the biggest atmospheric storage tanks, designed to hold large amounts of liquid product, do not have a fixed roof, but a metal deck that floats on the liquid surface. When the roof sustains damage, it may sink into the liquid below. When this happens, the liquid surface is exposed to the air and the product starts to evaporate with the release of vapours into the atmosphere (Necci et al., 2018a). In addition, the rainwater drains installed on the roof (now submerged) may cause the liquid to be released through the drain and outside the tank. The main causes of floating roof damage are water accumulation due to heavy precipitation and liquid sloshing due to earthquakes. When the liquid substance is flammable, natural hazards may ignite the material at the rim seal between the roof and the shell wall. This type of fire may escalate to a full surface tank fire. Lightning strikes and earthquakes have been responsible for a number of floating roof fires (Necci et al., 2018a; Girgin, 2011) (See also *Ignition and sparking*).

Displacement and overturning: A natural hazard can exert strong forces on equipment, creating translation and rotation phenomena. When this happens, units can be pushed against each other or topple (Krausmann and Salzano, 2017). This can cause collision damage and ruptures in the attached pipe network, both of which can result in loss of containment. Displaced and toppled storage tanks have been observed in earthquakes due to strong lateral acceleration (Eidinger et al., 2001). In floods and tsunamis, the uplifting buoyancy force, wave slamming, and water drag have also produced this type of damage (Necci et al., 2018a). Figure 9 and Figure 10 show examples of displacement and overturning of storage tanks due to storm surge.

Puncturing damage: Sharp objects pushed against the equipment may produce buckling and holes in the shell with a potential for loss of containment (Necci et al., 2018a). Both heavy low-speed objects carried by floods or tsunamis and lighter high-speed objects projected by strong winds can produce puncturing damage. Puncturing damage can affect equipment and pipes, especially those with low shell (or pipe) thickness.

Figure 9. Atmospheric storage tank displacement and damage from storm surge due to a hurricane, including displacement of a pipe.

Source: NOAA Office of Response and Restoration

Figure 10. Overturned and damaged atmospheric storage tank due to storm surge from a hurricane.

Source: NOAA Office of Response and Restoration

Ignition and sparking: Some natural hazards can directly ignite flammable and combustible materials, e.g. lightning and wildfires, causing fires at hazardous installations. Areas in process plants that contain flammable or explosive atmospheres are exposed to this damage mode. In these cases, the equipment units are not damaged by the natural hazard itself; instead, fires or explosions triggered by the natural hazard damage them. The most typical example of the result of ignition damage are fires at large atmospheric tanks that store oil and hydrocarbons. The most common natural source of ignition is lightning. A study on fires in atmospheric storage tanks (Chang and Lin, 2006) concluded that lightning strikes have caused over 90% of all tank fires. The lightning ignites the flammable vapour often present in some units (e.g., in the space above the floating roof or at vents of atmospheric storage tanks). Another cause of ignition are earthquakes. They can induce violent motion of metal parts that can collide or brush against each other generating sparks as a result. This phenomenon has been observed mainly at the seal between atmospheric storage tank walls and metal roofs floating on the liquid surface via liquid sloshing (Girgin, 2011). The increasing risk of wildfires may also pose an as yet little known risk to industrial equipment containing flammable substances.

Overfilling: Water can pour into important units containing hazardous materials during flooding and heavy rain events. When the amount of water exceeds the capacity of the unit, it overflows, carrying part of the unit's content with it. In this case, the unit is not technically damaged but its function and containment are compromised nonetheless. This is a frequent LOC event for parts of process plants that are open but contain residues or larger amounts of hazardous materials, such as drains, sewers, and some waste treatment facilities like tailings ponds and dikes (Necci et al., 2018a).

Table 2 shows the relationship between the natural hazards and the listed damage modes, while Table 3 shows the relevance of the listed damage modes for a selection of type of equipment unit.

Table 2. Typical damage modes classified by selected natural hazard triggers.

Damage mode	Earthquake	Flood(1)	Flash flood(2)	Heavy precipitation	Lightning	Wind	Landslide	Low temperature
Buckling	X	X	X	X		X	X	
Rupture of pipes and connections	X	X	X			X	X	X
Tearing	X	X	X			X		
Shell-to-bottom detachment	X		X					
Support leg failure	X		X				X	
Fixed roof damage	X			X	X	X		X
Floating roof damage	X			X	X	X		
Displacement	X	X	X			X	X	
Overturning	X	X	X			X	X	
Puncturing damage		X	X		X	X	X	
Ignition and sparking	X	X	X		X			
Overfilling		X	X	X				

(1) Slow-onset floods like coastal floods and river floods.
(2) Rapid-onset floods, including dam failures and tsunamis.

Table 3. Typical damage modes of relevance for selected process and storage equipment/facilities.

	Atmospheric storage tank	Pressurised vessel (bullet)	Pressurised vessel (sphere)	Heat exchanger	Phase separator	Column	Stack	Dike/Pond	Sewers
Buckling	X					X	X		
Rupture of pipes and connections	X	X	X	X	X	X			
Tearing	X								
Shell-to-bottom detachment	X								
Support leg failure	X	X	X	X	X	X			
Fixed roof damage	X								
Floating roof damage	X								
Displacement	X	X	X		X				
Overturning	X	X	X		X	X			
Puncturing damage	X								
Ignition and sparking	X								X
Overfilling	X							X	X

Box 3. Damage modes and operating conditions

It is also important to identify the operating conditions under which natural hazard damage is more likely to occur. For example, storage tanks with a high filling level are more likely to fail in earthquakes due to liquid sloshing (Eidinger et al., 2001), while tanks with lower filling level are more likely to fail in flood events because a lower weight increases the lift force due to buoyancy (Godoy, 2007).

Box 4. Structures designed to withstand natural hazard impact

Some installations are designed to withstand the natural hazards of relevance at an industrial site, in compliance with existing codes or standards. In these cases, **the operators may be tempted to claim that Natech accidents cannot occur** since the installation was designed to resist natural hazards. This **approach can be misleading** as the reference design intensity used may be exceeded in case of natural events that are more severe than design specifications.

Why?

Design procedures for industrial structures are based on the identification of “limit states”, which are values of the natural hazard intensity parameter that the structure is able to withstand without experiencing damage. The selection of limit states is, in fact, based on the occurrence frequency (or return period) of the natural hazard. However, the **structures do not resist all natural hazard severities possible** but only those with an intensity lower than the chosen limit states. There is a range of potential natural hazard severities (those with a larger return period than the scenario used for the design intensity) which exceed the design intensity of the structure. For this reason, the design procedure can only achieve a reduction of the risk for the structure, but it cannot erase the risk completely. This also means that some **residual risk is always present for any structure**, even when the structure has been designed to resist natural hazards. However, the extent of this residual risk is typically not considered when the major accident risk is assessed. The structural risk is neglected, because of the low occurrence frequency of the limit state. But what may appear to be a negligible rupture frequency for the structural engineer can, in fact, be a significant frequency for the occurrence of critical events (i.e., top events).

What should be done instead?

Operators should acknowledge that Natech accidents are possible even if the equipment has been designed to withstand some natural hazard severities, following the principle of “accidents despite precautions” described in the German rule TRAS 310 (2022). If possible, **the same natural hazard information source used during the definition of limit states should be employed for Natech risk assessment. Natural hazard scenarios with frequencies lower than that of the limit state should also be considered in the assessment of Natech accidents.** Only after the Natech scenarios have been analysed and evaluated should those natural hazard scenarios be discarded whose overall impact, considering also Natech accidents, is still considered negligible. When using a deterministic approach, the experts should choose the highest available natural hazard intensity as the worst-case natural hazard scenario, especially if it is the only value higher than the design intensity.

4.4 Accident contributing factors: safety barriers and utilities

One of the main features that characterises Natech accidents is natural hazard induced damage or disruption to control systems, instrumentation, safety barriers, and other equipment that do not contain hazardous materials but whose functioning may still be safety critical (Necci et al., 2018b; Krausmann and Salzano, 2017). Similarly, natural hazards can disrupt auxiliary systems and down utilities that are meant to ensure the correct functioning of the process plant. Since these systems may influence the outcome of an accident, their damage and disruption can be considered a **contributing factor to Natech accidents**. Under some conditions, contributing factors can become **indirect Natech accident triggers**, but typically they can change (usually for the worse) the outcome of Natech accidents by, e.g., **reducing the performance of existing safety barriers**.

This can produce either of the two following outcomes, or both:

1. **Safety systems** (e.g. leak/fire detection, fire suppression, automatic shutdown) **are disrupted due to natural hazard impact**. As a result, **hazardous situations can be created and easily turn into an accident which may then receive no mitigation**. This can lead to a higher likelihood of Natech accidents, and to unmitigated consequences with potentially aggravated impacts both inside and outside the boundaries of the site.
2. **Essential auxiliary systems or utilities** (e.g. electric power supply, compressed air, steam, cooling water) **are disrupted**, **leading to uncontrolled process upsets** that can become hazardous situations, and, eventually, turn into full-scale accidents (see also Section 4.5.2).

Although several studies have documented the vulnerability of auxiliary and safety systems to natural hazards (e.g., Necci et al., 2018a,b; Misuri et al., 2021; Girgin, 2011) there is still little to no quantitative data that can be used for risk assessment. A worst-case approach is therefore recommended. When considering the vulnerability of safety and auxiliary systems to a specific natural hazard scenario, the general rule is to **consider unavailable any system that is not specifically designed to withstand the intensity of the chosen natural hazard scenario**. Work has been launched to provide a more realistic assessment of safety barrier performance under natural hazard loading (Misuri and Cozzani, 2021).

The following list shows the most critical systems whose disruption can be dangerous at a process plant:

Power loss: Analysis of past accidents demonstrated that failure of the power supply is a recurrent feature of Natech accidents that can be caused by different types of natural hazards, e.g., via the disruption of overhead lines in storms or earthquakes or inundation of substations during floods. Power loss alone should not normally be sufficient to cause serious consequences, given that process plants usually have backup power sources that kick in should the primary power source fail, and that drive the installations to a safe shutdown. However, past Natech events showed that backup power equipment (e.g., UPS, backup generator) was often rendered unavailable by the same natural event that disrupted the main power supply. Many other systems also rely on electric power, e.g., control systems, pumps, compressors, agitators, and lighting.

Loss of water: Water is crucial for a number of functions in a process plant. Natural hazards can disrupt the water network by damaging water tanks and reservoirs, breaking/dislodging piping, or rendering the pumps unavailable. Water is essential to keep critical equipment (e.g., chemical reactors) refrigerated. When water is unavailable, the operator can lose control over critical processes, such as exothermic chemical reactions, potentially leading to runaway reactions and loss of containment. Additionally, firefighting systems require large quantities of water to control and extinguish fires.

Loss of steam: Steam is the main vector for providing heat to the installations in a process plant. Natural hazards can disrupt the steam network by damaging water tanks and reservoirs, disrupting or damaging boilers, breaking/dislodging piping, or causing leaks with subsequent depressurisation in the network. Similar to water loss, loss of steam may generate process upsets that can be difficult to control. In some installations, steam is used to cause a phase transition or to maintain the correct phase of the processed material. Process lines are also often traced with steam lines, which aim at preventing temperature drops between one process unit and another. This feature is extremely important in winter and in cold environments in general. When this feature is lost, temperature drops may cause the solidification of products in the process lines and the subsequent choking of the pipes. Eventually, these events may even cause a pressure increase in the lines that can cause the pipes to fail and leak.

Loss of compressed air: Compressed air is used in many installations to power pneumatic tools, as well as for automation equipment and conveyors. Compressed air is one of the key elements of industrial process control. Natural hazards can disrupt the compressed air network by damaging air tanks, breaking/dislodging piping, or causing leaks with subsequent depressurisation in the network. Loss of compressed air may result in loss of process control and hazardous process upsets.

Control systems failure: Control is an essential feature of all industrial processes. Process control systems consist of one or more control loops made of several different items: a sensor that measures the process variable(s), a transmitter that transports the information, the actual controller that elaborates the information, and the actuator that translates the signal into action. Damage to any of these items results in the failure of the whole control system. Large processes typically have a distributed control system (DCS) that contains many control loops. It is very common that control systems have one or more levels of redundancy to increase reliability. However, natural hazard impacts can affect both the main control system and the backup systems at the same time.

Instrument failure: Instruments for the detection and measurement of process variables can be damaged by natural hazards and as a consequence return incorrect data or no data at all to the control systems. For example, compromised gas, smoke and fire detectors on the site's premises may fail to detect a hazardous situation or an accident, or fail to activate alarms, thus increasing the time to respond to the threat. Similarly, faulty instruments can cause dangerous process variations.

Pump/compressor failure: Pumps and compressors may fail in different ways during a natural hazard impact; for example, they may stop working because of a lack of electricity due to a blackout, their motor could be submerged by floodwater, or flood- or wind-driven debris may have hit them. Their failure can produce depressurisation of process units or cause the interruption of flow (or reverse flow) in important process lines, thus producing uncontrolled process fluctuations that may lead to loss of containment.

Flare failure: Natural hazards can cause damage to or malfunction of the flare. Many industrial plants go into emergency shut down in response to some natural hazards, or if the natural hazard impact has caused damage, and the content of process units is blown to the flare to be safely disposed of. Flare failure means that the hazardous material is not combusted and instead released directly into the environment. Typical natural hazard impacts to the flare are malfunction of the pilot light, damage to the blowdown line, and damage to the flare stack.

Box 5. Common cause of failure

Natural hazards can disrupt, damage or destroy utilities, auxiliary systems and safety barriers at the same time. This can lead to scenarios that are normally considered impossible, where all safety measures fail at the same time, e.g., like in the 2017 Arkema accident that followed Hurricane Harvey (Necci et al., 2018a). It is therefore important that natural hazards be accounted for as common causes of failure for those items that may be impacted by them.

4.5 Natech hazard identification

Natech accidents are caused by the loss of containment of hazardous materials due to the impact of natural events that are external to the process. Natech events can be caused via direct natural hazard damage to critical equipment that contains hazardous materials or indirectly due to natural hazard induced process variations, loss of utilities or protection and control system malfunctions.

4.5.1 Direct effects of the natural hazard

Hazardous materials may be released when the primary unit they are contained in is damaged or destroyed by a natural event. The types of damage and damage modes for the most common equipment types have been discussed in Section 4.3. In this section we will discuss the possible accidents that can result from direct damage and their consequences. There are two main accident types that can be triggered by a natural hazard directly affecting hazardous materials and their containers:

1. Damage to the container with release of hazardous materials;
2. Ignition of flammable substances.

For the first accident type, the main objective is to determine whether or not the natural hazard scenario has the potential to damage the analysed system and if so what the extent of the damage will be. The best way to asses if and how the unit fails is to engage with the mechanical designer of the unit who can provide insight into the unit's performance under the loads exerted by the natural hazard. The simplest method to assess damage is to consider that containment has failed when the design specifications are exceeded with a "Yes/No" logic. Another classical method for assessing damage is the use of *damage states* coupled with *fragility curves* (Eidinger et al., 2001; FEMA, 2015). Damage states are usually divided into qualitative damage classes (e.g. none, minor, moderate, major, catastrophic). Classes can be specific or generic, depending on the data source of the fragility curve. In most cases each damage state represents a vast array of damage types and damage modes. Fragility curves provide values of probabilities that can be used for the assessment of the damage likelihood (see Section 4.7).

The second accident type is linked to the presence of areas with explosive atmospheres in the process or storage facilities at a hazardous site. An explosive atmosphere is a mixture of hazardous materials with air, under atmospheric conditions, in the form of gases, vapours, dusts or fibres in which, after ignition has occurred, combustion spreads to the entire mixture. The resulting fire or explosion often generates a major accident. However, frequently this also causes extensive damage to containers with the subsequent release of hazardous materials. When this happens, the resulting fire or explosion is typically much larger than the original fire initiated by the natural hazard. In addition, fires and explosions can extend to nearby installations or sites and produce a so-called "domino effect" (Reniers and Cozzani, 2013).

4.5.2 Indirect causes

Indirect causes of Natech accidents concern the identification of accident scenarios deriving from natural hazards induced uncontrolled process variations that may push industrial processes outside their safe operating routine. As mentioned in Section 3.4, the failure of utilities or of auxiliary support systems can also lead to hazardous situations or Natech accidents, even during or after a successful process shutdown. Past accident analysis showed that Natech accidents with indirect causes can occur also when redundant safety systems are in place as they can all be affected simultaneously by a natural hazard (Misuri and Cozzani, 2021). Consequently, indirect causes of Natech accidents should also be included in the risk assessment.

In principle, Natech accident scenarios with indirect causes can be identified with an analysis of the processes and of the relationship between the different process variables. There are a number of tools used for this purpose in conventional major accident hazard identification and analysis (e.g., HAZOP, FMEA, FMECA, LOPA, Checklists, What-If analysis). However, there are several factors that increase the complexity of accident hazard identification when Natech accidents are involved.

One of the main difficulties to overcome is the tendency of risk analysts to simplify. Although simplification is necessary to complete any risk analysis, oversimplification can lead to the loss of important information. For example, some scenarios may be considered as extremely unlikely or even impossible under normal conditions since they require the contemporary failure of many systems at the same time. These scenarios are usually neglected in conventional accident risk analysis for the sake of simplicity and perceived cost effectiveness (Krausmann and Necci, 2021). However, the failure of multiple systems at the same time is exactly what characterises Natech accidents. Natural hazards are therefore an important common cause of failure in many systems. In order to identify indirect Natech hazard scenarios in this phase, **risk analysts should not exclude accident scenarios from the risk analysis based on their "presumed impossibility", unless a detailed study of the potential impact of natural hazards on the affected systems has excluded a natural hazard trigger as truly inconsequential**.

4.6 Natech consequence analysis

One of the main challenges for Natech risk management is the identification and analysis of sound Natech consequence scenarios. Consequences and their likelihood can be determined by modelling the outcomes of an event or set of events, by extrapolation from experimental studies or from available data. A consequence scenario consists of a loss of containment and a chain of events that leads to a physical effect (e.g., a fire, an explosion or a toxic dispersion) that has the potential to harm people, damage the environment or destroy assets.

Natech scenarios differ from those of other types of technological risks (cf. Natech characteristics in Chapter 2), and it is usually **misleading to reuse non-Natech consequence scenarios for analysing Natech events** unless it has been verified that the scenario conditions are the same. The loss of containment of hazardous materials that follows natural hazard damage should be assessed to successfully model Natech scenarios. Conversely, models for the assessment of the physical effects of Natech accidents do not differ from those used for the analysis of the consequences of non-Natech accidents. Dedicated technical information and guidance is available in Mannan (2005) and van den Bosch and Weterings (2005).

4.6.1 Loss of containment and critical events

Critical events (or top events) are at the beginning of the process that leads to the actual Natech accident. There are two types of critical events that can be triggered by natural hazards:

- Critical events due to direct damage to a vessel or a pipe that contains hazardous materials;
- Critical events following a process upset and the subsequent equipment rupture or system malfunction.

Most critical events result in the loss of containment of hazardous materials but there are other types of critical events as well, such as runaway reactions, deflagrations, or fire. However, for the sake of brevity, we will refer to all the immediate outcomes of critical events as LOCs. The most common types of LOC scenario can be borrowed from the scenarios used to model non-Natech types of technological accidents. Examples of typical loss of containment scenarios are reported in Table 4.

Table 4. Generic LOCs for different types of systems.

LOC event	Description	Systems that present this LOC type
Instantaneous release	Instantaneous release of the complete inventory of hazardous material	Atmospheric storage and process vessels, pressurised storage and process vessels, heat exchangers
Continuous release in 10 minutes	Continuous release of the complete inventory of hazardous material in 10 minutes at a constant rate	Atmospheric storage and process vessels, pressurised storage and process vessels, heat exchangers
Continuous release from a hole in the vessel	Continuous release of hazardous material from a hole with a known size	Atmospheric storage and process vessels, pressurised storage and process vessels, heat exchangers
Full bore rupture	Continuous release of hazardous material from a pipe that has been torn in two halves (effective release diameter equal to the nominal diameter of the pipe). Release occurs usually from both sides.	Pipes, pumps, heat exchangers
Leak	Continuous release of hazardous material from a pipe that is leaking (e.g. effective release diameter equal to a fraction of the nominal diameter of the pipe).	Pipes, pumps, heat exchangers
Release from pressure relief device	Discharge from a pressure relief device with maximum discharge rate	Pressure relief devices
Dispersion of stored powder	Dispersion of a fraction of the packaging unit inventory as a breathable powder	Warehouses
Dispersion of stored liquids	Spill of the complete packaging unit inventory	Warehouses
Emission of toxic combustion products	Emission of unburned toxics and toxics produced in the fire	Warehouses
Mass detonation	Mass detonation in a storage unit	Explosive storages
Fire in the storage	Fire in a storage unit	Explosive storages

Source: Uijt de Haag and Ale, 2005.

A major challenge in Natech risk assessment is how to associate a typical chemical accident LOC scenario to a specific natural hazard damage. There is no definitive guidance on how to perform this task and currently this association relies on expert judgement. When the damage model used is simple and specific to one damage mode, the expected damage can be easily associated with a LOC. However, specific models are scarce and not available for most equipment types. For this reason, Natech risk assessment is often performed using more generic damage models like damage states and fragility curves. In this case, the task of assigning a LOC scenario to the natural hazard damage becomes much harder.

4.6.1.1 LOC scenarios for damage states

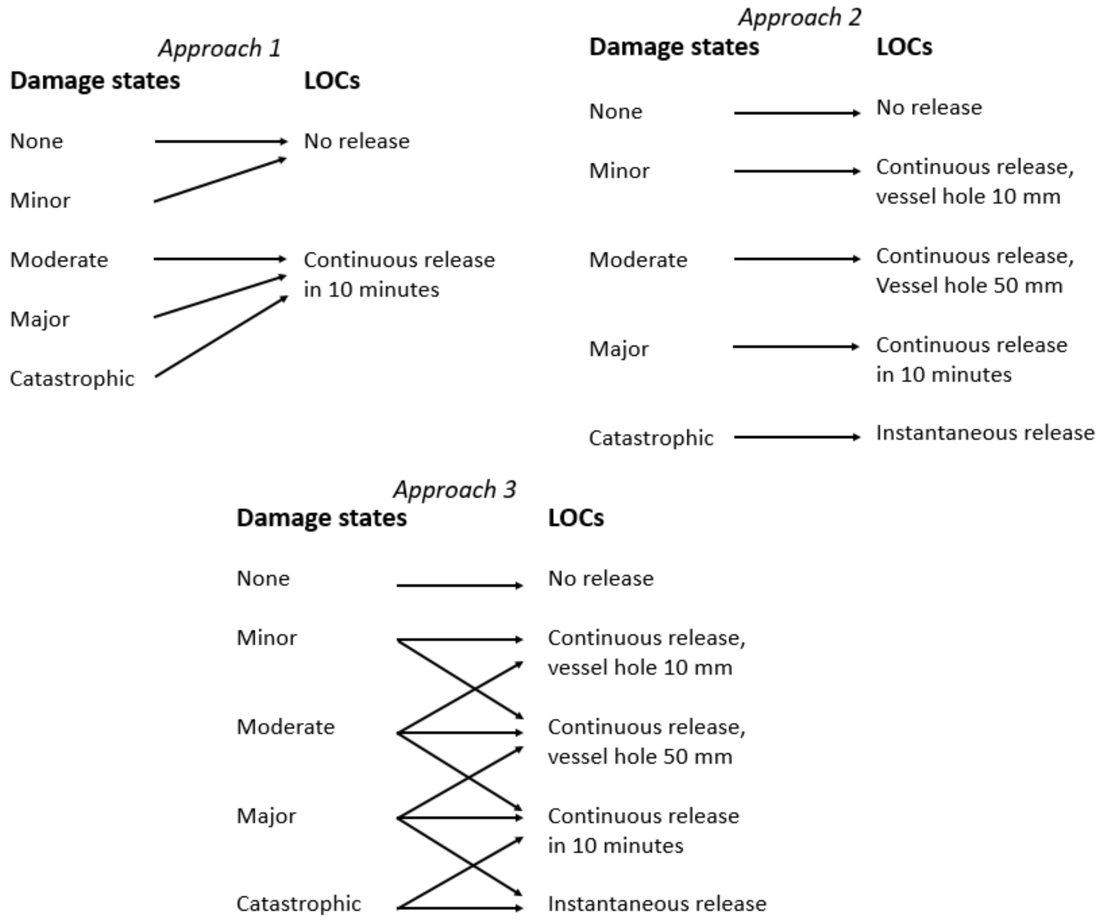
One common way to assess natural hazard damage to process systems affected by a known natural hazard impact is to use damage states as discussed in Section 4.5.1 (FEMA, 2015). Damage states do not provide a specific description of the damage, but a generic and qualitative description of the overall equipment status after the natural hazard impact. However, there is a recognized knowledge gap in this regard, since the statistics of natural hazard damage used to build damage states do not cover top events and LOCs, and vice versa. The task gets more complex when the damage model used provides many possible damage states resulting from the same natural hazard impact. When the only available damage estimation model is based on multiple damage states, there are three possible approaches to cope with the additional complexity:

1. **Assign the same LOC scenario to multiple damage states.** This solution is the simplest although the least accurate. Two categories of damage states are created: those than can produce a LOC and those that cannot. A frequent assumption is that damage states of the type “no damage” and “minor damage” would not result in a release, while all others would. The same LOC scenario is then linked to all damage states that can produce a release regardless of the extent of damage (e.g. LOC is “Continuous release in 10 min” for all damage states of moderate severity or greater). This approach has been applied in scientific studies on Natech risk assessment over the past years (Salzano et al., 2003, Antonioni et al., 2009)
2. **Assign a different LOC scenario to each damage state.** This approach is slightly more complex. Every damage state has its own LOC scenario (although there could still be two or more damage states with the same LOC). For example, LOC is “Continuous release from a hole in the vessel of 10 mm” for minor damage, “Continuous release from a hole in the vessel of 50 mm” for moderate Damage, “Continuous release in 10 minutes” for major damage and “Instantaneous release” for catastrophic damage. This approach has been implemented in the Natech risk analysis and mapping tool RAPID-N[4] (Girgin and Necci, 2018).
3. **Assign multiple LOC scenarios to each damage state.** This solution is the most complex, although it is also the most accurate. The hypothesis is that every damage state can result in many, or even, all possible LOC scenarios. However, the likelihood of each LOC scenario is taken into account with the use of probabilities. The probability of major LOC events is higher for severe damage states, while the probability of minor LOC events is higher for minor damage states. If damage states are incompatible with LOC scenarios (for example, a LOC scenario “leak” usually does not match with the “collapse” damage state), probability 0 should be assigned to that specific combination of damage state and LOC. This approach has never been used so far due to the additional complexity that it brings to the analysis. Moreover, to date, no statistical data is available to associate probabilities to LOC events and damage states.

The three approaches are summarised in Figure 11.

[4] RAPID-N is available free at https://rapidn.jrc.ec.europa.eu

Figure 11. Examples of the three approaches for the assignment of LOC scenarios to damage states.



4.6.2 Natech consequence scenario modelling

As mentioned in Section 4.4, natural hazard impacts can disrupt, damage or destroy control and auxiliary systems, as well as utilities, generating contributing factors to Natech accidents. Section 4.5.2 discussed how such damage can cause LOC and initiate an accident. This section discusses the repercussions of system unavailability on the outcome of the accident and provides indications on how to build sound Natech consequence scenarios that take into account the Natech characteristics listed in Chapter 2 and the contributing factors.

4.6.2.1 Natech chain of events

Safety barriers are physical or non-physical means implemented to prevent, control or mitigate hazardous situations or accidents (Sklet, 2005). Safety barriers may fail, or their performance can be reduced, during natural hazard impact because: 1) one or more of its components are damaged or rendered unavailable by the impact of the natural hazard, and 2) utilities and auxiliary systems, that are not part of the safety barrier but are required for its correct activation, are damaged or disrupted. When safety barriers function according to their design, the accident may be avoided altogether or its consequences are mitigated. When they fail to perform as planned, the result is an accident with unmitigated consequences (Misuri et al., 2021). **In Natech risk assessment, unmitigated accident scenarios should be considered when safety barriers are vulnerable to a natural hazard.**

Safety barriers also prevent accidents, like fires and explosions, from spreading to nearby installations. When a Natech accident propagates to nearby sites or installations causing one, or more, “secondary” accidents, the process is known as domino effect (Reniers and Cozzani, 2013). When the consequences of a secondary accident are larger than those of the “primary” accident, the accident has “escalated”. **In Natech risk assessment, the possibility of escalated scenarios should be considered when safety barriers are vulnerable to natural hazard impact**. Escalated scenarios often feature simultaneous accidents even when the primary Natech scenario is a single release scenario (see Section 4.6.2.2).

4.6.2.2 Simultaneous accidents

One of the main complications of Natech accidents is the possible **presence of multiple LOC events at the same time**. This can be addressed by considering all possible accidents that may follow the natural hazard impact. In order to do so, all scenario combinations composed of all couples, triplets, quadruplets, etc. must be considered. **Each combination represents a different Natech accident scenario that can be assessed**. However, the complexity of this approach increases exponentially with the number of scenarios considered. In general, **the higher the number of the accidents in a given combination, the lower is its probability**. This approach has been demonstrated by, e.g., Antonioni et al. (2009) who calculated the combinations for the simplest case using a Boolean logic (1 = Natech accident occurred; 0 = Natech accident did not occur). Once all the combinations are identified, the scenarios (combinations) that are the most relevant for risk assessment are considered, while the others are discarded. Establishing which combinations are the most relevant is not an easy task. In general, combinations that are more relevant are those with a higher probability of occurrence. However, combination of events that may result in catastrophic consequences with low probability should not be carelessly dismissed as they may represent high-impact low-probability (HILP) events.

In addition, in some combinations one accident may be significantly more prominent than the other(s). In these cases, the consequences of a combination of accidents or of the most serious accident alone would be very similar or even the same. In such cases, no scenario combinations are needed but it is sufficient to consider only the scenario with the largest consequences.

Another issue of simultaneous scenarios is how to consider the impact of two or more different effects on the same target, for instance an individual person. As discussed in Antonioni et al. (2007), the impact of two or more accidents can be assessed in different ways by a) adding the values of the harmful physical effects (e.g. thermal radiation), b) adding the doses (e.g. toxic dose) to which individuals are exposed, or c) adding the vulnerabilities of the target (e.g. death probability). Of these approaches, the third allows the assessment of combined vulnerabilities that are given by the different types of events (e.g. fires and toxic dispersions), while the first two can add the effects of accidents of the same type (e.g. two fires) (Cozzani et al., 2005). Using the third method, the combined vulnerability of *N* individual events as the union of vulnerabilities of all events is:

$$V_{\mathrm{com}} = \bigcup_{i=1}^{N} V_i \tag{1}$$

where V_{com} is the combined vulnerability of the *N* accidents and V_i is the vulnerability of each single accident *i*. It must be noted that, in principle, the values of the vulnerabilities are dependent on each other (e.g. a person may be more likely to die if she survived the impact of one accident, since she may have suffered injuries or been poisoned). However, data to support the impact of cumulative effects of different accidents on potential targets (e.g. humans) are scarce or missing. Therefore, the most common approach is to consider all events as independent. An example of the use of the independence hypothesis in the case of two separate accidents, a and b, is given by the following equation:

$$V_{\mathrm{com}} = V_{\mathrm{a}} + V_{\mathrm{b}} - V_{\mathrm{a}} \cdot V_{\mathrm{b}} \tag{2}$$

4.6.2.3 Environmental conditions

When determining the accident’s consequences, standard models are used that assume reference environmental conditions. However, some natural hazards can change the environmental conditions around industrial plants and it is important that the scenarios are modelled using appropriate values for the environmental parameters. These values must be coherent with the conditions of the triggering natural hazard scenario. For accidents triggered by flood, not only the intensity of the natural hazard (flood depth and speed) needs to be known, but also the direction in which the water is flowing. Released flammable and toxic substances can be carried over large distances by the floodwaters, possibly spreading fires or pollution to areas at a notable distance from the spill location (see Figure 12). Examples of the parameters used in standard models for accident consequence analysis and that may change during natural hazard impact are reported in Table 5.

Figure 12. Fire spreading on the water surface and dispersal with the floodwaters.

Source: USGS

Table 5. Examples of the effects of natural hazard impacts on environmental parameters used for consequence modelling.

Environmental parameter	Possible effects of natural hazards
Ambient temperature	Some natural hazards, like heat waves or freeze can only occur at specific (extreme) values of ambient temperature.
Wind speed	Storms and tornadoes require high values for the wind speed parameter.
Atmospheric stability	For storms and other atmospheric phenomena, one must choose values of the atmospheric stability from among the unstable classes.
Terrain roughness	Buildings and other obstacles (e.g. trees) can be destroyed by natural hazards like earthquakes, thereby possibly affecting the atmospheric dispersion of hazardous materials. Similarly, other natural hazards, like floods and storm surge may sweep new obstacles inland (e.g., silos, ships, barges), changing the surface roughness.
Soil/ground conditions	Ground can rupture or liquefy under the effect of earthquakes, increasing or decreasing its granularity. In the case of floods, the ground is assumed to be covered with water, which also changes the granularity. Snow and ice also affect the ground conditions significantly, as well as the presence of debris scattered all over the place.

4.6.2.4 Exposure and vulnerability of endpoint receivers

Compared to other types of technological accidents, endpoint Natech risk receivers are also influenced by the natural hazard. While typically only extreme natural events have a major impact on the population, the effects of natural hazards vary case by case, depending on the nature of the hazard and its intensity. These effects should be evaluated separately for each natural hazard that may involve the industrial site. Examples of effects of natural hazards on endpoint receivers are:

- The **number of people at risk may be reduced** compared to a regular day. On the one hand, the natural hazard may cause mass evacuation before the Natech accident happens. On the other hand, there may already have been fatalities due to natural hazard impact.
- The **exposure of the population might be increased**, as they might **not have any possibility to shelter in place**, as buildings may have collapsed or been heavily damaged. Also, people trapped under collapsed buildings are unable to escape and get to safety, while their families and the rescue teams may be unwilling to leave them behind.
- **The environment may be more susceptible to pollution** due to chemicals or hydrocarbons when it has already been damaged by the natural hazard.

To understand how the calculated physical effects of a LOC affect the population, standard vulnerability models can be used and no Natech-specific models are needed. For example, toxic effect models quantify the impact on human health of exposure to toxic gases, using thresholds, such as Median Lethal Concentration, Median Lethal Dose, or Immediately Dangerous for Life and Health (IDLH) concentration. Thermal radiation models assess the impact of radiation intensity on people (e.g., burn injuries, damage to structures), while shock-wave overpressure models aim to quantify the effects of overpressure from explosions (TNO, 1992). For all three types of phenomena, probit functions can also be used to quantify the vulnerability of the population to the effects of a LOC. Where data are insufficient for a quantitative analysis, qualitative consequence categories (e.g., minor, serious, very serious, major, catastrophic) can be defined and used instead.

4.7 Natech likelihood assessment

Risk analysis is by definition the analysis of the likelihood of an unwanted event. In process safety unwanted events are not all equal. This is the reason why risk is typically considered as a function of both likelihood and consequences. Here, the unwanted events are Natech accidents and their potential consequences. Assessing the likelihood is crucial for the evaluation of the risk and the prioritisation of investments for cost-effective Natech risk reduction. The most common way to assess Natech likelihood is to use probabilities but for some hazards, where uncertainties are large, qualitative likelihood descriptors are adopted. For Natech accidents, the Natech accident probability and the natural hazard probability are inherently linked. In fact, the probability of a Natech scenario is bigger if the natural hazard is a frequent event. Moreover, the probability of a Natech accident can never exceed that of the triggering natural hazard scenario.

Natech scenarios are complex events that are composed of a natural hazard scenario, a top event (or critical event) scenario and a consequence scenario. The probability of the Natech scenario is calculated as the joint probability of all these three events combined. Therefore, Natech probability assessment is composed of the following steps: First, the probability of the natural hazard is assessed using natural hazard statistics or modelling. Then the probability of the top events (e.g. LOC for a specific equipment) for the given natural hazard scenario is assessed using ad-hoc methodologies and the probability of the natural hazard as input. Finally, the probability of the Natech consequence scenarios can be determined with the use of event trees or equivalent methods. These methods allow the assessment of the probability of the many Natech consequence scenarios that may result from every critical event when conditions change (e.g., ignition/no ignition, safety barrier availability/unavailability). Equations (3) – (5) summarise the relationship between the probabilities of a specific Natech accident scenario, the probability of the critical event and the probability of the natural hazard scenario:

$$\mathrm{P(Top)} = \mathrm{P(Haz)} \cdot \mathrm{P(Top|Haz)} \quad (3)$$

$$\mathrm{P(Nat)} = \mathrm{P(Top)} \cdot \mathrm{P(Nat|Top)} \quad (4)$$

or combining Equations (3) and (4):

$$\mathrm{P(Nat)} = \mathrm{P(Haz)} \cdot \mathrm{P(Top|Haz)} \cdot \mathrm{P(Nat|Top)} \quad (5)$$

where $\mathrm{P(Nat)}$ is the probability of a specific Natech accident scenario, $\mathrm{P(Top)}$ is the top event (or LOC) probability, $\mathrm{P(Haz)}$ is the probability of the natural hazard, $\mathrm{P(Top|Haz)}$ is the conditional probability of a top event for a given natural hazard, and $\mathrm{P(Nat|Top)}$ is the conditional probability of the Natech scenario given the critical event.

As discussed in the previous sections, conducting Natech risk analysis is challenging as data availability is still insufficient. For this reason it may be difficult or even impossible to find reliable data for the calculation of the Natech scenario probability. In this case, it may be preferable to provide a qualitative description of the Natech scenario likelihood (e.g., very likely, likely, possible, unlikely, rare) that helps to establish a relative ranking among the identified Natech scenarios.

4.7.1 Release/top event likelihood

There are two main categories of top events:

- Natech accidents that result from direct natural hazard effects (damage) on the container structure (see Section 4.5.1);
- Natech accidents that are produced by indirect causes, e.g., due to natural hazard induced loss of utilities (for example blackouts) (see Section 4.5.2).

For the first category, the top event likelihood can be directly related to the probability that the equipment is damaged by the natural hazard impact. In this case, damage usually results in a LOC immediately, although sometimes the damaged equipment may maintain containment. The probability of loss of containment should consider this possibility. Equations (6) and (7) summarise the composition of the top event probability for a given damage scenario that may or may not result in a top event:

$$\mathrm{P(Top)} = \mathrm{P(Dam)} \cdot \mathrm{P(Top|Dam)} \tag{6}$$

$$\mathrm{P(Dam)} = \mathrm{P(Haz)} \cdot \mathrm{P(Dam|Haz)} \tag{7}$$

where $\mathrm{P(Top)}$ is the top event probability, $\mathrm{P(Dam)}$ is the damage probability, $\mathrm{P(Top|Dam)}$ is the conditional probability of a top event for a given damage, and $\mathrm{P(Dam|Haz)}$ is the conditional damage probability for a given natural hazard. While damage probability is typically not difficult to assess, there are almost no data relative to the conditional probability of top events given the damage. For this reason, the most common assumption is to consider the top event probability equal to the damage probability. The assessment of the damage likelihood is discussed in more detail in Section 4.7.1.1.

For the second category, the critical event probability can be assessed using known methods like HAZOP, LOPA, fault trees, FMEA, FMECA, etc. The challenge is to build the relations in a way that the Natech characteristics mentioned in Chapter 2 are properly considered. For this purpose in particular, it is crucial to consider the failure of safety barriers and auxiliary systems, the simultaneous failure of units and systems, and the inadequacy of some of the most common response strategies and activities.

4.7.1.1 Damage likelihood

Damage likelihood is always assessed using the relevant intensity parameter of the natural hazard (e.g., peak ground acceleration, water height, wind speed). This parameter must be linked with one, or more, damage modes. The simplest method to assess that damage has occurred is to consider that containment has failed when the design specifications of the unit are exceeded by the natural hazard intensity parameter with a “Yes/No” logic. In this case, the failure likelihood can be assessed as the probability of occurrence of a natural event that exceeds the design specification of the equipment. When the natural event is described as one discrete scenario, the probability of damage for a specific natural hazard scenario $\mathrm{P(Dam|Haz)}$ is equal to 1 if the value of the intensity parameter of the natural-hazard scenario exceeds the design specifications, while $\mathrm{P(Dam|Haz)}$ is equal to 0 if the design specifications are more stringent than the value of the intensity parameter.

A typical method for assessing damage probability for a specific natural hazard scenario is the use of damage states and fragility curves (Eidinger et al., 2001; FEMA, 2015). Different curves are available for assessing the damage probability of industrial equipment, instrumentation, and utilities in case of natural hazard impact (FEMA, 2015). Fragility curves and damage modes for common equipment types have been provided in several studies (FEMA, 2015; Eidinger et al., 2001; Cooper, 1997; Landucci et al., 2012).

Fragility curves may be associated with a vast array of damage types. For the sake of simplicity, all these types of damage are usually divided into damage classes (see Section 4.6.1.1). Fragility curves typically provide probability values for each damage state. Some or all damage states may result in one or more critical event(s).

One possible method to reduce the complexity of the analysis is to consider only one reference LOC scenario (see Approach 1 in Figure 11). In this case all damage states that equal or exceed a certain damage level (e.g. moderate damage or greater) will be considered as triggering the selected LOC scenario and their probabilities are added. This method has been applied in past studies (e.g. Antonioni et al. 2007; 2009; Salzano et al., 2003).

4.7.1.2 Likelihood of critical events due to direct damage

As mentioned in Section 4.6.1. it is difficult to assign one type of critical event to one specific damage type, let alone to assign a probability value to it. Analysis of past accidents showed that **not all damage caused by natural hazards has actually triggered a release**. As of today, no study has ever investigated the statistical relationship between damage and release; all available data is qualitative. Moreover, there are certain types of damage that inevitably result in a release. For example, pipe network rupture (or detachment), total collapse of a vessel, and detachment of the shell-to-bottom connection of a tank result in release 100% of the time ($\mathrm{P(Top|Dam)} = 1$), provided that the damaged equipment is at least partially full. On the other hand, there are types of damage that, on its own, never results in a release ($\mathrm{P(Top|Dam)} = 0$). For example, some types of roof damage or buckling damage may never produce a release.

This type of assessment becomes even more complex when damage states and fragility curves are used to assess equipment damage and its probability. For some types of equipment, even a damage state that is considered “minor” can result in a release. Also, damage levels that are more severe are more likely to result in a release. With these uncertainties, it is recommended to use a value of 100% for the critical event probability whenever doubt exists. Generally, experts in process safety, aided by structural engineers, are the best qualified to assess the critical event likelihood.

4.7.1.3 Probability of indirect Natech accidents

Indirect accidents can be triggered via process upsets caused by the impact of a natural hazard on the industrial plant. Process upsets are also routinely evaluated as a cause of (non-Natech) technological accidents. Accordingly, the same methods can be used to identify critical events (e.g. checklists, what-if analysis, HAZOP, FMEA/FMECA) and to assess the damage/failure probability (e.g. fault trees, bow ties). However, one or more components of a system may be damaged by a natural hazard, disrupting important control and auxiliary systems. Therefore, **particular attention should be paid to the identification of the “cut sets” in which one (or more) component is vulnerable to natural hazards**. In this case, the reference reliability values of components (typically retrieved from common reliability data sources) and systems may change significantly due to the possibility of natural hazard damage.

It is challenging to estimate the damage probability for systems (and their components) because structured and systematic studies on equipment vulnerability exist only for some of the most common equipment types, in particular storage tanks (Cooper, 1997; Landucci et al. 2012; Eidinger et al., 2001). In this regard, reliability values of components hit by a natural event should be chosen carefully. Many protection and control systems are unreliable or unavailable during natural hazard impact. **Systems unable to survive the natural event should be considered as failed (reliability equal to 0) in any critical event probability assessment** (e.g., using fault trees or similar methods). When the assessment of the components’ survivability is uncertain, the most conservative approach is to consider the system (or component) failed, unless it has been specifically designed to withstand the natural hazard, and the scenario used for the design has an intensity equal or higher than that used in the assessment.

Whenever available, fragility curves should be used to estimate the probability of damage to the analysed component or system (e.g. tailored fragility curves for the affected components). This probability value could be used to assess the system reliability (or availability). One simple way to assess the reliability using the damage probability is to consider the lower value between the reference value of the component’s reliability (retrieved from reliability databases, e.g., European Safety, Reliability & Data Association (ESReDA), Offshore and Onshore Reliability Data (OREDA)) and the complement to 1 of the estimated damage probability.

Box 6. Example: Simple reliability estimate

A hypothetical blowdown system is attached to a flare which has a reliability of 99%. There are two natural hazards of concern at the site, earthquakes and strong winds. According to the analysis performed for the earthquake scenario, the flare has a damage probability of 10^{-3} if this scenario occurs. This means that the system is less likely to fail due to the earthquake than on its own. The reliability of the system would still be 99% for the earthquake scenario. According to the analysis performed for the strong wind scenario, the flare has a damage probability of 10^{-1} if this scenario occurs, which means that the system is more likely to fail due to strong wind than by other generic causes. For the strong wind scenario, the reliability of the system should be considered as 90% instead of 99%.

4.7.2 Natech-specific event trees

Event trees can be used when assessing the likelihood of Natech consequence scenarios that may arise from every Natech critical event. These logic graphs are typically used when many scenarios can result from a single event (the critical event). Each scenario is derived considering the occurrence, or non-occurrence, of one or more intermediate events. One example of event that may change the outcome of the Natech accident is the activation of a safety barrier. Successful safety barrier performance results in a mitigated scenario, while unsuccessful performance results in an unmitigated scenario. Other examples of events that determine the outcome of the scenario can be, e.g., the occurrence of ignition or the presence of a secondary containment. **While determining the event trees, the specific conditions of the Natech scenarios should be taken into account, including all the contributing factors.** This applies to the types of events that are relevant in the event tree, but it also applies to the probabilities assigned to the successful and unsuccessful occurrence of each event.

For instance, the value of the ignition probability of flammable substances can be considered equal to 1 in case of accidents triggered by lightning strikes, as lightning itself is an ignition source. Similarly, for Natech scenarios triggered by major floods, secondary containment (e.g. a dike) – even if present – should be considered absent since it would be filled with water and could not contain the spilled substance.

When the success of the event is determined by the activation of a complex system (i.e., composed of many different components that could fail to activate), fault trees may be used to assess the overall reliability of the system. In this case, the overall reliability of the system should take into account both the natural hazard scenario and the Natech critical event. In particular, due to the natural hazard, some components may have one (or more) **common cause(s) of failure**. Furthermore, all components that are considered failed as condition for the Natech critical event to occur should also be considered failed in the event tree.

Given any Natech critical event, all components that were considered as failed (or unavailable) when assessing the Natech critical event must be considered failed also for all other events that follow. For instance, if one critical event is caused by power loss, then all events that follow that critical event must also consider power loss as a fact (probability equal to 1). The reliability (i.e. the survivability) of all other components of the safety systems that are affected by the natural hazard should be analysed as well, as standard reliability values may not apply.

Box 7. Examples of event trees affected by natural hazard impact

Systems are unavailable

In one hypothetical scenario, the water network that feeds the firefighting system has been damaged by an earthquake, allowing a tank to be damaged by a nearby small electric fire and release flammable fuel (top event). Normally, the fire resulting from the spill of flammable fuel could be mitigated by the firefighting system; however, because the firefighting system is considered failed as a condition for the critical event to occur, it cannot mitigate the consequence of a possible second larger fire.

Failure on demand is increased because of loss of redundancy

In one hypothetical scenario, the natural hazard has damaged the power network of a chemical plant, leading to a process upset and ultimately to the release of a flammable liquid. The firefighting system uses two redundant pumps, one powered by an electric engine and one powered by a diesel engine. The fire resulting from the spill of flammable fuel can be mitigated by the firefighting system; however, since the power network is down, the firefighting system can only rely on its diesel-powered pump. As a result, the firefighting system has a higher chance to fail on demand.

Failure on demand is increased because of possibility of damage

In one hypothetical scenario, a shut-down valve is vulnerable to an earthquake scenario, however, its failure is uncertain. A damage probability is calculated for the component as high as 10%. Its reliability in normal circumstances would be 99.9%. Because of the very concrete chances for damage, the analyst reconsiders the valve reliability to be only 90% (see Section 4.7.1.3).

4.8 Natech risk evaluation

The likelihood and consequence information calculated in the previous sections of Chapter 4 needs to be combined to present the total risk in a format that is useful for the decision-making process. This is often referred to as risk integration. This process is the same for Natech or non-Natech types of risk and only depends on the risk analysis approach chosen. If a quantitative risk analysis has been performed, the resulting risk measures are usually *individual risk* (e.g., the risk to an individual at a particular location – individual risk curves) and *societal risk* (the risk of, e.g., 100 or more fatalities – F-N curves). If the analysis carried out is qualitative, the likelihood and consequence severity classes are combined in a *risk matrix*. For a more detailed discussion of risk integration approaches, as well as their advantages and disadvantages, the reader is referred to Cox (1998).

Natech risk analysis helps the operators to detect system weaknesses and set priorities for risk reduction, e.g. via the ranking of identified risks. At the same time, the outcome of the risk analysis can be used for comparison with accepted risk targets or criteria (risk evaluation) in compliance with a country's regulatory requirements. Should these criteria not be met, risk reduction measures need to be implemented. In the European Union such risk criteria are not uniform and they can be risk-based (e.g., acceptable levels of individual risk) or consequence-based (e.g., permissible levels of overpressure, heat radiation or toxic concentration). For Natech risk evaluation, approaches typically used for chemical accident scenarios can also be applied and no Natech-specific extensions are needed.

5 Measures to reduce Natech risk

Hazardous industrial sites with a relevant Natech risk should implement both technical and operational measures to prevent Natech accidents that they have identified in their risk analysis and to mitigate their consequences. Priority should be given to the prevention and mitigation of the Natech accidents whose risks are higher, or for which the uncertainties in the assessment are large. This section discusses the resources and procedures necessary for operators to manage Natech risk at hazardous sites.

5.1 Natural hazard impact mitigation

One of the main strategies for mitigating Natech risk is to protect the sites, or their critical installations from the impact of all relevant natural hazards. This is achieved by reducing the severity of the natural hazard that is expected on the site via implementing physical or procedural prevention measures.

5.1.1 Physical measures

Examples of possible strategies to mitigate natural hazard impact are:

- **Building of levees** around exposed sites to protect them from floods;
- **Building of artificial channels** that convey flood waters away from the site**;**
- **Erection of sea walls that** mitigate the effects of coastal floods, storm surge, and tsunamis;
- **Riverbank stabilisation** to prevent erosion and spill-over when a river swells;
- **Soil compaction/stabilisation** to mitigate the potential ground motion effect of earthquakes;
- **Rearranging of the plant layout** by moving critical equipment to areas where it is less exposed to natural hazards (e.g. outside the floodplain area);
- **Erection of elevated dry areas** where safety-critical systems should be placed in case the site is located in an area with flood or tsunami hazard (e.g., control rooms, electric substations, firewater reservoirs and pumping rooms, backup power generators);
- **Installation of lightning protection systems** to protect the power network and the installations where flammable substances are stored;
- **Selecting the location of the site** outside of natural hazard zones or where the natural hazard severity is the lowest (e.g. outside floodplains, at a distance from known earthquake fault lines).

Some of these actions can be taken during the operational phase of an industrial plant's life, while others are restricted to the design phase. In general, it is safer and cheaper to avoid natural hazards, rather than to protect the installations from impacts.

5.1.2 Procedural measures

Natural hazards can generate large losses and threaten the life of the personnel inside an installation. Operators should identify specific procedures that define the actions to be taken in response to natural hazard impacts and early warning provided by the relevant authorities.

Procedures to cope with natural events should include:

- The roles and responsibilities of personnel within the installation;
- The list of actions to be performed by each role;
- The amount of time each action takes;
- The exact conditions that initiate the procedure.

Personnel should be aware of the natural hazards the site may be subject to. Also, they should be trained in the procedures to adopt in case of natural hazard impact. Procedures should be aimed at increasing the chance of survival for staff, especially for those that cover key roles in the response to Natech accidents, while at the same time preventing the occurrence of Natech accidents.

5.1.2.1 *Before the event*

When forecasts predict a natural hazard in the following days or hours, actions can be taken to prepare the site for a possible impact. Natural hazards have different onset times, depending on their nature. While a hurricane can be forecast several days before its landfall, other types of storms and atmospheric phenomena may only offer a lead-time of a few hours. In general, earthquakes cannot be anticipated in advance. Nevertheless, if the epicentre is sufficiently distant from the industrial plant, operators may have a very short warning time (usually seconds, sometimes more than one minute) to react before the site is hit by the earthquake's shockwaves. Procedures can be effective in avoiding or mitigating Natech accidents if actions are taken in a timely manner.

For each natural hazard, the conditions under which emergency procedures should be activated must be clearly identified (e.g. when a nearby river swells above a critical threshold, when a hurricane warning is called). It should be noted that different actions may activate under different conditions. The following list shows some of the most recurrent and effective actions that can be taken in preparation for natural-hazard impact:

Emergency shut-down: The operator evaluates the need to shut down the installations. If the processes are halted when the natural hazard hits, Natech accidents are less likely to occur.

Ride-out crew: Removing all unnecessary site personnel before a natural hazard hits helps to reduce the potential loss of life associated with Natech events. This includes, in particular, all external contractors. The operator should identify a ride-out crew with the minimum amount of personnel needed to secure the site and to implement emergency procedures. Since some natural hazards can last for days, operators should organise the workload in shifts to guarantee the turnover of the ride-out crew and to ensure that the needed response activities are not interrupted in the middle of the emergency.

Securing floating objects: Accidents can be caused by objects floating on floodwaters and impacting critical installations. This can be prevented by securing floating objects, e.g. with straps, or by removing them from the site in case of a flood.

Securing equipment: Light equipment is vulnerable to the uplift force exerted by floods. Some equipment could be secured with bolts anchored to the ground. Empty tanks could be filled with water to increase their resistance to floating due to flooding.

Applying temporary natural hazard defences: Some installations can be protected from the impact of the natural hazard by applying defences that mitigate the natural hazard impact in the protected area (e.g., set up portable dikes, barricade windows with plywood shields, seal doors of rooms with electric equipment).

Communication with the authorities: Authorities responsible for the external emergency plans should be warned when a natural event is about to occur, or is already occurring, and the operator suspects that Natech accidents could be triggered.

Training: Ensure that employees are aware of the natural hazard(s) at the site and that they are properly trained in the procedures to cope with their impacts.

Natural hazard monitoring: The operator follows the formation and evolution of natural hazards in their area. Those of atmospheric origin, like storms, snow and extreme temperatures, can be easily monitored via weather forecast services and following the early warning from the local civil protection entities. Likewise, authorities that already monitor natural hazards through dedicated agencies should be pro-active in warning sites with major accident potential of approaching natural hazards in a timely manner to allow operators to take effective preventive action and to prepare.

5.1.2.2 *After the event*

Even if a natural hazard did not trigger a Natech accident immediately, industrial plants should be extra careful in the aftermath of an impact and when resuming normal operations. Natural disasters may leave in their wake damaged equipment, contamination to clean up, and failures that may have gone unnoticed. Moreover, under such conditions, staff is usually more stressed and distracted. The start-up of major industrial processes is a hazardous phase in itself, even more so after the impact of a natural hazard. It is conceivable that some damage caused by the event may not be immediately noticeable, or that conditions are not safe for a restart (e.g. equipment soaked in water). It is therefore extremely important that procedures for start-up include actions that take into account possible prior natural hazard damage, such as (USCSB, 2005; CCPS, 2019):

- Inspecting damaged equipment and instrumentation to spot hidden failures before starting-up;
- Securing all units and restoring all safety systems that were turned off;
- Completing the required repair, maintenance, and clean-up operations, including the removal of rubble and debris produced as a result of the damage or brought on site by the natural event;
- Managing the workforce effectively and in particular waiting with start up until all essential personnel who suffered harm, injuries or losses (including taking care of their houses and family members) have recovered or have been replaced (including training of new personnel);
- Making sure that the site has all the necessary supplies, as there may be a scarcity of construction materials after a disaster;
- Recommissioning is needed for sites or installations that suffered extensive damage.

5.2 Equipment design and retrofitting

Risk can be reduced by increasing the resistance of the installations and preventing natural hazard damage. Critical process and storage units should be designed to withstand natural hazard impacts. **Existing equipment units that may be damaged by natural hazards, causing a significant Natech risk, should be retrofitted to improve their ability to survive natural events** (e.g. installation of flexible pipe-tank-pump connections, anchoring of equipment, elevated supports, waterproof shelter for electrical equipment). Figure 13 and Figure 14 show examples of implemented retrofitting strategies.

When the Natech risk has been analysed and it is evaluated as unacceptable, despite the units having been designed according to state-of-the-art standards, then the criteria used for the equipment design should be changed. One way to do this is to change the way designers choose values of the “limit states” used in equipment design (see Section 4.3) by considering the results of a preceding Natech risk assessment. Setting higher values of the limit states means that the unit can survive natural hazards with higher intensity than before and that failures are less frequent. Values of the limit states could, for example, be chosen using a risk-based approach that takes into consideration the results of the Natech risk assessment and which ensures that the risk of Natech accidents remains below a specific target level.

Figure 13. Additional bracings to reinforce the support legs of a spherical storage tank against earthquakes.

Photo credit: E. Krausmann

Figure 14. Installation of a flexible steel pipe at a large oil tank to allow for displacement of the tank and piping.

Photo credit: A.M. Cruz

5.3 Safety barriers and auxiliary systems

The same consideration applies to safety barriers and auxiliary systems that are critical for Natech accident prevention or consequence mitigation. **Such safety barriers and auxiliary systems should be designed to withstand the particular natural hazard that is the Natech trigger.** It is important that critical systems are identified and assessed. Priority should be given to the systems that are involved in the accident scenarios that provide the largest contribution to the Natech risk. The reliability of safety barriers and auxiliary systems with respect to natural hazard impact can be improved in different ways, such as:

System design: Systems can be designed to resist natural hazard impact. The design goal should be that the system as a whole does not lose its function during a natural hazard impact. For example, a firefighting system in a seismic area should be designed in such a way that it performs reliably even during a strong earthquake.

Retrofitting: When not designed specifically for a natural hazard, systems can be retrofitted to perform better when hit by a natural hazard.

Redundancy: Systems can be made more reliable with redundancy. The redundancy can be included within the system for its most critical parts, or the entire system can be redundant. In order to prevent Natech accidents effectively, **redundant systems should not fail under the same natural hazard conditions** which is, however, not easy to do for sites with multiple hazards. For instance, in a system with two redundant pumps one can be mounted on an elevated support, away from the flood hazard, while the other one can be built at ground level with a sturdy foundation which is a better arrangement in case of earthquakes.

Mitigating the natural hazard impact: Auxiliary systems and safety barriers can be shielded from the effect of natural hazards in a similar manner as discussed for the main equipment units (Section 5.1).

5.4 Emergency planning and response to Natech accidents

Emergency plans for Natech accidents may include particular actions due to the characteristics of Natech accidents which are important to consider for response to be effective. Some of the strategies used for responding to other types of technological accidents may not be effective or appropriate during a natural hazard impact, meaning that Natech accidents require targeted emergency planning. In particular, operators should ensure that the implemented accident prevention and mitigation measures will be effective even during natural hazard conditions, e.g., during earthquakes, floods, heavy precipitation, high winds or extreme temperatures. When this is not possible, **measures that are not effective in an emergency situation should be considered unavailable, and the emergency plans should not rely on such measures.**

Since many natural hazards have the potential to down utilities, such as the power grid, or the local aqueduct, stand-alone utilities at site level (e.g., power generators, onsite water networks and reservoirs) should remain available even after the impact of a natural hazard has occurred. For this reason, **hazardous sites in natural hazard zones should have back-up utilities and sufficient emergency resources to keep the operation running until offsite services become available again, or until the installations have all shut down safely**. Emergency plans should clearly state which utilities can be guaranteed to remain available. If their continued service cannot be assured, the emergency plan should not rely on it. Accordingly, **emergency plans should include response strategies to adopt when both the main and backup utilities are unavailable**.

The operator should evaluate the timing of natural hazard impact and compare it to the timing of the emergency procedures in place at the site, with a view to **address potential time gaps between when an emergency measure is needed and when it might be available**. This should include potential sources of delay that the natural event itself may impose. For instance, the main communication networks (e.g., phone lines, the internet, SMS) may be disrupted during a natural event. This can create delays when contacting the local authorities for the initiation of the external emergency plans. Furthermore, **natural hazards can hamper access to the site** (e.g., roads destroyed, inundated or obstructed by debris), **delaying the intervention of external responders**.

Plant personnel and responders should be protected from both the natural hazard impact and the effects of Natech accidents, using specific personal protection equipment (PPE). Furthermore, the operators should consider purchasing **specific emergency equipment to better respond to major accidents (both Natech and not Natech) during exceptional conditions (e.g. storms, earthquakes, floods)**. The type of equipment should be chosen carefully to ensure responders' effectiveness and safety, taking into account the actual on-site natural hazards (e.g. life jackets and boats in case of floods or tsunamis; tractors and machinery for debris removal in case of earthquakes or windstorms).

When a natural hazard with the potential to down lifelines is identified, the operator should have ready alternative means of communication with the authorities should a major accident occur. For example, operators could use portable radios with autonomous power source, and a reserved direct radio channel should be open to reach the authorities under any conditions.

Plant personnel may themselves fall victim to the effects of natural disasters. Moreover, the duration of the emergency situation could extend over hours or days, adding burden on exhausted staff that may be asked to work during several shifts in a row. Preparedness should therefore aim at training personnel to effectively respond to natural disasters, maximising their chances of survival and allowing them to join the response activities against Natech accidents. **Emergency plans should, however, also consider the unavailability of personnel on site** (e.g. due to the natural disaster, panic and flight behaviour) **and designate adequate replacement for the manpower lost in the natural disaster** (Krausmann and Salzano, 2017). Plans should include procedures to ensure constant turnover of fresh responders.

5.5 Learning from past Natech accidents

Accident analysis is an essential tool in which information on the causes, dynamics and consequences of past accidents, including all circumstances that facilitated their occurrence, is used to prevent or better mitigate such accidents in the future. One of the reasons that accidents keep occurring is that lessons from past events have not been learned or were disregarded (Krausmann and Necci, 2021).

Accident analyses provide insights into the most common equipment damage and failure modes after natural hazard impact, hazardous materials release paths and consequences, or types of process and storage equipment that are particularly vulnerable. For example, in-depth studies of a pool of available

Natech accident data have shown that atmospheric storage tanks (and especially those with floating roofs) are particularly vulnerable to earthquake, flood and lightning impact. Individual case histories also indicate a high susceptibility to damage from heavy rain and high wind. Such studies also suggest that during Natech accidents the ignition probability is higher than during accidents caused by human or technical error (Krausmann et al., 2017). Similarly, accident analysis allows the identification of contributing factors that may have led to the accident in the first place or resulted in the aggravation of its consequences (e.g. Necci et al., 2018b).

Learning lessons requires the systematic collection and analysis of past accident data, including of near misses. **Operators should collect detailed information about past Natech incidents at their plant(s), store it in an interactive database that can be interrogated, and carefully analyse the data sets to help them prepare updated scenarios and design appropriate risk reduction measures**. Analysis of a single accident provides immediate lessons for that specific event; it might, however, miss accident causal patterns not easily recognisable within a single accident. Analysis of a set of accidents from a broader data pool provides lessons that are more widely applicable (Krausmann et al., 2017). This may, for example, help to identify organisational weaknesses that are systemic and require improvement, or causes associated with certain types of substances or industrial activities.

General accident data can also be retrieved from industrial accident databases but the quality of Natech accident data is not uniform and frequently lacks the necessary details (e.g. natural hazard information - flood height, wind speed, earthquake intensity at the location of the hazardous installation or site). This makes it difficult to reconstruct the dynamics of a Natech event. To support Natech data collection and analysis, the Joint Research Centre has developed a dedicated Natech incident database (eNATECH[5]) that reflects the advanced accident representation needed to capture the characteristics of Natech events (e.g. multiple accident sequences occurring in parallel or sequentially).

[5] eNATECH is available free at https://enatech.jrc.ec.europa.eu

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List of abbreviations and definitions

Critical event	See *Top event*.
Cut set	A set of primary events, i.e., of basic or undeveloped faults, which give rise to the top event.
Damage distance	The maximum distance at which an accident can cause a specific adverse effect (e.g., injuries).
Domino effect	The process of propagation of an industrial accident from one site (or installation) to another that results in an escalation of the accident consequences.
Equipment	Machines, components and systems required for an industrial process. Examples of process equipment used in the process industry are pumps, valves, vessels, filters, coolers, heat exchangers, columns, and piping.
Establishment	The whole location under the control of an operator where dangerous substances are present in one or more installations, including common or related infrastructures or activities; establishments are either lower-tier establishments or upper-tier establishments. This term is used in the context of the Seveso Directive. For the purpose of this guidance we use the term *(industrial) site* or *(industrial) plant*.
Event tree analysis	A modelling technique that identifies possible outcomes, and if required their probabilities, following an initiating event. It is used to identify the sequence of events leading to specified consequences, assuming that each event in the sequence is either a success or a failure.
Fault tree analysis	A top-down failure analysis method in which an undesired state of a system is analysed using a graphical representation of the combination of faults and Boolean logic. This analysis method aims to understand how systems can fail by reverse-engineering the root causes of the failure.
FMEA	Failure Mode and Effects Analysis. The process of reviewing as many components, assemblies, and subsystems as possible to identify potential failure modes in a system and their causes and effects. FMEA is often the first step of a system reliability study.
FMECA	Failure Mode, Effects, and Criticality Analysis. An analysis method which involves quantitative failure analysis. FMECA is an extension of FMEA that includes a criticality analysis to chart the failure mode probability against the severity of their consequences.
Hazard	Condition, event, or circumstance that could lead to or contribute to an unplanned or undesirable event. The intrinsic property of a hazardous material or physical situation, with a potential for creating damage to human health or the environment.
Hazard map	A map that highlights areas that are affected by or are vulnerable to a particular hazard. It is typically created for natural hazards, such as earthquakes, volcanoes, landslides, flooding and tsunamis.
Hazardous material	Hazardous substance or mixture that poses a threat to human health and the environment. Hazardous materials are toxic, corrosive, ignitable, explosive or chemically reactive. This term is equivalent to *dangerous substance* used in the frame of the Seveso Directive.
HAZOP	Hazard and Operability study. A qualitative technique for process hazard analysis which consists of a structured and systematic examination of an industrial process that aims to identify hazards and evaluate problems that may represent risks. The complex process is divided into a number of simpler sections called “nodes” which are then individually reviewed with the help of standardised guidewords.
Installation	A technical unit within an establishment and whether at or below ground level, in which dangerous substances are produced, used, handled or stored; it includes all the equipment, structures, pipework, machinery, tools, private railway sidings, docks, unloading quays serving the installation, jetties, warehouses or similar

structures, floating or otherwise, necessary for the operation of that installation. This term is used in the context of the Seveso Directive.

LOC	Loss of Containment of a hazardous substance.
LUP	Land Use Planning.
Major accident	An occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment, and leading to serious danger to human health or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances.
MAPP	Major Accident Prevention Policy. Sets out the operator's overall approach and measures, including appropriate safety management systems, for controlling major accident hazards. This term is used in the context of the Seveso Directive.
Minimum cut set	A cut set that does not contain within itself another cut set.
Natech	Natural hazard triggered technological accident.
Natural hazard	A natural process or phenomenon, including all geological, hydrological, climatic and meteorological phenomena that, because of their location, severity, and frequency, might have a negative impact on human health, the natural and built environment, and the economy.
Operator	Any natural or legal person who operates or controls an establishment or installation or, where provided for by national legislation, to whom the decisive economic or decision-making power over the technical functioning of the establishment or installation has been delegated.
Process unit	A unit that performs operations that involve a physical change or chemical transformation, such as separation, crystallization, evaporation, filtration, reaction, etc. Such operations are connected to create the overall process.
Reliability	The ability of an item to perform a required function under stated conditions for a stated period of time.
Risk	The likelihood of a specific effect occurring within a specified period or in specified circumstances.
Safety report	A safety report should contain details of the establishment, the dangerous substances present, the installation or storage facilities, possible major-accident scenarios and risk analysis, prevention and intervention measures and the management systems available, in order to prevent and reduce the risk of major accidents and to enable the necessary steps to be taken to limit the consequences thereof. The term safety report is equivalent to *safety case* outside the EU or in industrial sectors other than those falling under the Seveso Directive.
Scenario	A projection of a possible future event. Scenarios are used to consider alternative possible outcomes.
Site	See *establishment*.
SMS	Safety Management System. The SMS provides a systematic way to identify hazards and provide assurance the controls remain effective. An SMS should be systematic, comprehensive, and integrated with other processes within the facility. Like all management systems, the SMS provides for setting goals, planning, measuring performance, and support for a culture of continual improvement.
Top event	An undesired event, such as a hazardous situation or equipment failure. Typical top events are releases of flammable or toxic substances, fires, explosions and failures of some kind.
What-if analysis	What-if analysis is a structured brainstorming technique that aims to determine what can go wrong in a given scenario. A team generates What-if questions relating to each step of the process and each component to determine possible sources of errors and failures.

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