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Natech accidents triggered by cold waves

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ABSTRACT

Natural events are a widely recognized hazard for industrial sites where relevant quantities of hazardous substances are handled, due to the possible generation of cascading events resulting in severe technological accidents (Natech scenarios). To date, research efforts were mainly dedicated to the study of Natech scenarios triggered by earthquakes, floods, and hurricanes. However, a number of recent events evidenced the potential hazard of Natech scenarios triggered by cold waves and winter storms. The present study aims at providing a comprehensive analysis of past accidents involving hazardous substances triggered by cold waves affecting the industrial infrastructure. A dataset of over 740 Natech events was collected from specialized sources. A detailed analysis of the primary events and damage modes of the equipment items involved was carried out, highlighting that most of the accidents were linked to the phase transition from the liquid to the solid state of the process fluid or of atmospheric water. The analysis of the events allowed the identification of several aspects of the cause-consequence chains, such as the technological scenarios and the equipment items more frequently involved. A specific focus was also on the vulnerability and failure modes of safety barriers. The lessons learned derived from the analysis of the accidents provide key elements to prevent similar accidents from happening in the future. These were used to suggest specific safety barriers integrating winterization and freeze protection programs.

1. Introduction

Natech accidents are defined as major accidents involving hazardous substances triggered by natural events (Nascimento and Alencar, 2016; Showalter and Myers, 1994). The concern related to these events is growing due to the increasing number of natural disasters reported (Centre for Research on the Epidemiology of Disasters, 2023) and to the severe consequences related to the technological scenarios involving hazardous substances (Krausmann and Cruz, 2017). Previous studies addressing Natech scenarios mostly focused on the interaction between industrial sites and intense natural events such as earthquakes (Antonioni et al., 2007; Huang et al., 2020; Salzano et al., 2009), floods (Antonioni et al., 2015; Caratozzolo et al., 2022; Zeng et al., 2021), hurricanes (Cruz and Krausmann, 2008; Misuri et al., 2019; Qin et al., 2020), and wildfires (Khakzad, 2019; Ricci et al., 2021b, 2021c), also addressing the quantitative assessment of risk (Antonioni et al., 2009; Cozzani et al., 2014). However, Natech accidents may be triggered by any kind of natural event (Krausmann and Cruz, 2017; Krausmann and Salzano, 2017), including those typically characterized by lower intensities. Among these, natural events related to temperature extremes are becoming of particular concern. Indeed, climate change is modifying the mean, shape, and variance of temperature distributions in wide areas of the planet, leading to changes in frequency, intensity, duration, and spatial extent of extreme weather conditions such as extreme temperatures (Intergovernmental Panel on Climate Change, 2012). In addition, recent studies demonstrated that extreme temperatures are relevant as triggering factors of Natech events, being the cause of at least 12% of Natech accidents according to Ricci et al., (2021a) and Casson Moreno et al. (2019).

Within the definition of extreme temperatures, two opposites can be recognized: events related to high temperature (hot weather, heat waves) and events characterized by low temperature (cold weather, cold waves, winter storms). These two categories of events greatly differ when considering the interaction with industrial sites (Ricci et al., 2020).

Previous studies demonstrated that cold weather affects industrial sites more frequently than heat waves, as highlighted by Luo et al. (2020) in a study concerning Natech accidents in the United States of America. In addition, a recent report by Necci and Krausmann (2022) suggests that cold waves represent a specific hazard for industrial

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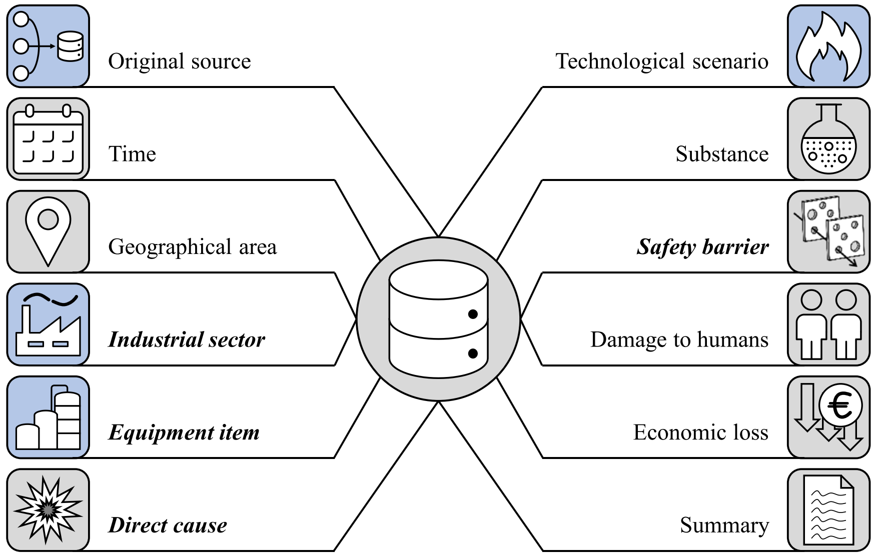

Fig. 1. Structure of the database. Grey icons represent free entry fields. Light blue icons represent itemized fields. Specific fields introduced in the present study are reported in italic.

Table 1
Categories of equipment items considered in the present study.

Equipment category	Examples
Storage equipment	Atmospheric storage vessel, pressurized storage vessel, …
Process equipment	Column, reactor, heat exchanger, …
Valves/ instrumentation	Valves, control devices, …
Machinery	Pump, compressor,.
Pipework	Pipelines, pipeworks, …
Road/rail tanker	Road tanker, rail tanker, tanker, …

installation. Actually, Krausmann and Baranzini (2012) report that low temperature is the third cause of Natech accidents in Europe, preceded only by lightning and flood. The study also reports that the perceived risk due to these accidents is significantly underestimated by the European Member States, remarking the importance of increasing hazard awareness. The relevance of the issue is also confirmed by the U.S. Chemical Safety and Hazard Investigation Board (2022, 2018a), which carried out a thorough analysis of two milestone accidents caused by cold waves, the fire that occurred at Valero-McKee Refinery in 2007 (U. S. Chemical Safety and Hazard Investigation Board, 2008) and the toxic release that took place at the DuPont chemical plant in 2014 (U.S. Chemical Safety and Hazard Investigation Board, 2019). Moreover, a further report from the same organization documents that the number of reported accidents doubled in the last quarter of 2022 when compared to those reported in the same period of the previous years, suggesting that the increase is mainly due to the cold wave that hit the United States of America in the last weeks of 2022 (Bushard, 2022; Reimann, 2022).

Even if the relevance of Natech accidents caused by cold waves is clearly documented in the previous studies cited above, a systematic investigation of the features of this category of Natech accidents is not present in the literature. Moreover, albeit several documents address winterization measures (e.g. see the safety digest of the U.S. Chemical Safety and Hazard Investigation Board, 2018a and the recommended practice of the American Petroleum Institute, 2019), a specific focus on the prevention of Natech accidents caused by cold waves is still missing. Furthermore, the potential suggestions and integrations deriving from a specific assessment of safety barrier integrity and expected performance during cold waves are not yet exploited.

The prevention of technological accidents and the mitigation of their consequences rely on safety procedures and specific technical solutions, which are referred to as safety barriers (Center for Chemical Process Safety, 2001; Dedianous and Fievez, 2006; Landucci et al., 2016; Sklet, 2006; Yuan et al., 2022). Previous studies have shown that the availability and effectiveness of safety barriers may decrease in Natech accidents, due to the effect of the natural event on the barrier. Although criticalities concerning the operation of conventional safety barriers during natural events are recognized (Girgin, 2011; Krausmann and Cruz, 2013; U.S. Chemical Safety and Hazard Investigation Board, 2018b), only a few studies, limited to earthquake and flood effects, addressed specifically the failure and/or performance degradation of safety barriers in Natech scenarios (Misuri et al., 2020, 2021a). Thus, a specific analysis concerning the possible effect of cold waves on safety barriers is still missing in the literature.

In this panorama, a complete understanding of the possible interaction between industrial installations and the consequences of cold waves is of paramount importance. The present study focuses on the analysis of Natech accidents triggered by low temperatures and related events (e.g. as snowfalls, formation of ice, etc.). An extended dataset of past Natech accidents was collected and analyzed. In the following, Section 2 describes the methodology used to build and analyze the accident dataset. Section 3 reports the results of the analysis of the dataset collected, focusing in particular on the technological scenarios, the equipment items mainly affected by cold waves, and the performance of safety barriers. Lessons learned and prevention measures are discussed in Section 4. Conclusions are reported in Section 5.

2. Methodology

2.1. Dataset structure

A specific dataset was built to collect data on past Natech accidents caused by cold waves. Fig. 1 shows the structure of the dataset used to organize the available information. Blue icons represent fields where itemized lists are used to codify information, whereas grey icons identify free-text fields. Table 1 reports the categories of equipment items included in the itemized list defined, while further details on the other itemized entries are reported in Appendix A.

The structure of the dataset is derived from that of the database developed by Ricci et al. (2021a). However, further information was included. In particular, the specific list of equipment categories shown in Table 1 was introduced. Specific fields were defined to report the direct causes that triggered the technological scenario in cascading sequences

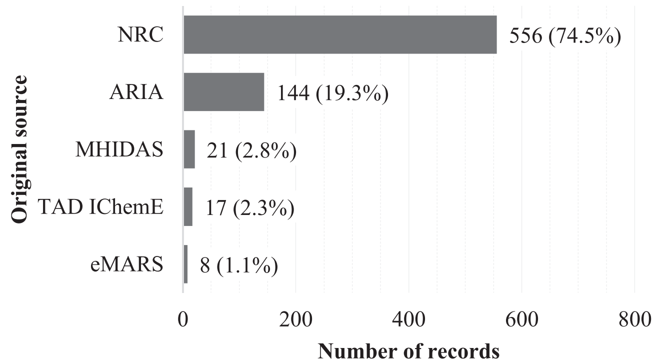

Fig. 2. Original sources of information on the events collected in the dataset.

Table 2
Share among the continents of the collected records.

Continent	Number of records	Share (%)
Americas	588	78.8 %
Europe	153	20.5 %
Antarctica	2	0.3 %
Asia	2	0.3 %
Unknown	1	0.1 %

and the performance/role of safety barriers. These fields allow gathering specific data on the failure modes of the equipment and on safety barriers failure, representing an innovative feature of the present study.

2.2. Data collection

The Natech accident database developed by Ricci et al. (2021a) was the main source of the information included in the present study. The database from Ricci et al. (2021a) consists of a collection of past Natech accidents mostly retrieved from other databases reporting industrial accidents: eMars (European Major Accident Hazards Bureau, 1982), MHIDAS (Harding, 1997; U.K. Health and Safety Executive, 1986), TAD IChemE (Institution of Chemical Engineers, 1997), ARIA (Bureau for Analysis of Industrial Risks and Pollutions, 1950), NRC (U.S. Coast Guard, 1990), and CONCAWE (Cech et al., 2019). More details on the sources can be found in Ricci et al. (2021a).

First, the relevant events included in the present study were retrieved interrogating the database using the following specific keywords: “low temperature”, “snow”, “hail”, “cold weather”, and “cold wave”. Considering their peculiarity, offshore facilities and transportation via water were excluded from the present analysis, limiting the data to fixed installations and transport via pipeline, road, or rail.

Then, the original sources used for the compilation of the database of Ricci et al. (2021a) were consulted to include additional information not reported in the database (e.g. concerning equipment features, safety barriers, etc.), needed to compile the specific fields added or modified in the present study, shown in italics in Fig. 1.

Finally, the open literature and industrial accident databases were consulted to update and integrate the dataset. For the sake of consistency, the same procedure used to populate the original database by Ricci et al. (2021a) was adopted for its integration. More specifically, the same past accident databases were interrogated and the same criteria were used to retrieve data from publications. The update and integration aimed, on the one hand, at including the more recent Natech accidents caused by cold wave-related natural events, and, on the other hand, to include as far as possible also near misses, to provide additional elements for the identification of possible causes and chain of events affecting the industrial infrastructure during cold weather.

2.3. Data analysis

Statistical analysis was the main tool applied to investigate the different features of past accidents. Where possible, data were compared to those obtained for generic Natech events in the recent study by Ricci et al. (2021a).

With respect to the assessment of the possible failure of safety barriers, information derived from past accidents was integrated with the results of a What-If analysis. What-If analysis is a hazard identification technique used to systematically investigate the consequences of specific deviations from normal operating conditions. Further details on the technique and its application are reported in the literature (Center for Chemical Process Safety, 2008; Mannan, 2005).

The What-If analysis was used to investigate the potential consequences on safety barrier operation of the two main effects of cold waves: extremely low temperatures and snow/hail. The What-If analysis was applied to the set of reference safety barriers defined by Misuri et al. (2020). This includes an extended list of safety barriers widely used for fire mitigation and escalation prevention (American Petroleum Institute, 2019; Oil Industry Safety Directorate, 2007). The list and definition of the safety systems and safety barriers considered are reported in Appendix B. Pressure safety valves, originally excluded from the list, were also considered in the present study.

3. Results and discussion

3.1. Original sources and geographical distribution of the events included in the dataset

On the basis of the criteria discussed in Section 2, a total of 746 records were included in the dataset analyzed. Fig. 2 shows the original sources of the records included in the present study. The NRC database represents the main source of data, providing around 75% of the total records collected (556 records), followed by the ARIA database (144 records, 19.3% of the total). About 6% of the records are obtained from all the other sources consulted. Not surprisingly, the share among the original sources is similar to that of the database by Ricci et al. (2021a). It is worth mentioning that the eMARS and the TAD IChemE databases, even if reporting a limited number of relevant events, provide records with a higher level of detail among all the other sources consulted, apart from specific accident reports and investigations collected from the open literature.

Table 2 reports the geographical distribution by continent of the collected records. Americas (588 records, 78.8% of the total) and Europe (153, 20.5%) are the two continents where most of the accidents considered took place (99% of the entire dataset). However, these results mostly depend on the geographical coverage of the original sources. In particular, the NRC database only reports events that occurred in the United States of America, while the ARIA and the eMARS databases mostly report events that occurred in Europe. The higher number of records collected from the NRC database with respect to those obtained from ARIA and eMARS may explain the lower incidence of events that occurred in Europe with respect to North America. No specific sources in the open literature are available for Asia and Latin America, causing a possible underreporting of events in these continents.

In spite of the limited geographical coverage of the available data, due to the similarities in the vulnerability of energy and chemical sites and infrastructure all over the world, the results obtained and the lessons learned are considered to have general validity.

Since a significant part of the events included in the dataset occurred in the United States of America (USA), it is interesting to compare them to the overall distribution of generic Natech events and to the occurrence of cold waves in the USA. Fig. 3 reports data concerning the geographical distribution of industrial sites, of generic Natech accidents, of cold wave-related natural events, and of cold wave-related Natech accidents. More specifically, Fig. 3-(a) shows in dark colors the areas

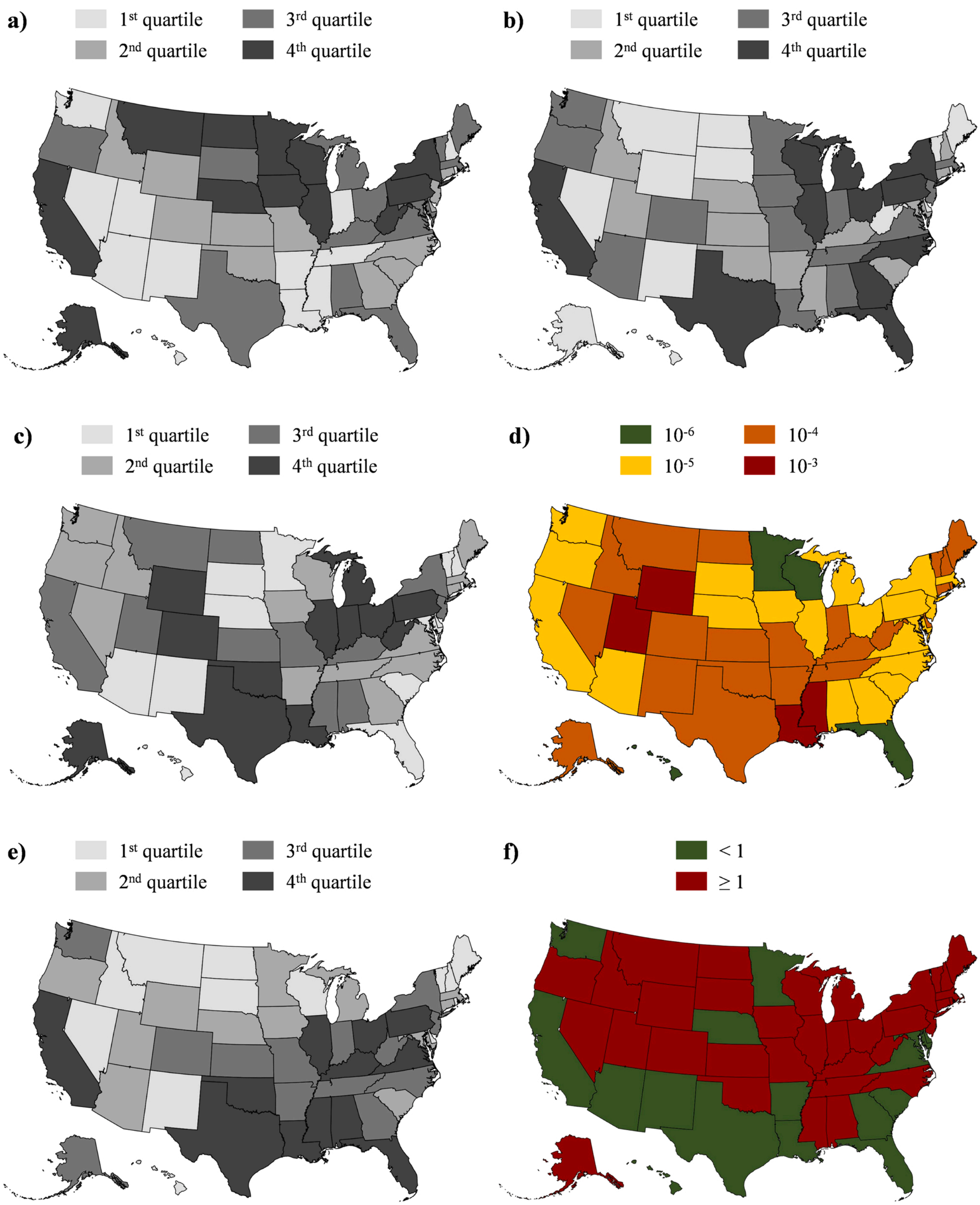

Fig. 3. (a) Number of cold waves that occurred in each state of the USA from 1950 to 2018 (NOAA National Centers for Environmental Information, 2022). (b) Number of manufacturing sites in each state of the USA (MNI, 2023). (c) Number of Natech accidents triggered by cold waves reported in each state of the USA. (d) Ratio between the number of Natech accidents triggered by cold waves, reported number of cold waves, and industrial sites in each state of the USA. (e) Geographical distribution of generic Natech accidents (Ricci et al., 2021a). (f) Ratio between the normalized number of Natech events triggered by cold waves and the normalized number of generic Natech accidents in each state of the USA.

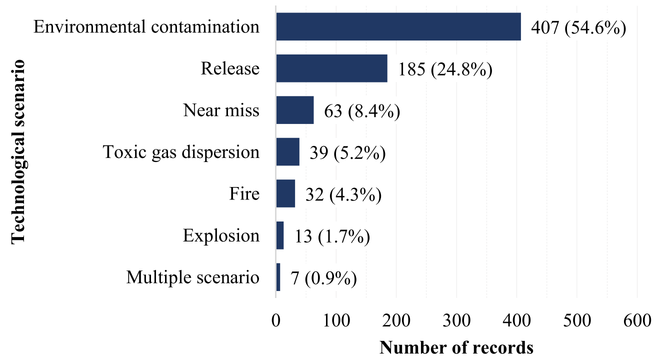

Fig. 4. Technological scenarios that occurred in Natech accidents triggered by cold waves. The definition of technological scenarios is reported in Table A1 (Appendix A).

Table 3
Substance categories more frequently involved in past Natech accidents caused by cold waves.

Category	Substances	Number of records	Percentage
Flammable/combustible liquid hydrocarbons	Fuel oil	142	19 %
	Oil	96	12.9 %
	Benzene	25	3.4 %
	Motor oil	24	3.2 %
	Other flammable/ combustible liquid hydrocarbons	*11*	*1.5 %*
Flammable gaseous hydrocarbons	Natural gas	47	6.3 %
	Liquefied Petroleum Gas (LPG)	16	2.1 %
	Other flammable gaseous hydrocarbons	*13*	*1.7 %*
Toxic gaseous substances	Chlorine and chlorine-based substances	33	4.4 %
	Ammonia and ammonium-based substances	27	3.6 %
	Other toxic gaseous substances	*7*	*0.9 %*
Wastewater	Wastewater	54	7.2 %

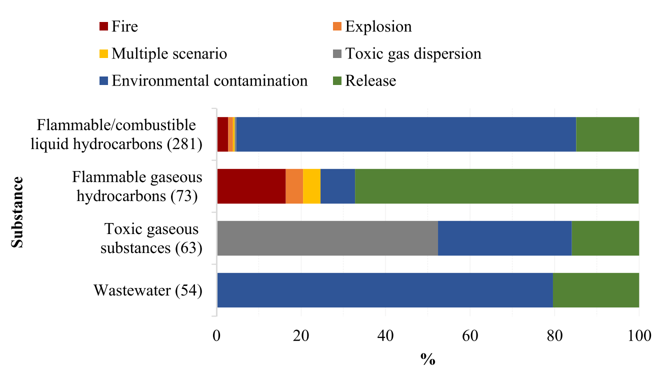

Fig. 5. Technological scenarios reported for the categories of hazardous substances more frequently released in Natech events triggered by cold waves. The definition of the technological scenarios considered is reported in Table A2 (Appendix A).

more exposed to cold waves, while in Fig. 3-(b) the dark colors correspond to the areas where a higher number of manufacturing sites are present. Fig. 3-(c) shows that a higher number of Natech accidents triggered by cold waves, as expected, is reported in areas where both a high occurrence of cold waves was recorded and a high number of manufacturing sites is present.

Fig. 3-(e) shows the number of generic Natech accidents that occurred in each state of the USA reported in the database developed by Ricci et al. (2021a). Fig. 3-(f) reports the ratio of the normalized number of Natech events triggered by cold waves that occurred in each USA state divided by the normalized number of generic Natech events. Internal normalization was applied, dividing the number of events in each state by the total number of accidents recorded. As shown in the figure, in all the southern regions of the USA, where a lower occurrence of cold waves is reported, the ratio is lower than 1, confirming that, as expected, these areas are less affected by accidents caused by cold waves with respect to other types of Natech events.

However, further details may be obtained when considering the number of industrial sites and of cold waves reported in the different areas. Actually, Fig. 3-(d) shows the number of Natech events triggered by cold waves divided by the number of industrial sites and by the total number of cold waves recorded in the corresponding time period in each state of the USA. High values of this ratio are obtained for states such as Louisiana, Wyoming, and Mississippi, which are not among the regions more frequently affected by cold waves. This may be possibly caused by a lower preparedness of industrial facilities to cold waves. By converse, areas largely affected by cold waves (e.g., Minnesota) score lower values of the ratio shown in Fig. 3-(d), suggesting that in areas that frequently experience this category of natural events, industrial sites possibly adopt effective procedures to contrast the hazards caused by cold waves.

The above findings thus suggest that the hazard concerning Natech events triggered by cold waves should not be considered only in the areas more frequently affected by such events. Actually, in regions that rarely experience cold waves a lower preparedness of industrial sites may be present, enhancing their vulnerability to such category of accidents. This remark is important also considering climate change issues, that may lead to the occurrence of cold waves in areas normally not affected by such phenomena.

3.2. Technological scenarios and hazardous substances involved

Fig. 4 shows the technological scenarios that occurred in Natech accidents caused by cold waves. Environmental contamination was the most frequent outcome, followed by the release with no further consequences, which together represent around 80% of the entire dataset. A total of 63 (8.4%) near missed are documented. In the remaining 12% of the events, toxic gas dispersions (39 events, 5.2%), fires (32 events, 4.3%), and explosions (13 events, 1.7%) occurred. Multiple scenarios (fire and explosion) were reported only for a limited number of events (7 events, 0.9%). The distribution of technological scenarios shows only limited modifications with respect to the data obtained for generic Natech accidents by Ricci et al. (2021a).

Data on the hazardous substances involved in the technological scenarios are available for a total of 681 events in the dataset. The release of over 110 different hazardous substances is reported. Table 3 lists the substance categories more frequently involved in the events collected. Overall, the substances in Table 3 were involved in over 60% of the events in the dataset.

Fig. 5 shows the technological scenarios generated by the four categories of hazardous substances more frequently involved in Natech accidents caused by cold waves. Near misses are not considered in the figure. Fig. 5 evidences that the occurrence of ignition is reported for about 4.3% of the events involving flammable liquid hydrocarbons. As expected, a much higher value is obtained for the occurrence of ignition in the case of flammable gaseous hydrocarbons (around 25%). These data are comparable to those obtained for generic Natech accidents by Ricci et al. (2021a), even if a slight decrease in the occurrence of ignition can be observed in the case of flammable liquids.

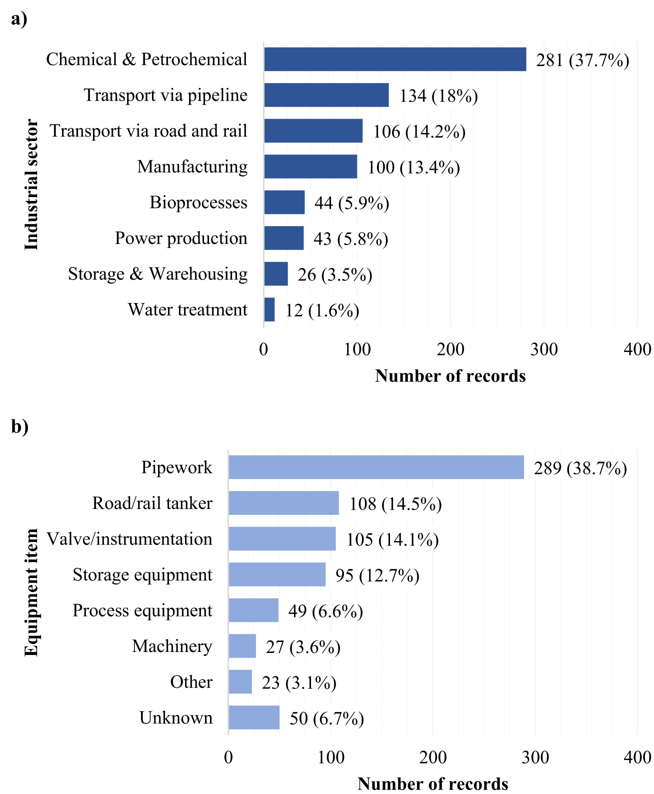

Fig. 6. (a) Industrial sectors and (b) equipment items involved in the cold wave Natech events. The definition of industrial sectors and equipment categories is reported in Table A2 (Appendix A) and Table 1, respectively.

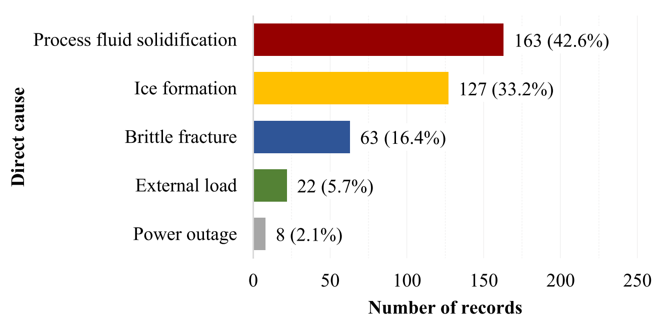

Fig. 7. Direct causes of the Natech events occurred in fixed installations.

3.3. Industrial sectors and categories of equipment items involved

The industrial sectors affected by the past cold wave Natech accidents analyzed in the present study are shown in Fig. 6-(a). The Natech events of interest occurred mostly in the chemical and petrochemical sector (37.7% of events). The high vulnerability of this sector can be attributed to the large number of installations handling relevant quantities of hazardous substances. However, the transportation sector, when considering together transportation by pipeline (18%) and by road and rail (14.2%), scores a similar share of accidents (32.2%). As for road and rail transport, extreme weather conditions related to cold waves introduce additional risk factors, e.g. related to the formation of ice on the transport infrastructure.

Fig. 6-(b) shows the categories of equipment items involved in the accident dataset considered. Data on equipment items involved were available only for 696 events. The figure clearly shows that plant components, such as pipework and valves/instrumentation are more frequently affected (38.7% and 14.1.% share respectively) than machinery, process, and storage equipment (overall 22.9% of events). Road and rail tankers are also frequently involved in these accidents (14.5% of events).

The data in Fig. 6 evidence the relevant impact of cold waves in causing accidents during the transportation of hazardous substances, confirming the high vulnerability of the transport systems and infrastructure to the impact of cold waves.

3.4. Direct causes of accidents

In analyzing the cause-consequence chain, it is paramount to identify the direct cause of the events that triggered the cascading sequence leading to the technological scenario. The direct cause represents the consequence of the cold wave on the system or installation considered, which determines the failure mode of equipment items or of the system components and triggers the accident sequence.

Due to their different features, transportation accidents were considered separately from accidents involving equipment items in industrial sites. Indeed, in the case of road and rail tankers, the more important direct cause of failure resulted the formation of ice from the atmospheric water on roads and rails (69 events, over 60% of accidents that involved tankers). In a marginal number of cases, accidents were caused by malfunctioning of the tanker or its components due to the effects of the cold wave (around 8%). In the remaining events, the direct cause of the accidents is unknown.

Fig. 7 shows the direct causes identified for accidents involving storage equipment, process equipment, valves/instrumentation, machinery, and pipework. It should be remarked that the direct cause was reported in only about 68% of the 565 records concerning this category of equipment, thus for a total of 383 events.

Five main direct causes were identified for the cold wave Natech events that occurred in the fixed installations included in the dataset analyzed. In most of the accidents, the direct cause was related to the transition to the solid state of a fluid. Specifically, two different primary events were identified: the solidification of the process fluid and the formation of ice outside the equipment. The first event occurred in around 42% of the records, and it represents the most frequent direct cause of the Natech scenarios of concern. In these events, the process fluid inside the equipment (process water or other substances) solidifies forming plugs or blocks inside pipes or vessels. These in turn can stop or limit the flow in pipes, or cause damage due to their displacement inside the equipment. It is worth noting that this direct cause may explain the presence of benzene as one of the substances more frequently involved in the accidents analyzed, as shown in Table 3. Indeed, benzene has a melting point at atmospheric pressure of about 5.5 °C (Southard et al., 2019), and therefore it may easily become solid at low temperatures, e.g in pipework exposed to low ambient temperature in the absence of heat tracing. Moreover, in most cases, and specifically in the case of water, the solidification causes an expansion that may damage the equipment in which the transition takes place.

The formation of ice outside the equipment is caused by the phase transition of liquid water present due to condensation of atmospheric humidity, rain, hail or snow. The formation of ice may cause several malfunctions, e.g. it may block the stems of control valves, damage instrumentation or components, block drains, etc. The formation of ice on the external surface of equipment items and/or components was reported as the direct cause of equipment failure in around 33% of the events analyzed.

A further direct cause of Natech events triggered by cold waves is the failure of equipment due to the brittle fracture of structural elements and/or components (16.4% of the cases). Indeed, low temperatures may exceed the brittle transition temperature of steels and polymeric materials not intended for low-temperature applications.

Excessive loading of structural elements, mostly tank roofs, due to snow or hail accumulation was also experienced as the direct cause of several Natech accidents in the case of cold waves (5.7%).

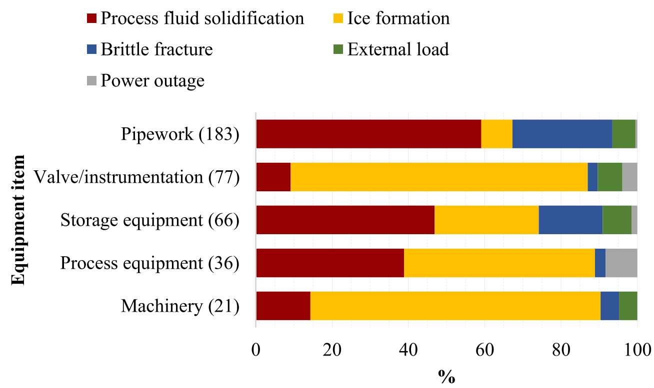

Fig. 8. Direct causes of Natech events for the categories of vulnerable equipment identified in fixed installations.

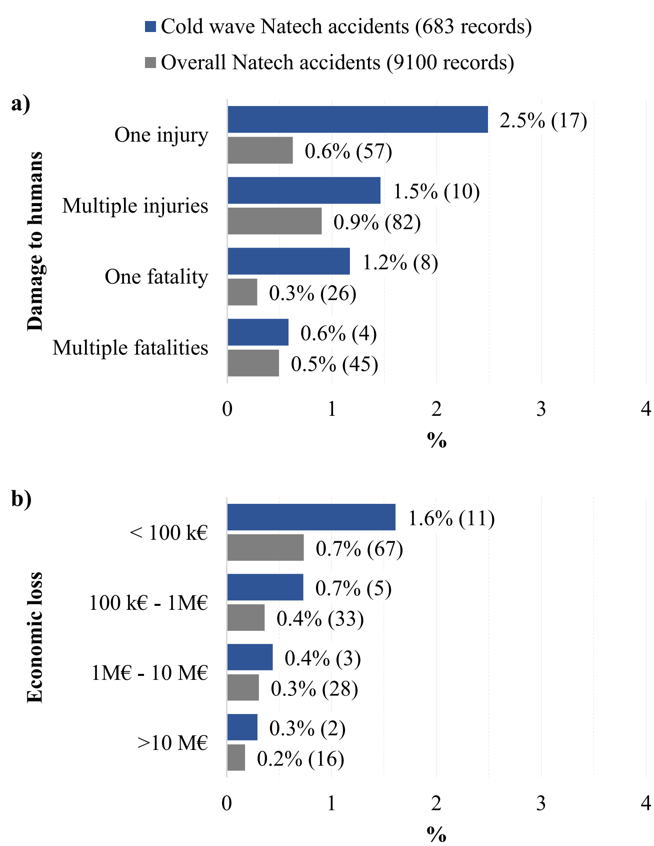

Fig. 9. Probability of damages to humans and economic losses in accidents triggered by cold wave-related events.

Finally, utility failure and specifically power outage was the direct cause of some events (2.1%).

Fig. 8 shows the direct causes of Natech events triggered by cold waves for each category of equipment considered in fixed installations. As shown in the figure, process fluid solidification is the main cause of damage to pipework, process, and storage vessels. The more vulnerable elements are components and vessels where the process fluid accumulates and no flow is normally present, such as bypass pipes and unstirred tanks.

Valves/instrumentation and machinery are mostly affected by the formation of ice on the external surface. Indeed, the external formation of ice is responsible for about 80% of the Natech events where the release of hazardous substances was caused by the failure of these components. Brittle fracture is an important direct cause of failure for

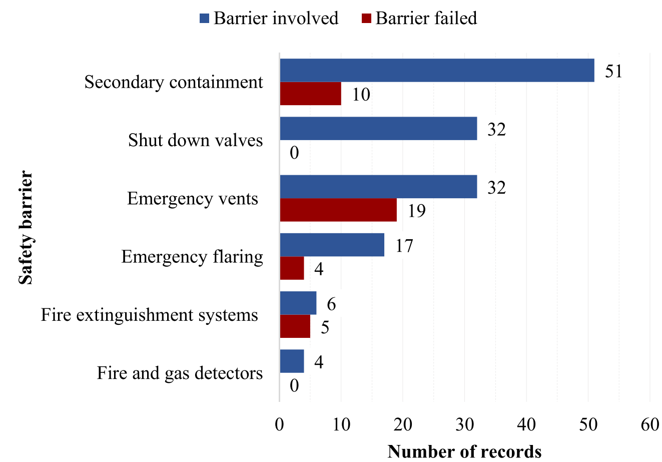

Fig. 10. Number of events in which safety barriers are mentioned in the accident file and in which the barrier was reported to have failed.

pipework and storage vessels, having lower relevance for the other equipment categories. Accidents caused by power outages mostly affected process equipment.

3.5. Damages to humans and economic losses

Fig. 9 reports the available data concerning the severity of Natech accidents triggered by cold waves. The analysis was carried out excluding the records classified as near misses (as defined in Appendix A). Thus, a total of 683 records were considered.

In 39 events (5.7%) damages to humans are reported, recording a total of 24 fatalities and 167 injuries. As shown in Fig. 9-(a), four severity classes were defined to assess the magnitude of the consequences, ranging from one injury to multiple fatalities. Records reporting both injuries and fatalities are conservatively assigned to the more severe fatality class applicable. Fig. 9-(a) shows that fatalities are recorded in 1.8% of Natech events caused by cold waves. The figure also shows that, overall, the % of accidents in which injuries or fatalities were recorded is higher with respect to that obtained by Ricci et al. (2021a) for generic Natech events. Information on economic losses in Natech events caused by cold waves is reported only in 21 records. Fig. 9-(b) shows the results obtained introducing four severity classes to assess the entity of consequences. It should be recalled that data on economic losses are affected by a large uncertainty (Iannaccone et al., 2020). Nevertheless, the % of accidents where economic losses were recorded is higher for all four categories of economic losses considered. These results confirm that cold waves represent a serious hazard for industrial installations and that the consequences of accidents can be severe both in terms of damage to humans and to assets.

3.6. Safety barriers

The dataset was specifically investigated to assess safety barrier performance in Natech accidents caused by cold waves. Both active and passive barriers were considered in the analysis, following the widely applied categorization based on the barrier operating principle (Andersen et al., 2004a; Landucci et al., 2017; Misuri et al., 2021a, 2021b; Salvi and Debray, 2006). Information on safety barriers was available in 125 events. A total of six different categories of safety systems were involved in the past accidents included in the collected dataset:

- Secondary containment (bunds, catch basins, etc.)
- Shut down valves
- Emergency vents (including pressure safety valves, pressure relief valves, and open vents to the atmosphere)

Table 4
Qualitative assessment of safety barrier failure credibility due to the five main direct causes of system failure during cold waves identified in the present study. Safety barriers are defined in Appendix B.

Safety barrier	Process fluid solidification	Ice formation	Brittle fracture	External load	Power outage
Active safety barriers					
Inert-gas blanketing system	Not possible	Credible	Credible	Unlikely	Not possible
Automatic rim-seal fire extinguishers	Credible	Credible	Credible	Unlikely	Unlikely
Fixed / Semi-fixed foam systems	Credible	Credible	Credible	Unlikely	Unlikely
WDS / Water Curtains / Sprinklers	Credible	Credible	Credible	Unlikely	Unlikely
Hydrants	Credible	Unlikely	Unlikely	Unlikely	Unlikely
Fire activated valves	Credible	Credible	Unlikely	Unlikely	Not possible
Fire and gas detectors	Not possible	Unlikely	Not possible	Not possible	Unlikely
SDVs	Credible	Credible	Unlikely	Unlikely	Not possible
BDVs	Credible	Credible	Unlikely	Unlikely	Not possible
Passive safety barriers					
Pressure safety valves	Credible	Credible	Unlikely	Unlikely	Not possible
Fire walls	Not possible	Not possible	Not possible	Not possible	Not possible
Blast walls	Not possible	Not possible	Not possible	Not possible	Not possible
Fireproofing	Not possible	Not possible	Not possible	Not possible	Not possible
Bunds / Catch basins	Not possible	Not possible	Not possible	Not possible	Not possible
Emergency blowdown line to flare stack	Credible	Unlikely	Unlikely	Unlikely	Not possible
Mounding tanks	Not possible	Not possible	Not possible	Not possible	Not possible
Burying tanks	Not possible	Not possible	Not possible	Not possible	Not possible

Table 5
Effectiveness of freeze protection approaches proposed by the American Petroleum Institute (2019) in contrasting the direct causes identified in the present study.

Freeze protection approaches	Process fluid solidification	Ice formation	Brittle fracture	External load	Power outage
Eliminating vulnerable piping (especially dead legs)	Effective	Effective	Effective	Effective	No effect
Increasing "bird screen" mesh size on tank vents	No effect	Effective	No effect	Effective	No effect
Placing piping underground	Effective	Effective	Effective	Effective	No effect
Using dry barrels or "traffic type" fire hydrants	Effective	No effect	No effect	No effect	No effect
Using dry-pipe sprinklers or deluge systems	Effective	No effect	No effect	No effect	No effect
Moving vulnerable equipment indoors (or building protective shelters)	Effective[1]	Effective[1]	Effective[1]	Effective	No effect
Blowing water from lines with air	Effective	No effect	No effect	No effect	No effect
Maintaining flow in water lines	Effective	No effect	No effect	No effect	No effect
Heat tracing (steam or electric)	Effective	Effective	Effective	Effective	No effect
Insulating vulnerable resources	Effective	No effect	Effective	No effect	No effect
Inspection prior to/during/after freezing weather	Effective	Effective	No effect	Effective	No effect

[1] Protective shelter has no effects concerning the direct cause.

- Emergency flaring (including the emergency blowdown lines to flare stack and the flare stack)
- Fire extinguishment systems (including rim-seal fire extinguishers, foam systems, and sprinkler systems)
- Fire and gas detectors.

Fig. 10 shows the number of events in which the safety systems are mentioned in the dataset (blue bar) and the number of events in which the failure of the barrier was reported (red bar).

Secondary containments are the safety barriers more frequently involved in the event sequences that occurred in past accidents, as

Table A1
Definition of technological scenarios considered in the present study (adapted from Ricci et al., 2021a). Please note that the fields reported in italics were modified, following the approach described in the methodological section.

Technological scenario	Definition
Fire	An uncontrolled combustion process characterized by the emission of heat and smoke. Includes all types of industrial fires, i.e. pool fires, flash fires, jet fires, and fireballs (Van Den Bosh and Weterings, 2005).
Explosion	A sudden release of energy that causes a blast wave (Van Den Bosh and Weterings, 2005). Includes all types of industrial explosions, i.e. unconfined and partially confined gas and vapor explosions (VCE), confined explosions, and mechanical explosions (Reniers and Cozzani, 2013).
Toxic gas release	The dispersion of a toxic substance in the air (Andersen et al., 2004b).
Environmental contamination	Contamination of surface waters (rivers, lakes, seas,.) or of the aquifer by substances harmful to the aquatic environment (Andersen et al., 2004b).
Release	The release of a liquid or gas from its containment (Van Den Bosh and Weterings, 2005), in quantities and concentrations that have no short-term potential consequence for persons and the environment.
Near miss	*An event that does not result in an actual loss but has the potential to do so (*Rathnayaka et al., 2011*).*

Table A2
Definition of industrial sectors considered in the present study (adapted from Ricci et al., 2021a). Please note that the fields reported in italics were modified, following the approach described in the methodological section.

Industrial sector	Definition
Chemical & Petrochemical	Chemical activities, including pesticide production, pharmaceutical industry, and production of basic chemicals. Petrochemical activities, including refineries.
Storage & Warehousing	Sites where chemicals are stored in appointed equipment (i.e., storage tanks) and storage buildings (e.g., warehouses, depots).
Power production	Power production plants using hydrocarbons (thermal power stations). Nuclear power plants were not included in the present analysis.
Bioprocesses	Treatment of organic waste and waste fermentation juices; food industry.
Water treatment	Treatment of water for industrial and domestic purposes (excluding bioprocess-es-related waters and slurries).
Transport via *road and rail*	*Transportation of hazardous materials* via *road and rail.*
Transport via pipeline	Oil and gas transportation via pipelines.
Manufacturing	Metalworking, textile industry, and activities related to the automotive sector where hazardous substances are used.

documented by the available accident files. Their failure is reported in around 20% of the accidents involving such barriers. Concerning the failure mode, records mainly report the overflow of the liquid from the bund or catch basin, usually due to the presence of water, hail, or snow inside the basin.

The second category of barriers more frequently involved in Natech accidents caused by cold waves are emergency shut down valves (SDVs). These were never reported to be affected by cold waves, even if in general valves were found to be among the items more vulnerable to cold waves, as shown in Fig. 6-(a) and Fig. 8.

Emergency vents were also frequently involved in past accidents caused by cold waves. Indeed, these barriers are directly exposed to cold weather, since emergency venting to the atmosphere is frequently used. A failure of such safety systems was reported in around 60% of the events that mention their involvement in the accident sequence.

Fire extinguishment systems also resulted critically affected by cold waves. Indeed, these systems are typically composed of several equipment items identified as vulnerable in Section 3.3 (e.g., pipework, valves, storage tanks, etc.). In addition, the presence of water or water solutions inside the piping components as well as the discontinuous flow in some parts of these systems make them vulnerable to the main direct causes of failure during cold waves discussed in Section 3.4.

Table B2
Definition of safety barriers considered in the present study (adapted from Misuri et al., 2020b). Please note that the fields reported in italics represent additional barriers included in the present study.

Safety barrier	Classification	Description
Inert-gas blanketing system	Active	System for inert gas delivery to storage tanks to prevent the possible formation of flammable atmospheres.
Automatic rim-seal fire extinguishers	Active	Automatic foam delivery system for prompt extinguishment of rim-seal fires developing in the roof area of atmospheric storage tanks.
Fixed / Semi-fixed foam systems	Active	Systems for tank fire extinguishment by means of foam/water delivery.
WDS / Water Curtains / Sprinklers	Active	Systems for water delivery during a fire, either for flame extinguishment or critical asset protection (e.g., LPG vessels).
Hydrants	Active	Water sources for fire brigades located in multiple areas of the plant.
Fire activated valves	Active	Valves activating in case of fire nearby.
Fire and gas detectors	Active	Field sensors for detection of flames and gases.
SDVs	Active	Isolation valves activating during emergency situations.
BDVs	Active	Depressurization valves activating during emergency situations.
Pressure safety valves	*Passive*	*Spring valve used to reduce the overpressure in a system when it exceeds a defined threshold value.*
Fire walls	Passive	Physical barriers for fire protection.
Blast walls	Passive	Physical barriers for blast protection.
Fireproofing	Passive	Coating materials for fire protection.
Bunds / Catch basins	Passive	Physical systems for liquid retaining in case of spill.
Emergency Blowdown line to flare stack	Passive	Line for flaring employed during emergency situations.
Mounding tanks	Passive	Locating vessels into gravel/ground mounds for fire protection.
Burying tanks	Passive	Locating vessels underground for fire protection.

Also flare stacks were frequently affected by cold waves, failing in 4 of the 17 events in which the barrier was mentioned (over 20% of the events). In most cases, failure was due to the formation of ice in the water used as a liquid seal in the flare stack drum. The liquid level increased in the drum due to the ice plugs obstructing the siphon, reaching the burner and causing its failure.

Fire and gas detectors are mentioned in a few events (around 0.5% of the entire dataset), and their failure was never reported.

Thus, the data obtained from the analysis of the dataset confirm that safety barriers may be critically affected by cold waves. However, even if the data reported in Fig. 10 are significant and provide useful information, they possibly provide only a partial figure of how safety systems may be affected by cold waves. Indeed, data on safety barriers are available only for a limited number of accidents in the dataset (around 17%) and for six different types of safety systems.

However, the identification of the factors that more frequently affected technical systems during accidents caused by cold waves, discussed in Section 3.4, may be used to complete the analysis. More specifically, as discussed in Section 2.3, a What-If analysis was applied to the assessment of the extended set of technical barriers reported in Appendix B. The What-If analysis was aimed at understanding the possible consequences that may arise from the impact of cold waves on such systems and identifying recommendations useful to prevent barrier failures. Two effects of cold waves were analyzed, specifically extremely low temperatures and snow/hail. The complete results of the What-If analysis are reported in Appendix C. For most of the safety barriers, the results evidence that the possible direct causes of failure identified

Table C1
What-if analysis carried out considering the set of safety barriers defined in Table B1 accounting for extremely low temperatures and snow/hail as effects of cold waves.

Cold weather effects	Consequences	Recommendations
Inert-gas blanketing system		
Extremely low temperature	• Formation of ice from ambient humidity on valves compromising their operability • Failure of pipework or valves due to brittle fracture • Driving force limitation in the vaporizer leading to a reduced flowrate of inert gas	• Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures • Consider indoor installation of vaporizers
Snow / Hail	• Accumulation on snow / hail on pipework and skids possibly leading to failures • Clogging of finned surfaces of vaporizers leading to a reduced flowrate of inert gas	• Avoid direct exposure to snowfall / hailfall – consider indoor installation or sheltering
Automatic rim-seal fire extinguishers		
Extremely low temperature	• Solidification of firefighting water /water solutions creating plugs or blocks on pipework and valves • Formation of ice from ambient humidity on valves compromising their operability • Failure of pipework or valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Consider using dry-pipe systems or maintaining flow in lines • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation on snow / hail on pipework and valves possibly leading to their failure	• Avoid direct exposure to snowfall / hailfall – consider sheltering
Fixed / Semi-fixed foam systems		
Extremely low temperature	• Solidification of firefighting water /water solutions creating plugs or blocks on pipework and valves • Formation of ice from ambient humidity on valves/nozzles hindering their operability • Failure of pipework or valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Consider using dry-pipe systems or maintaining flow in lines • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail on pipework and valves possibly leading to their failure	• Avoid direct exposure to snowfall / hailfall – consider sheltering
WDS / Water Curtains / Sprinklers		
Extremely low temperature	• Solidification of firefighting water /water solutions creating plugs or blocks on pipework and valves • Formation of ice from ambient humidity on valves/nozzles compromising their operability • Failure of pipework or valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Consider using dry-pipe systems or maintaining flow in lines • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail on pipework and valves possibly leading to their failure • Obstruction of nozzles	• Avoid direct exposure to snowfall / hailfall – consider sheltering
Hydrants		
Extremely low temperature	• Solidification of firefighting water creating plugs or blocks on valves • Formation of ice from ambient humidity on valves and connections compromising their operability • Failure of valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Consider using dry-pipe systems or maintaining flow in lines • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail on valves and connections possibly hindering operability	• Avoid the exposure of valves and connections to direct snowfall / hailfall – consider sheltering
Fire activated valves		
Extremely low temperature	• Solidification of firefighting water creating plugs or blocks on valves • Formation of ice from ambient humidity on valves compromising their operability • Failure of valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Consider using dry-pipe systems or maintaining flow in lines • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail on valves possibly leading to rupture	• Avoid the exposure of valves to direct snowfall / hailfall – consider sheltering
Fire and gas detectors		
Extremely low temperature	• Formation of ice from ambient humidity may hinder the detection of gases and fires	• Protect detectors from ice formation
Snow / Hail	• Accumulation of snow on sensors may hinder the detection of gases and fires	• Position the detectors to avoid snow accumulation
SDVs		
Extremely low temperature	• Possible solidification of the process fluid creating plugs or blocks on valves • Formation of ice from ambient humidity on valves compromising their operability • Failure of pipework or valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail on valves possibly leading to rupture	• Avoid the exposure of valves to direct snowfall / hailfall – consider sheltering
BDVs		
Extremely low temperature	• Possible solidification of the process fluid creating plugs or blocks on valves • Formation of ice from ambient humidity on valves compromising their operability • Failure of pipework or valves due to brittle fracture	• Apply heat tracing to vulnerable pipework • Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail on valves possibly leading to rupture	• Avoid the exposure of valves to direct snowfall / hailfall – consider sheltering
PSVs		
Extremely low temperature	• Formation of ice from ambient humidity on valves compromising their operability • Failure of pipework or valves due to brittle fracture	• Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures
Snow / Hail	• Accumulation of snow / hail in vent pipe in case of direct venting to environment	• Appropriate design of venting pipe to avoid obstruction by snow/ hail

(continued on next page)

Table C1 (*continued*)

Cold weather effects	Consequences	Recommendations
Fire walls		
Extremely low temperature	No relevant consequences identified	Not available
Snow / Hail	No relevant consequences identified	Not available
Blast walls		
Extremely low temperature	No relevant consequences identified	Not available
Snow / Hail	No relevant consequences identified	Not available
Fireproofing		
Extremely low temperature	• Possible cracks due to temperature cycling • Possible cracks due to very low temperatures	• Check design temperature range of fireproofing material
Snow / Hail	No relevant consequences identified	
Bunds / Catch basins		
Extremely low temperature	• Formation of ice from ambient humidity obstructing drain system	• Consider heat tracing of drain system
Snow / Hail	• Formation of ice from hail /snow obstructing drain system • Accumulation of snow / hail in bunds / catch basins reduces the storage capacity	• Consider heat tracing of drain system
Emergency Blowdown line to flare stack		
Extremely low temperature	• Formation of ice from ambient humidity on valves compromising their operability • Failure of pipework or valves due to brittle fracture • Solidification of process water used as a liquid seal in flare stack drums causing malfunctioning of the flare	• Assure that moving parts of valves are protected from water and vapor freezing • Select construction materials compatible with long exposure to extremely low temperatures • Apply heat tracing to critical sections
Snow / Hail	• Accumulation on snow / hail on pipework possibly leading to rupture • Accumulation of snow / hail causing flare obstruction	• Avoid direct exposure to snowfall / hailfall – consider sheltering • Appropriate design of venting pipe to avoid obstruction by snow/ hail
Mounding tanks		
Extremely low temperature	No relevant consequences identified	Not available
Snow / Hail	No relevant consequences identified	Not available
Burying tanks		
Extremely low temperature	No relevant consequences identified	Not available
Snow / Hail	No relevant consequences identified	Not available

through the What-If analysis are the same that were obtained from the analysis of the dataset collected in the present study (see Section 3.4): process fluid solidification, ice formation, brittle fracture, external load and power outage.

Based on the results of the What-If analysis, Table 4 provides a qualitative assessment of the failure credibility of each safety system. Three categories were defined to rank barrier vulnerability with respect to each direct cause of failure:

- Credible: barrier architecture makes the safety system specifically vulnerable to the direct failure cause considered.
- Unlikely: in principle, the barrier may be affected by the direct cause under analysis. However, the architecture of the safety system makes failure unlikely unless in extreme cases.
- Not possible: the direct cause cannot lead to the failure of the barrier for physical reasons (e.g., no process fluid is present, the fluid cannot solidify at low ambient temperatures, the power supply is not required, etc.).

Table 4 shows that failure results credible for several safety barriers when exposed to cold waves. Active barriers are in general more vulnerable than passive barriers to the direct causes expected in the case of cold waves. Systems related to fire extinguishment (e.g., rim-seal fire extinguishers, foam systems, and sprinkler systems) and critical assets protection systems (e.g., WDS, water curtains) may fail or be unavailable due to direct causes related to cold waves. Indeed, as discussed above, the presence of stationary firefighting water or water solutions represents a crucial aspect, as well as the exposure of components to atmospheric humidity and low temperature.

As for passive barriers, these resulted less affected by cold waves. In the case of fire walls, blast walls, and protective systems such as mounding and burying of equipment, no relevant consequences of cold waves were identified by the What-If analysis. The possibility of cracks in the material due to temperature cycling and very low temperatures should be considered in the case of fireproofing.

Criticalities were highlighted in the case of bunds/catch basins. Snow and hail can fill the catch basin reducing its storage capacity and leading to an overflow of the contained materials. Similar consequences may also occur in the case of drain blockage due to cold weather.

Possible issues were identified also for inert-gas blanketing systems and pressure safety valves. Extremely low temperatures may limit the driving force available in the vaporizer of the inert-gas system, leading to a reduction of inert gas flow rate and availability. Similarly, the presence of snow may clog the finned surface of the vaporizer.

In the case of pressure safety valves, ice may cause valve blockage and snow or ice may plug the vertical vent pipe in the case of direct venting to the atmosphere.

4. Lessons learned and preventive measures

4.1. Lessons learned from accident analysis

The results discussed above evidence that cold weather and related temperature extremes cannot be disregarded as triggers of potentially severe Natech accidents. Besides the characterization of such events, the information contained in the dataset collected allowed the identification of critical pathways which may lead to severe consequences. Thus, lessons learned are drawn in the following which can be useful to prevent or mitigate similar accidents in the future:

- As shown in Fig. 8, the presence of stationary fluids in pipework, such as bypass pipes or dead legs, can cause severe events in the case of cold waves. A relevant example is the accident that occurred at the Valero-McKee Refinery in 2014 (U.S. Chemical Safety and Hazard Investigation Board, 2008). To prevent this category of accidents, bypass pipes and dead legs should be identified and monitored, avoiding that process fluid remains stationary within the equipment by installing proper drainages or, alternatively, adopting heat tracing.
- Several accidents in the dataset were caused by the blockage of valves caused by the formation of ice on the stem and/or on external components. This may prevent correct flow regulation, and/or opening/closing of vents and drainages. It is important to identify the valves mostly exposed to the formation of ice, to protect them and/or to adopt valves not affected by the formation of ice.
- Brittle fractures causing the failure of process equipment and/or of components due to low ambient temperatures were reported as the cause of several accidents. The properties of metallic alloys and plastic materials may change when exposed to extremely low temperatures. Indeed, at low temperatures, the strength of most materials is significantly reduced possibly leading to brittle fractures. Thus, it is paramount to identify equipment items that may undergo

these phenomena during cold waves and to protect them by thermal insulation and/or heat tracing. The selection of construction materials less affected by cold weather, if possible, may also represent a good strategy to protect equipment from brittle fractures. In design procedures, minimum design temperatures should be selected considering the possible exposure to extremely low ambient temperatures in areas exposed to cold waves.

- Equipment items should be properly protected from snow and hail accumulation, resulting in an undesired external load. The analysis of the accident dataset suggests that the failure of equipment items and structural elements in process installations may occur due to the accumulation of snow or hail on horizontal or slightly inclined surfaces. Snow accumulation is particularly critical for floating and fixed roof atmospheric storage tanks, as it may cause the collapse of the roof with the consequent failure of the equipment and release of its content. Procedures are available to design tank roof accounting also for the snow load, e.g. the American Petroleum Institute (2007) Standard 650. However, extreme atmospheric phenomena in the framework of climate change may affect the intensity of snowfalls, which could result in a significant increase in credible snow loads during equipment operating life.
- The dataset analyzed also evidenced the possible damage of equipment items caused by the detachment of icicles that may hit underlying equipment. Appropriate protection from the detachment of icicles should be adopted in design. Regular monitoring and preventive procedures (such as the controlled detachment of icicles) should be applied in case of cold waves.
- Power failure during cold waves was also evidenced as a cause of accidents. Indeed, recent studies and past Natech accidents suggest that the damage or impairment of safety systems and utilities may lead to major accidents even without the direct damage of an equipment item (Misuri and Cozzani, 2021; Tokyo Electric Power Company Incorporated, 2012; U.S. Chemical Safety and Hazard Investigation Board, 2018b; Weightman, 2011). Although a low number of events caused the power outage was recorded in the database, these confirm that this indirect pathway to Natech accidents is possible also in the case of cold waves. Thus, the proper design of the main and backup power supply to withstand the requirement of the winter period is paramount to avoid accidents and ensure the continuity of plant operations.

4.2. Suggested measures integrating winterization programs

Lessons learned and results discussed in the previous sections confirm the hazards due to cold weather identified by the American Petroleum Institute (2019), where a list of possible problems that can be encountered in industrial sites during cold waves was listed. The direct causes of accidents identified in Section 3.4 are coherent with the criticalities remarked by the American Petroleum Institute (2019) and highlight additional failure modes that should be taken into account.

Besides the identification of accident pathways, the definition of programs and procedures to face cold waves and related temperature extremes is of paramount importance. The American Petroleum Institute (2019) outlines the main characteristics that a winterizing and freeze protection program should take into consideration:

- Identification of equipment items vulnerable to cold waves natural events and related extremes.
- Definition of protection measures to be implemented (e.g., eliminating vulnerable items, moving vulnerable items indoors, insulating vulnerable items, blowing water from lines with air, heat tracing).
- Establishment of plans specific for vulnerable equipment items.
- Inspection of the industrial site before, during, and after cold weather.

Concerning the identification of critical equipment items, conceptual formats for a winterization audit checklist are reported in the technical literature (Allianz Global Corporate and Specialty SE, 2018; American Petroleum Institute, 2019; FM Global, 2015). These represent a solid base for building a proper checklist based on the specific features of each industrial site.

In this framework, the effectiveness of the freeze protection approaches proposed by the American Petroleum Institute (2019) in contrasting the direct failure causes identified in Section 3.4 was assessed. The results are reported in Table 5.

Table 5 clearly shows the effectiveness of eliminating the dead legs to tackle the issues potentially posed by most of the direct causes identified in this study, in line with the results of the past accident analysis discussed in previous sections (see Section 3.4). In addition, moving equipment items indoor or underground has similar effectiveness, reducing exposure to extreme temperatures, snow accumulation, and ice formation. Indeed, according to the qualitative failure assessment proposed in Table 4, buried/mounded tanks are normally not affected by cold waves. The installation of heat tracing is also an effective strategy to contrast most of the direct failure causes and was also identified as a possible protective measure in the What-If analysis. Noteworthy, the possible unavailability of electric heat tracing should be accounted for in the case of power outages due to cold waves.

The approaches proposed by the American Petroleum Institute (2019) mainly focus on the prevention of process fluid solidification, confirming the relevance of the issue. Indeed, most of the strategies result to have positive effects against this direct cause.

However, none of the measures included in the list is suggested to contrast the possibility of a power outage. Thus, the list in Table 5 may be integrated with the assessment of the backup power supply system to avoid power interruptions to safety-critical systems, including heat tracing, during cold waves.

As a final remark, this study confirms that the development of winterizing and freeze protection programs is of paramount importance to increase preparedness to contrast the hazards of cold waves and to prevent the occurrence of Natech accidents. When properly designed, these programs allow for the reduction of the risks associated with cold waves and temperature extremes, thus contributing to an effective management of the risk caused by Natech events. Therefore, also considering the climate change framework, the design and adoption of an appropriate winterization program is not only necessary in geographical areas prone to cold wave-related natural events, but it as well important for industrial sites located in areas presently less exposed to such events. Indeed, as shown by the analysis of past accidents (see Fig. 3), severe events may be caused by scarce awareness and scarce preparedness to contrast hazards due to cold weather and temperature extremes.

5. Conclusions

Cold waves and low temperatures are becoming of increasing concern as their interaction with industrial installations may lead to Natech accidents characterized by severe consequences. In the present study, a database containing over 740 past Natech events caused by cold weather was built and analyzed. Results demonstrated that industrial sites can be particularly vulnerable to these natural events, even if they are typically considered to be of low intensity. Safety barriers may be affected by cold waves, reducing their availability and effectiveness. A high number of accidents occurred in geographical areas where this type of climate is less frequent, thus highlighting a lower preparation of these areas and therefore a greater vulnerability of the same. The most frequent cause of accidents was linked to the phase transition from the liquid to the solid state of substances (process fluid or water from the external environment). Lessons learned were drawn from accident analysis which can guide the proper development of winterizing and freeze protection programs. The results of the present study represent a step forward in the understanding of Natech accidents triggered by cold waves and provide key elements to prevent similar accidents from happening in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

This section reports the list and definitions of technological scenarios (Table A1) and industrial sectors (Table A2) used in the present study. The entries reported in the tables represent also the codification for itemized fields in the database. Definitions are adapted and integrated from those provided by Ricci et al. (2021a). Modifications introduced in the present study are reported in italic.

Appendix B

Table B2 reports the list of safety barriers considered in the present study together with a brief description of each system. The list and the definition are adapted from the classification provided by Misuri et al. (2020b).

Appendix C

This section reports the results of the What-If analysis carried out considering the set of safety barriers defined in Table C1 and two possible effects of cold waves: extremely low temperatures and snow/hail.

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