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Performance of Prevention and Mitigation Barriers in Natech Scenarios Triggered by Cold Waves

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The concern related to the interaction between natural events and industrial sites handling hazardous substances leading to Natech scenarios is rising. While current research primarily focuses on intense natural events, such as earthquakes and hurricanes, Natech events can also stem from lower-intensity events like cold waves. Even though their hazard to chemical industries is significant globally, there is a lack of attention and preventive investigations specifically addressing Natech accidents caused by cold waves. The present study emphasizes the importance of systematically examining safety aspects during cold waves, particularly focusing on safety barrier vulnerability and failure modes. Through detailed analysis, existing winterization measures are evaluated, strengths and areas for improvement are identified, and enhancements for winterizing and freeze protection programs are proposed. By addressing this knowledge gap, the study contributes to a better understanding of Natech accidents triggered by cold waves and provides essential insights to prevent similar incidents in the future.

1. Introduction

Natural events pose a well-acknowledged threat to industrial sites handling significant amounts of hazardous substances. The interaction of natural events and industrial installations can give rise to cascading scenarios, leading to critical technological accidents known as Natech events (Salzano et al., 2009). The concern about Natech accidents is on the rise due to the escalating frequency of natural disasters in recent decades (Centre for Research on the Epidemiology of Disasters, 2020) and the potentially serious consequences associated with such accidents (Krausmann et al., 2017). Current research endeavors have predominantly focused on examining the interaction between industrial sites and intense natural events like earthquakes, floods, and hurricanes (Mesa-Gómez et al., 2020). Nevertheless, Natech scenarios can arise from a variety of natural events, including those characterized by lower intensities (Casson Moreno et al., 2019). Indeed, instances of severe accidents, like the 2007 fire at Valero-McKee Refinery (U.S. Chemical Safety and Hazard Investigation Board, 2008) and the 2014 toxic release at the DuPont chemical plant (U.S. Chemical Safety and Hazard Investigation Board, 2019), underscore the impact of extremely low temperatures and harsh winter conditions on industrial installations. Moreover, recent studies have shown that low temperatures and other hazards related to cold waves triggered a non-negligible number of accidents worldwide (Ricci et al., 2020), being one of the more relevant causes of Natech accidents both in Europe (Krausmann and Baranzini, 2012) and in the United States of America (Luo et al., 2020).

In spite of the significance of the matter, scarce attention has been devoted in the existing literature to the study of Natech accidents caused by cold waves, and the effects of such natural events on safety systems are only marginally considered. Safety systems are crucial for managing risks in industries dealing with hazardous materials and processes (Mannan, 2005). Barriers play a key role in preventing or reducing the consequences of accidents (Yuan et al., 2022), enhancing safety by minimizing risks, controlling hazards, and preventing accidents. Integrating barriers into risk assessment methods is essential for developing robust safety management systems focused on continuous improvement for safeguarding people, assets, and the environment. However, safety systems may fail to activate when needed or may prove ineffective (Center for Chemical Process Safety, 2001). These failures are more likely during accidents triggered by natural disasters,

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which can directly impact barriers (Misuri et al., 2020) and emergency response (Ricci et al., 2024). The depletion of barrier performance (Misuri et al., 2023) and the criticalities related to the emergency response procedures (Ricci et al., 2022) can exacerbate the consequences of primary accidents and raise the probability of cascading events, worsening the risk associated with Natech scenarios. Despite growing interest in critical safety barrier issues, there are limited methods for assessing barrier performance in Natech scenarios, and quantification is currently available for only a few natural events, mainly floods and earthquakes (Misuri et al., 2020).

This study aims to bridge this gap by conducting a systematic examination of their safety-related aspects in Natech scenarios triggered by cold waves. The emphasis was placed on the vulnerability and failure modes of safety barriers. The analysis delved into the performance of safety barriers, considering the potential impact of extremely low temperatures and other events associated with cold waves. In addition, programs addressing winterization measures were scrutinized in light of the vulnerability and failure modes of the barriers, to identify both their strengths and areas for improvement. Suggestions and integrations stemming from the specific assessment of safety barrier integrity and expected performance during cold waves have been identified. Overall, this marks a significant step forward in the understanding of safety barrier performance in Natech accidents triggered by cold waves, providing key elements to guide the proper development of winterizing and freeze protection programs.

2. Methodology

To identify potential consequences and possible failure mechanisms of safety systems exposed to the effects of cold waves and related hazards, a “What-If analysis” is performed. What-if analysis systematically examines the repercussions of specific deviations from normal operating conditions, and it is a widely applied hazard identification technique (Uijt de Haag and Ale, 2005). In this study, this technique was employed to assess the potential impacts of cold waves, specifically extremely low temperatures and snow/hail, on the operation of safety barriers. The analysis was conducted on a predefined set of 17 safety barriers, reported and defined in Table 1, which encompasses a comprehensive list of those commonly utilized for fire mitigation and escalation prevention (American Petroleum Institute, 2019).

Table 1: Definition of safety barriers considered in the present study. Adapted from Misuri et al. (2020).

Safety barrier ID	Safety barrier	Classification	Description
AB.1	Automatic rim-seal fire extinguishers	Active	Automatic foam delivery system for prompt extinguishment of rim-seal fires.
AB.2	Blowdown valves	Active	Depressurization valves activating during emergency situations.
AB.3	Fire activated valves	Active	Valves activating in case of fire nearby.
AB.4	Fire and gas detectors	Active	Field sensors for detection of flames and gases.
AB.5	Fixed / Semi-fixed foam systems	Active	Systems for tank fire extinguishment by means of foam/water delivery.
AB.6	Hydrants	Active	Water sources for fire brigades.
AB.7	Inert-gas blanketing system	Active	System for inert gas delivery to storage tanks to prevent flammable atmospheres.
AB.8	Shutdown valves	Active	Isolation valves activating during emergency situations.
AB.9	WDS / Water Curtains / Sprinklers	Active	Systems for water delivery during a fire, either for flame extinguishment or critical asset protection.
PB.1	Blast walls	Passive	Physical barriers for blast protection.
PB.2	Blowdown line	Passive	Line for flaring employed during emergency situations.
PB.3	Bunds / Catch basins	Passive	Physical systems for liquid retaining in case of spill.
PB.4	Burying tanks	Passive	Locating vessels underground for fire protection.
PB.5	Fire walls	Passive	Physical barriers for fire protection.
PB.6	Fireproofing	Passive	Coating materials for fire protection.
PB.7	Mounding tanks	Passive	Locating vessels into gravel/ground mounds for fire protection.
PB.8	Pressure safety valves	Passive	Spring valve used to reduce the overpressure in a system.

Once the What-If analysis is performed and consequences and recommendations are identified, it is possible to recognize the main causes that can lead to the failure or depleted performance of barriers. Five main causes of failure were identified through the What-If analysis and classified: solidification of process fluid, formation of ice, brittle fracture, external load, and power outage. A detailed description of each cause is given in Section 3.1. Then, three categories were defined to rank the vulnerability of safety systems concerning each identified cause of failure:

- Credible: the safety system is vulnerable to the specific cause considering its architecture;
- Unlikely: the safety system can be affected by the specific cause in case of extremely severe cold waves;
- Not possible: the safety system cannot be affected by the specific cause for physical reasons.

Then, to provide a more concise result, an overall assessment of the qualitative failure probability of the safety system is proposed. The ranking was performed according to the following considerations:

- Very high: the failure of the safety system is considered at least credible for three of the identified causes
- High: the failure of the safety system is considered at least credible for two of the identified causes
- Moderate: the failure of the safety system is considered at least credible for one of the identified causes
- Low: the failure of the safety system is considered at most unlikely for the identified causes
- Very low: the failure of the safety system is considered not possible for the identified causes

Noteworthy, the occurrence of severe Natech accidents triggered by cold waves (U.S. CSB, 2019, 2008) paved the route to the development of winterizing and freeze protection programs mainly aimed at identifying vulnerable equipment, defining protection measures, and establishing specific emergency plans. Among others, the American Petroleum Institute (2019) proposed a list of freeze protection approaches aimed at protecting equipment items vulnerable to cold wave-related hazards. In this context, the effectiveness of the approaches proposed by the American Petroleum Institute was tested concerning the protection of safety barriers by comparing them with the recommendations resulting from the What-If analysis. Finally, possible additional approaches aimed at protecting safety barriers from the effects of cold waves are presented and discussed. The application of such measures could greatly reduce the probability of failure of safety systems when affected by cold waves.

3. Results

3.1 Qualitative assessment of safety barrier failure probability

According to the results of the What-If Analysis, five main causes of failure or performance depletion were identified for the safety systems taken into account:

- Solidification of process fluid. The fluid inside the safety barrier (water or other substances) solidifies forming plugs or blocks that damage the structure.
- Formation of ice. The formation of ice on the external surface of safety barrier elements due to the phase transition of liquid water present due to condensation of atmospheric humidity, rain, hail, or snow.
- Brittle fracture. Very low temperatures may exceed the brittle transition temperature of construction materials, leading to the fracture of equipment.
- External load. Failure of components due to excessive loading of structural elements due to hail/snow accumulation.
- Power outage. Failure of equipment that requires electrical supply to activate and work.

It is worth mentioning that such failure causes are in line with those identified by Ricci et al. (2023) and by the American Petroleum Institute (2019) when considering equipment items involved in past Natech accidents triggered by cold waves and related events.

Table 2 shows the qualitative vulnerability assessment of the safety systems concerning each identified cause of failure according to the methodology described in Section 2.1. The same table also reports the overall qualitative failure probability associated with each safety system.

Active systems are the most susceptible to the effects typically associated with cold waves. Among these, systems designed for fire extinguishment and critical asset protection systems (e.g., AB.1, AB.5, AB.9) resulted to be of particular concern. Indeed, these systems are characterized by the presence of stationary firefighting water or water solutions, which may solidify and create plugs in pipework and valves, making the system unavailable in case of demand. Moreover, these systems are also exposed to atmospheric humidity and low temperatures due to their typical location in industrial sites, adding relevant factors that contribute to the failure probability. Besides, additional issues were identified for the inert-gas blanketing system (AB.7). Specifically, low temperatures can limit the driving force in the vaporizer, reducing the inert-gas flow rate, and snow accumulation may obstruct the finned surface, affecting its performance.

In contrast, passive barriers appear to be less impacted by cold waves and related consequences. Indeed, the What-If Analysis did not identify significant consequences of cold waves on most of the passive systems included in the analysis. Indeed, only blowdown lines (PB.2) and pressure safety valves (PB.8) resulted in being vulnerable to the typical causes of failure recognized also for active systems. Nevertheless, it is important to note that specific consequences have been identified for some passive barriers, for example, the possibility of material cracking due to temperature fluctuations and extremely low temperatures when considering fireproofing. Concerns were raised also regarding catch basins, where snow and hail accumulation can reduce storage capacity and lead to material overflow, and low temperatures may result in drain blockage.

Table 2: Safety systems vulnerability concerning each identified cause of failure and overall qualitative failure probability of the safety barrier. See Table 1 for safety barrier ID. ●: Credible. ◐: Unlikely. ○: Not possible.

Safety barrier ID	Solidification of process fluid	Formation of ice	Brittle fracture	External load	Power outage	Qualitative failure probability
AB.1	●	●	●	◐	◐	Very high
AB.2	●	●	◐	◐	○	Very high
AB.3	●	●	◐	◐	○	High
AB.4	○	◐	○	○	◐	Low
AB.5	●	●	●	◐	◐	Very high
AB.6	●	◐	◐	◐	◐	Moderate
AB.7	○	●	●	◐	○	High
AB.8	●	●	◐	◐	○	High
AB.9	●	●	●	◐	◐	Very high
PB.1	○	○	○	○	○	Very low
PB.2	●	◐	◐	◐	○	Moderate
PB.3	○	○	○	○	○	Very low
PB.4	○	○	○	○	○	Very low
PB.5	○	○	○	○	○	Very low
PB.6	○	○	○	○	○	Very low
PB.7	○	○	○	○	○	Very low
PB.8	●	●	◐	◐	○	High

3.2 Effectiveness of existing freeze protection approaches

The freeze protection approaches proposed by the American Petroleum Institute (2019) are reported in Table 3. These approaches were developed to protect vulnerable equipment items from the hazards posed by cold waves and related events. Indeed, some of these approaches are very specific and targeted to a particular type of equipment, thus being not effective in the prevention of safety barriers failure. Some examples of interest regarding pipelines are the removal of dead legs or placing them underground, measures that do not find application when considering safety barriers. However, it is interesting to note that burying (PB.2) and mounding (PB.7) critical equipment is one of the barriers analyzed in the what-if analysis found to be not exposed to cold wave effects (very low failure probability according to Table 2), demonstrating its effectiveness in the context under study.

Looking at Table 3, it is interesting to note that there is at least one effective approach among those proposed by the American Petroleum Institute (2019) for almost all safety barriers whose credibility of failure is rated equal or higher than "low". This is not surprising considering that the main causes of failure of the barriers identified in this study are in line with the hazards identified by the American Petroleum Institute, as discussed in the previous section. However, most of the proposed approaches focus on preventing the solidification of the process fluid inside the system, and the other possible causes of failure are only marginally considered. As a way of example, using dry-pipe sprinklers or deluge systems, blowing water from lines with air, and maintaining flow in water lines are approaches whose sole purpose is to avoid the formation of solids within the system.

It is important to underline some critical issues related to the proposed approaches. When considering moving equipment indoors or building protective shelters, the second approach is the most effective concerning safety barriers. Indeed, it is typically not possible to move the system indoors, limiting the choice to the construction of shelters. A single exception concerns the inert-gas blanketing system (AB.7), for which it is possible to consider moving the vaporizer indoors to avoid the limitation of the driving force and the clog of the finned surfaces. Regarding heat tracing, the implementation of this measure has proven effective for many of the safety barriers analyzed (see Table 3). However, it is important to consider the potential power outage due to the impact of cold waves, which could lead to the failure of the protection system if electric heat tracing is implemented.

Therefore, the implementation of steam heat tracing is suggested to overcome this issue, at least on the particularly vulnerable elements.
Finally, the inspection of the site before, during, and after freezing weather was not expressly considered in the recommendations of the What-If Analysis. Nevertheless, this measure, when possible based on weather conditions, can help identify possible issues as they arise, allowing for consideration of ad-hoc measures to prevent complete malfunction of the affected system.

Table 3: Effectiveness of freeze protection approaches proposed by the American Petroleum Institute (2019) in the prevention of safety barriers failure. See Table 1 for safety barrier ID.

Freeze protection approaches	Identified in What-If Analysis?	Safety barriers on which it is effective
Eliminating vulnerable piping (especially dead legs)	No	-
Increasing “bird screen” mesh size on tank vents	No	-
Placing piping underground	No	-
Using dry barrels or “traffic type” fire hydrants	Yes	AB.6
Using dry-pipe sprinklers or deluge systems	Yes	AB.1, AB.3, AB.5, AB.9
Moving equipment indoors or building protective shelters	Yes	AB.1, AB.3, AB.4, AB.5, AB.6, AB.7, AB.9, PB.2,
Blowing water from lines with air	No	-
Maintaining flow in water lines	Yes	AB.1, AB.3, AB.5, AB.6, AB.9
Heat tracing (steam or electric)	Yes	AB.1, AB.2, AB.3, AB.5, AB.6, AB.8, AB.9, PB.2, PB.3
Insulating vulnerable resources	No	-
Inspection prior to/during/after freezing weather	No	-

3.3 Additional suggestions for effective winterization programs

In addition to the measures already discussed in the previous section to mitigate the likelihood of safety system failure, the What-If Analysis has highlighted other aspects that were not considered by the freeze protection approaches proposed by the American Petroleum Institute (2019). The additional recommendations identified are primarily aimed at mitigating causes such as ice formation on the external surface of components and brittle fractures, which were partially disregarded in existing programs.
Regarding ice formation on external surfaces, it is crucial to identify all vulnerable elements of safety systems susceptible to this consequence. Among these, the most important are the moving parts of valves, and it is vital to protect them from water and vapor freezing. Clearly enough, it is not possible to define in advance how these elements should be secured, as it depends on the plant configuration, element criticality, and other specific aspects. However, an effective winterization program must involve identifying these elements and implementing specific measures to ensure their proper functioning. Noteworthy, this measure applies to many of the safety barriers studied, as most require valve implementation.
Brittle fracture of components can be prevented by choosing appropriate materials during the design phase, compatible with prolonged exposure to very low temperatures. In this regard, it is paramount to properly define the minimum design temperature, also considering the possible long-term effects of climate change. For existing systems, instead, protective measures against brittle fractures can be represented by the implementation of thermal insulation or heat tracing, as reported also in the previous section.
A critical issue specifically identified for safety valves is the obstruction of vent lines by snow and ice when the release occurs directly into the environment. A similar problem may be encountered in blowdown lines, as ice and snow can block the flare. In these cases, it is crucial to proceed with an appropriate design of these lines to prevent the accumulation of snow and ice, thus preventing their obstruction and ensuring the proper functioning of the safety systems.
Regarding fireproofing, it is relevant to underline that the material can be prone to cracks due to thermal cycles and exposure to severe low-temperature conditions. Thus, it is crucial to carefully check the design temperature range of the fireproofing material and to arrange for repeated inspections during the most critical winter periods to verify its integrity.
The recommendations and suggestions provided stem from a specific study conducted on the operation of safety systems. However, it is important to emphasize that the guidelines provided in this section can be easily applied and extended to equipment and facilities with similar criticalities concerning cold wave effects.

4. Conclusions

The interaction between natural events and industrial installations presents a significant threat, often leading to critical technological accidents known as Natech events. While research has primarily focused on intense natural disasters like earthquakes and floods, the impact of cold waves on industrial safety systems has been largely overlooked. Safety systems are crucial for managing risks in industries dealing with hazardous materials, yet failures during natural disasters can compromise their effectiveness. The depletion of safety barriers during cold waves can exacerbate the consequences of accidents, highlighting the need for robust risk assessment methods tailored to Natech scenarios. This study addresses this gap by systematically examining safety-related aspects in Natech scenarios triggered by cold waves, focusing on the vulnerability and failure modes of safety barriers. As a result, active safety barriers such as those implemented for fire suppression and critical assets protection are particularly vulnerable to cold waves. The effectiveness of existing freeze protection approaches is tested to validate their applicability to safety systems. Moreover, areas for improvement and additional measures are identified to allow the protection of safety systems against the effects of cold waves. This research provides valuable insights to enhance safety barrier performance and guide the development of effective freeze protection programs. Overall, this study represents a significant advancement in understanding and mitigating the risks associated with Natech accidents triggered by cold waves.

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