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Natech Accidents Triggered By Heat Waves: Performance Of Safety Barriers

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Abstract

Technological accidents involving hazardous releases due to natural hazards are known as Natech. These high-impact and low-probability scenarios typically involve large areas, causing simultaneous releases and leading to on- and off-site secondary cascading events. Thus, preventing and mitigating their consequences is fundamental to implement safe and reliable technologies. Among the possible causes of climate-related technological accidents, extreme temperatures have been recognized as natural events responsible for many scenarios. Recently, due to the increasing concern regarding climate change and global warming, the interest in the impact of heat waves (e.g., high temperatures and drought) on industrial installations has significantly grown. In this context, the availability and effectiveness of safety barriers play a crucial role. This study focuses on analyzing the performance of safety barriers in the case of Natech events caused by heat waves. Data available in the literature are used to identify the most common types of systems used to protect facilities against these natural events. An ad-hoc analysis is performed to highlight the most frequent failure modes of safety barriers and the related consequences. Moreover, the systems most affected by heat waves are identified to build knowledge about the susceptibility of the different technologies (e.g., cryogenic technologies) to these events. The outcomes of the work provide key information to derive useful lessons that may guide the proper development and implementation of effective and improved safety barrier systems, helping to prevent the future occurrence of analogous accidents.

Keywords: natural hazard, Natech events, heat waves, safety barriers, failure modes, extracting lessons

1. Introduction

In the last decades, technological disasters triggered by natural events (Natech) have become topics of primary concern due to the increasing number of climate-related accidents reported (Luo et al., 2021; Ricci et al., 2021) . Despite their long return periods, natural events are a great issue for industrial facilities because of their potentially severe impact (Mesa-Gómez et al., 2020). Indeed, Natech events can affect several components at the same time, causing simultaneous releases of hazardous materials from different locations in the plant (Krausmann and Cruz, 2013). Moreover, further pieces of equipment can be involved due to the escalation of the accidents (i.e., domino effect (Girgin, 2011)) and disruptions can affect utilities and safety systems with consequent heavy damages (Misuri, Antonioni, et al., 2020). Examples of the severe impact of natural events, such as hurricanes (Cruz and Krausmann, 2008; Qin et al., 2020), earthquakes, and tsunamis (Krausmann and Cruz, 2013) on industrial facilities can be found in the literature.

To date, emphasis has been mostly placed on the investigation of the impact of short-lived natural events (e.g., earthquakes, floods, hurricanes, and lightning) and several strategies for the Quantitative Risk Assessment (QRA) in case of such events have been developed (Antonioni et al., 2009; Cozzani et al., 2014). However, also "low" intensity long-lasting natural events can trigger Natech accidents. In fact, as highlighted in previous studies, extreme temperatures have been identified as responsible for 12% of the Natech accidents recorded until now (Moreno et al., 2019; Ricci et al., 2021). In the perspective of climate change and global warming, the interest in the analysis of the impact of these natural events on industrial plants is foreseen to significantly grow.

Moreover, since the global ambient temperature is predicted to further increase in the near future, resulting in hotter seasons and prolonged drought periods (Internal Panel on Climate Change, 2023), heat waves will be a topic of high concern.

Extreme temperatures include two opposite natural events: cold waves (i.e., extremely low temperatures, snow, and hail) and heat waves (i.e., extremely high temperatures and drought). The first have been demonstrated to be the third leading cause of Natech accidents in Europe (Krausmann and Baranzini, 2012) and their impact on both equipment items and safety barriers in industrial facilities has been investigated by extracting lessons learned from past accidents (Ricci et al., 2023a). The same approach has been used to build detailed statistics regarding the components categories (e.g., storage equipment, road tankers, pipeworks) involved in Natech accidents triggered by heat waves, as well as their impact and the resulting technological scenarios (Ricci et al., 2023b). It has been proven that the hazardousness of heat waves derives from five direct causes of failure, with the pressure increase inside the equipment (40.2%) and the self-ignition of materials and substances (11.3%) being the most critical ones. In addition, material degradation, lens effect (i.e., the heating of a material due to the convergence of sunrays into a small area caused by a glassy material), and power outage have also been indicated as relevant direct causes. However, for a significant share (32.4%) of the accidents, the direct impact of heat waves has not been identified. In terms of technological scenarios that occurred in Natech accidents triggered by heat waves, the most common ones are fires, releases without ignition, and environmental contamination. Only in a limited number of cases the technological scenario resulted in toxic dispersions, explosions, and near misses (Ricci et al., 2023b).

Until now, the impact of natural in the Natech framework has been mainly investigated considering exclusively the "direct" impact of the natural events on equipment items and the possible consequent loss of containment events (LOCs) of hazardous substances (Misuri and Cozzani, 2021). However, there are evidence (Crosby, 2018; Tokyo Electric Power Company Inc, 2012) that Natech events can also be generated by the failure of safety systems and utilities caused by natural events. Thus, their "indirect" impact on these systems must be investigated to be included in a comprehensive Natech risk assessment. At present, the analysis of the effects of heat waves on safety barriers is still missing in the literature.

The present study investigates the possible interactions between heat waves and safety barriers (SBs). This relationship is assessed through a What-if analysis, a systematic method for exploring the consequences of various hypothetical situations widely applied in the literature (Ricci et al., 2023a). The effects of heat waves (extremely high temperatures and drought) on safety systems are identified and recommendations to mitigate and prevent their degradation or malfunctioning are highlighted. The outcomes of this work enhance the understanding of the relationship between the target natural events and safety barriers. They provide an overview of their resilience to heat waves and valuable information to improve and design effective and reliable safety systems able to withstand heat wave-triggered Natech events.

2. Methodology

Measures implemented in the process industry to shield equipment items from hazards are referred to as safety barriers (Rausand, 2011). In this study, their performance in case of heat wave-triggered Natech events is qualitatively assessed through a "What-if" analysis. This is a scenario-based hazard evaluation procedure relying on a brainstorming approach aimed at identifying the possible malfunctioning and failures of items, their consequences, and judging their likelihood (Center for Chemical Process Safety, 2008). The flowchart of the methodology is illustrated in Figure 1.

The initial step of the methodology consists of the definition of the boundaries of the review. In the present study, the safety barriers are the only components that fall within the scope of the analysis. Generally, they are classified into three groups based on their working principles principles (Center of Chemical and Process Safety, 2012; Center of Chemical Process Safety, 2001):

- passive: physical protections permanently available that do not require any activation;
- active: technical systems that require activation (e.g., automatic and/or manual) to be in function;
- procedural: operative procedures and plans to be performed by personnel.

Procedural safety barriers are not considered in the present study.

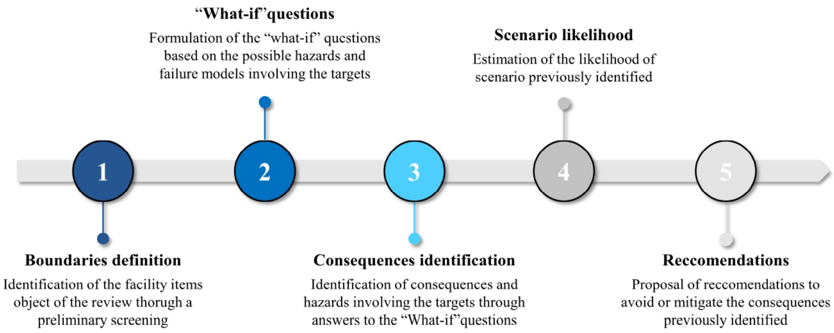

Fig. 1. Flowchart of the "What-if" methodology.

The passive and active safety barriers mostly present in industrial plants and typically considered in performance assessment studies (Misuri et al., 2021; Misuri, Landucci, et al., 2020) are summarized and briefly described in Table 1.

Table 1. Passive and active safety barriers in process plants.

Safety barriers	Classification	Description	SB ID
Automatic rim-seal fire extinguishers	Active	Pressurized foam storage connected to a N_2 charging activated through melting elements	SB01
Blast walls	Passive	Physical barrier resistant to blast waves	SB02
Blow Down Valves (BDVs)	Active	Fail-open venting process fluid to flare for fast depressurization of the item	SB03
Buried storage	Passive	Storage tanks positioned under ground level	SB04
Bund/Catch basins	Passive	Structures sized to retain the whole liquid content of a tank and prevent liquid spread	SB05
Emergency Blow Down (EBD) line to flare stack	Passive	Line after the EBD valves that vents the process fluid to a flash KO drum and to the flare stack	SB06
Fire activated valves	Active	Valves activated through melting elements or heat detectors	SB07
Fire and gas detectors	Active	Sensors to detect fire, smoke and heat	SB08
Fire walls	Passive	Physical barrier resistant to fires	SB09
Fireproofing	Passive	Coating specific to protect equipment items form fire	SB10
Fixed/semi-fixed foam systems	Active	Deliver water-based foam system (water storage tanks, diesel tank, water, diesel and electric pumps)	SB11
Hydrants	Active	Sources to connect firehoses and deliver water to burning areas	SB12
Inert gas blanketing systems	Active	Inert gas (N_2) storage tank, vaporizers and delivery pipes	SB13
Mounded storage	Passive	Tank positioned into above-ground piles of gravel/earth (mounds)	SB14
Shut Down Valves (SDVs)	Active	Fail-close valves activated manually or by shut-down logic to isolate the equipment item	SB15
Water Delivery System (WDS)/Water curtains and sprinklers	Active	Sprinklers and water system distribution	SB16

In this stage, a preliminary screening is performed to identify the SBs that can be impacted by the heat waves and exclude the systems whose performance is not sentitive to such natural events. The screening is done considering the working principle of each safety system and its components, as well as the direct failure modes identified in the literature for heat waves (Ricci et al., 2023b), that are:

- Pressure increase
- Self-ignition
- Material degradation
- Lens effect
- Power outage

Secondly, a list of “What-if” questions is formulated around the possible scenarios (i.e., hazards and failure modes) involving the components of interest. These questions can address several situations, from process conditions disruptions to equipment failure or external influences, such as weather. After all the potential “What-if” scenarios have been exhausted, the consequences are found by answering the questions. Finally, the likelihood of each scenario is discussed. Based on the outcomes of the review, a list of recommendations whose implementation may reduce or even avoid the identified consequences is proposed.

3. Results

As a result of the preliminary screening, six safety barriers have been excluded from the analysis since the reduction of their performance as a consequence of heat waves does not seem to be credible. It is worth noticing that five of them are passive systems (SB02, SB04, SB05, SB09, and SB14, see Table 1 for the definition of the acronyms) and only one is active (SB12). The five passive barriers (i.e., blast walls, buried storage, bund/catch basins and mounded storage) have been ignored in the following analysis because they are made of resistant materials, such as concrete, for which degradation and self-ingition mechanisms due to hot temperatures caused by heat waves are not credible. Moreover, in these barriers no other substances are present and no power supply is required. Therefore, also all the other failure modes are not possible. Similarly, hydrants (SB12) have been excluded because of the absence of temperature susceptible materials and power source.

The results of the “What-if” analysis applied to the remaining ten safety systems are reported in Table 2.

Table 2. Results of the "What-if" analysis on the safety barriers defined in Table 1 and whose performance is impacted by the effect of heat waves. BDVs = Blow DownValves; EBD = Emergency Blow Down; SDVs = Shut Down Valves; WDS = Water Delivery System.

Heat wave effect	Consequences	Effect on the system	Recommendations
SB01: Automatic rim-seal fire extinguishers			
Hot temperatures	• Pressurization due to the vaporization/heating of the fluid inside (glass bulbs filled with a glycerin-based liquid) the seal with consequent activation of the component	• No material available for fire extinction if needed	• Use fluids with high temperature ratings
	• Degradation of the fusible (fusible link fire sprinklers) materials with consequent activation of the component	• No extinguisher available for fire extinction if needed	• Use fusible with high temperature ratings
	• Lens effect (glass bulbs filled with a glycerin-based liquid) heats up the fluid inside with consequent activation of the component	• No extinguisher available for fire extinction if needed	• Use glass with high temperature ratings
	• Lower foam performance due to degradation reactions promoted by the increase of the storage temperature	• Difficulties in extinguishing the fire (e.g., longer time and higher amount of foam required)	• Avoid, or at least minimize, the exposure of the foam storage tank to high temperatures placing the tank indoors, where temperature cycling is reduced, or in temperature controlled environments
Drought	• No relevant consequences	• No effects	• Not available
SB03: BDVs			
Hot temperatures	• Increase of the velocity through the valve due to the vaporization of the fluid in the line upstream the BDV	• Vibration of the valve and possible damages • Accumulation of the fluid in the line downstream the BDV (the restriction orifice after the valve limits the flow rate to the flare that could lead to the fast pressurization and cooling of the depressurization section with possible negative effects on the flare stack (e.g., due to the Joule-Thompson effect))	• Apply an insulation system on the most critical lines (e.g., lines with cryogenic liquids)
Drought	• No relevant consequences	• No effects	• Not available

Table 2 (Continued)

SB06: EBD line to flare stack			
Hot temperatures	- Pressurization of the line and Flash KO drum due to the heating/vaporization of the fluid	- Vibration of the valve and possible damages - Higher amount of vapor in the flash KO drum and consequently higher flow rate to the flare stack and less liquid to waste disposal/pressurization of the KO drum - Less auxiliary fuel to the flare stack	- Apply an insulation system or use materials with high temperatures for the Flash KO drum and line
Drought	- No relevant consequences	- No effects	- Not available
SB07: Fire activated valves			
Hot temperatures	- Degradation of the material of the melting elements	- Activation of the valve and unexpected and unwanted venting of the fluid (loss of fuel)	- Change the material of the melting element
Drought	- No relevant consequences	- No effects	- Not available
SB08: Fire and gas detectors			
Hot temperatures	- Local temperature increase due to Lens effect because of the presence of glass in the detector	- Wrong detection and activation of fire proofing systems (only for detectors activated by temperature)	- Add protection
Drought	- No relevant consequences	- No effects	- Not available
SB10: Fireproofing			
Hot temperatures	- Possible cracks due to temperature cycling	- Not effective fire protection of the tank	- Check design temperature range of fireproofing material
Drought	- No relevant consequences	- Not available	- Not available
SB11: Fixed/semi-fixed foam system			
Hot temperatures	- Pressurization of the diesel tank (for energy supply) due to vaporization of the fluid	- Venting of the vaporized fluid with consequent reduction of the energy supply (less diesel available), thus no water to produce the foam	- Apply a protection on the tank - Recirculation system of the vaporized fluid
	- Lower foam performance due to degradation reactions promoted by the increase of the storage temperature	- Difficulties in extinguishing the fire (e.g., longer time and higher amount of foam required)	- Avoid, or at least minimize, the exposure of the foam storage tank to high temperatures placing the tank indoors, where temperature cycling is reduced, or in temperature controlled environments
Drought	- No alternative water sources (e.g., water drainage sewers and environmental ponds)	- No reduction of operational costs and no constructions benefits - Reduction of fire extinguishing water	- Use of alternative water supply/cooling water tower basins - Use of cooling water tower basins
SB13: Inert gas blanketing system			
Hot temperatures	- Pressurization of the inert gas (N_2) inside the storage tank	- Venting of the inert gas and less gas available for barrier operation	- Apply/improve the insulation of the storage tank
Drought	- No relevant consequences	- No effects	- Not available
SB15: SDVs			
Hot temperatures	- Increase of the velocity through the valve due to the vaporization/heating of the fluid in the line upstream the SDV	- Vibration of the valve and possible damages	- Apply an insulation system on the most critical lines (e.g., lines with cryogenic liquids)
Drought	- No relevant consequences	- No effects	- Not available
SB16: WDS/Water curtains and sprinklers			
Hot temperatures	- No relevant consequences	- No effects	- Not available
Drought	- No alternative water sources (e.g., water drainage sewers and environmental ponds)	- No reduction of operational costs and no constructions benefits - Reduction of fire extinguishing water	- Use of alternative water supply/cooling water tower basins - Use of cooling water tower basins

The outcomes of the qualitative assessment of the likelihood of the failure of the safety barriers due to the impact of heat waves are reported in Table 3. The same failure modes identified for equipment and mentioned in Section 1 have been considered. The failure of the SB has been defined as credible (C) when the safety barrier is highly vulnerable to the heat wave, unlikely (U) when the SB is impacted by the heat wave only under extreme circumstances, and not possible (NP) when the performance of the barrier is not influenced by the natural event due to physical reasons.

Table 3. Qualitative assessment of the likelihood of safety barrier failure due to the impact of the heat wave; C = Credible, U = Unlikely, and NP = Not Possible.

Direct causes	Pressure increase	Self-ignition	Material degradation	Lens effect	Power outage
SB01	U	NP	U	C	U
SB02	*Safety barrier not affected by heat waves*				
SB03	C	NP	U	NP	NP
SB04	*Safety barrier not affected by heat waves*				
SB05	*Safety barrier not affected by heat waves*				
SB06	C	NP	U	NP	NP
SB07	NP	NP	U	NP	NP
SB08	NP	NP	NP	C	U
SB09	*Safety barrier not affected by heat waves*				
SB10	NP	NP	U	NP	NP
SB11	C	NP	C	NP	U
SB12	NP	NP	NP	NP	U
SB13	C	NP	NP	NP	NP
SB14	*Safety barrier not affected by heat waves*				
SB15	C	NP	C	NP	NP
SB16	NP	NP	NP	NP	U

4. Discussion and preventive measures

The results reported in Table 2 clearly highlight heat waves can negatively affect the performance of safety barriers, mainly due to the consequent extremely hot temperatures. On the contrary, the effect of drought can be neglected for almost all the systems, except for the ones that require water (SB11 and SB16). In fact, in case of prolonged periods of drought, the reserve of usable water is reduced due to the lack of rainwater. Thus, the provision of larger water reservoirs or the use of alternative sources (e.g., water from cooling tower basins) is needed.

As already mentioned above (see Section 4), none of the five direct causes identified as impacts of the heat waves on systems are possible for five passive safety systems. The first exception is the emergency blowdown (SB06), due to the presence of pipes and a flash drum that can be pressurized due to heating/vaporization of the fluid inside. The second is the fireproofing system, whose integrity could be compromised by frequent temperature cycles that cause the dilatation and compression of the tank material upon which the system is fixed. Among the remaining active safety barriers, the ones used in firefighting operations (SB01, SB07, SB08, SB11, and SB16) are not significantly affected by heat waves. In fact, the likelihood of impact of the direct causes is classified as either unlikely or not possible for most cases. This is coherent with the function of these systems, which are designed to activate in case of fire and are therefore sensitive to extremely high temperatures, much higher than those caused by heat waves. In terms of direct causes of the natural event on the systems, the pressure increase is the most credible, while the self-ignition of materials is not credible in any case.

It is worth noticing that in the present analysis, the impact of heat waves on safety systems has been assessed considering on effect at time, either high temperatures or drought. However, by combining these two, it is credible that the likelihood of some impacts could increase. For instance, as pointed out before, the scarcity or, in the worst-case scenario, the absence of rainwater could lead to the necessity to use part of the cooling water (e.g., the cooling water of tower basins) for different purposes, such as in WDS. Therefore, the remaining amount of water could be not sufficient to effectively refrigerate equipment in the facility and protect them from high temperatures. As a result, the degradation of some materials particularly vulnerable to high temperatures could occur faster.

Given the results of the analysis and to avoid or at least mitigate the possible impact of heat waves on safety barriers, some protection approaches (Table 4) are proposed (American Petroleum Institute, 2019). Most of them are effective in the prevention of the pressure increase in safety barrier systems and are also able to avoid the degradation of materials, while others are specific for systems that require the use of water.

As already mentioned and visible from Table 3, heat waves do not represent a significant threat to safety systems because they are often unlikely to affect their performance or, in the best cases, SB are completely invulnerable to them. However, the analysis of their effects, particularly in terms of hot temperature, could be a significant for some type of equipment, such as cryogenic components.

Table 4. Protection approaches for safety barriers against heat waves.

Protection approaches	Target heat wave impact	Benefit of the system
Using alternative water sources for fire extinguishing	• Water sources for fire extinguishing systems	• More water for fire extinguishing systems • No need to use of cooling water tower basins • Reduction of operational costs and construction benefits
Using cooling water tower basins	• Water sources for fire extinguishing systems	• More water for fire extinguishing systems
Using independent contingency power sources for firewater pumps to decrease the vulnerability of the system	• Vaporization of the fuel used to for pump activation (e.g., diesel) and reduction of the energy supply • Foam performance in fire extinguishing	• Compensation of the power supply for water pumps in fire extinguishing systems (e.g., fixed/semi-fized foam systems) • Higher foam performance in fire extinguishing
Insulating vulnerable resources	• Heating/vaporization of fluids inside equipment and consequent pressurization • Degradation of materials and melting elements	• No unexpected activation of valves/fire extinguishing systems (e.g., Automatic rim-seal fire extinguishers) • No vibration of elements (e.g., valves) • No need to manage higher flow rates (e.g., in the lino to the flare stack)
Avoiding glass surfaces and components in critical areas	• Lens effect	• No material degradation • No local temperature increase and wrong activation of temperature-based fire detection systems
Placing piping underground	• Heating/vaporization of the fluid inside equipment and consequent pressurization	• No vibration of elements (e.g.,valves) • No need to manage higher flow rates (e.g., in the lino to the flare stack)
Moving vulnerable equipment inside	• Heating/vaporization of the fluid inside equipment and consequent pressurization • Degradation of materials and melting elements • Lens effect	• No unexpected activation of valves/fire extinguishing systems (e.g., Automatic rim-seal fire extinguishers) • No vibration of elements (e.g., valves) • No need to manage higher flow rates (e.g., in the lino to the flare stack) • No local temperature increase and wrong activation of temperature-based fire detection systems • No material degradation
Eliminating/substituting vulnerable equipment	• Heating/vaporization of the fluid inside equipment and consequent pressurization • Degradation of materials and melting elements • Lens effect	• No unexpected activation of valves/fire extinguishing systems (e.g., Automatic rim-seal fire extinguishers) • No vibration of elements (e.g., valves) • No need to manage higher flow rates (e.g., in the lino to the flare stack) • No local temperature increase and wrong activation of temperature-based fire detection systems • No material degradation

Cryogenic components containing cold fluids, such as storage tanks for Liquefied Natural Gas (LNG) or liquid hydrogen (LH_2), are always protected with high-insulating materials to minimize the heat transfer from the environment to the cold fluid, that is driven by the high temperature difference (around 273 K for LH_2 considering at ambient temperature of 293 K and a storage temperature of 20 K). In this way, the vaporization of the cryogenic liquid fluid and the consequent pressurization of the equipment are reduced and it is possible to avoid fuel losses (i.e., there is no need to depressurize the equipment by venting the vapor phase through a relief device). Clearly, for equipment placed outdoors the increase in the ambient temperature is an issue in this sense because it enhances the heat transfer by increasing its driving force (i.e., the temperature difference). While cryogenic storage equipment components go beyond the focus of the current study, the methodology applied in this study could be adapted to qualitatively investigate the impact of heat waves on this type of equipment and could build the basis for further quantitative assessment.

5. Conclusions

In the present study, the consequences of the impact of heat waves on safety barriers have been assessed through a “What-if” analysis to investigate the potential degradation of their performance due to exposure to extremely high temperatures and drought. High temperatures have been identified as the major cause of safety barriers performance degradation, while it has been assessed that the impact of drought is not relevant in most cases. Considering the type of safety systems, active safety barriers appear as more vulnerable to this type of natural event compared to passive ones. Moreover, systems designed for fire protection purposes are quite resilient to heat waves, given that they are designed to operate in the presence of a fire and to stand extremely high temperatures. Finally, based on the impact of the heat waves on safety barriers, defined in terms of five main direct causes (i.e. pressure increase, self-ignition, material degradation, Lens effect, and power outage), recommendations for their mitigation and prevention have been proposed. The results of this work contribute to the knowledge of Natech events triggered by heat waves, provide key information to support the design of more resilient and effective safety systems, and outline interesting future research directions to follow-up with detailed safety barrier performance analysis.

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