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Combinations of fires with other types of hazards in nuclear and process industry installations

Keywords

fire, event combination, hazard, operating experience, screening

Abstract

Operating experience from different types of industrial installations has shown that combinations of different types of external and internal hazards can occur during the entire lifetime of the installations. Typically, site specific occurring hazards cause or induce other hazardous events (cascading effects) to occur. In particular, natural hazards rarely occur alone. Operating experience collected from nuclear installations has indicated that combinations of fires and other anticipated events do occur during the entire lifetime of these installations from the construction, over the operational phase up to the decommissioning of the installation. Therefore, it was decided to investigate combination of fires and other events or hazards in more detail. This paper presents an overview on lessons learned from event combinations of fires and other hazards occurred at nuclear installations and provides a partly automated approach for selecting credible combinations for different types of installations and the complete spectrum of site.

1. Introduction

Operating experience from nuclear installations has shown that combinations of fires and other anticipated events do occur during the entire lifetime of these installations. Therefore, it was decided to investigate combination of fires and other events or hazards in more detail. The required function of systems, structures, and components important to safety may be impaired in case of the occurrence of such event combinations. Thus, it is very important to note that almost any event combination of hazards is possible and that it is necessary to identify these interactions specifically for each type of industrial facility and to determine ways to mitigate the effects of such hazard combinations, called combined hazards, as far as reasonably practicable. Therefore, it was decided on an international basis to investigate combinations of fires and other anticipated events, in particular hazards, in more detail. For this investigation, three types of combined hazards are being distinguished:

- *causally related*, so-called *consequential* or *subsequent events*, such as initial fire and consequential event, or initial event and consequential fire,
- *correlated events*, such as flooding and fire occurring correlated by a common cause initiator, such as an earthquake or tsunami,
- *unrelated events* occurring independently of each other simultaneously, such as a fire and another event, e.g. a longer duration flooding

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occurring independently simultaneously (one during the mission time of the other).

For each of these groups of combined fire hazards it has to be systematically checked based on the site characteristics and the specific design of the installation being investigated which types of internal or external hazards can occur in combination with fires. Such a hazards screening process is needed to select for the installation a) potentially possible combined fire hazards and b) credible combined fire hazards, for which a detailed fire safety assessment is needed. As a result, a complete list of possible combinations can be generated representing the basis for future assessments, even though only some of them have so far been observed from the operating experience recorded in international databases such as the international Fire Incidents Records Exchange (FIRE) Database launched by the OECD Nuclear Energy Agency (NEA).

Basis for the investigation of the operating experience feedback presented hereafter is the updated OECD/NEAFIRE Database in the most recent version 2019:01 containing in total 546 fire events up to the end of 2019. A set of 62 of these fire events has been identified as event combinations of fires and other events. More than half of these event combinations represent fires subsequent to a high energy arcing fault (HEAF).

Some fire hazard combinations are combinations of multiple events (so-called event chains), which show cascading/domino effects comparable to situations also known in other industrial installations, in particular in process and chemical industry.

The chapter consists of seven parts with this Introduction as Section 1, Sections 2 to 6, and some brief concluding remarks and an outlook in Section 7. Section 2 is devoted to combinations of fires and other hazards. The categorisation of different types of internal and external hazards and their combinations is presented in Section 3, followed by a description of the hazards screening process for analyses in Section 4. The corresponding operating experience feedback on combined fire hazards is provided in Section 5. Finally, a summary of results for both types of industries is given in Section 6. The possibility of a wider application of in-depth analyses for combinations of fires and other hazards is considered in this chapter and suggested in the last Section 7.

2. Cascading effects

The complexity of domino and cascading effects requires the application of a proper risk assessment methodology. In the common practice, the risk evaluation is performed for independent events where single risk indexes are determined.

Cascading effects are the dynamics present in accidents in which the impact of a hazard or the development of an initial technological or human failure generates a sequence of events. Thus, an initial impact can trigger other phenomena leading to severe consequences. Cascading effects are complex and multi-dimensional and evolve constantly over time. They are associated with a high degree of vulnerability.

However, when considering domino and cascading effects which are often induced by external hazards, the resulting risk may be higher than the simple aggregation of the individual risk. For this reason, multi-risk assessments should be carried out taking into account all possible interactions of risks due to cascading effects.

Combinations of events have already been investigated in process and chemical industry for many years because several major accidents occurred, often damaging equipment enclosures. Operating experience from different types of industrial installations has shown that event combinations of fires and other events occur throughout their entire lifetime.

The nuclear operating experience from the recent past also underlines the necessity to take into account event combinations in the safety assessment of nuclear power plants, because the required function of systems, structures and components (SSCs) important to nuclear safety may be impaired in case of the occurrence of event combinations of fires and events. For example, combinations of causally related events such as earthquakes and consequential fires may significantly impair or even totally disable SSCs and even may not be limited to one reactor unit at multi-unit sites.

3. Different types of hazards and hazard combinations

When considering those hazards which may impair the safe operation of an industrial facility such as nuclear installations, in principle, two types of hazards have to be distinguished: internal and external hazards.

Internal hazards are those occurring under the responsibility of the operator of the nuclear installation on the site of the corresponding installations (e.g. one plant or more plants).

External hazards are those ones occurring independent of the facility being analysed, off-site, and out of the responsibility of the plant operator. External hazards may result from natural causes – so-called natural hazards – or maybe induced by humans – so-called human induced (or man-made) hazards.

Natural hazards can be further subdivided into different classes of hazards corresponding to the types of phenomena covered.

When combining hazards with other anticipated events, three different categories of combinations – combinations of consequential events, of correlated events, and of unrelated events – need to be distinguished according to recent guidance provided by the International Atomic Energy Agency (IAEA) in (IAEA, 2021).

3.1. Combinations of consequential events

The events of this group of event combinations are causally related, they occur subsequent to each other. An initial event, for example, an external hazard, results in another consequential event, for example, an internal hazard. Typical examples are seismic and consequential internal explosion and/or fire, internal fire and consequential internal flooding, external flooding and consequential HEAF of a component and subsequent fire.

It has to be noted that not only combinations of two events but event chains of three or more events are in principle possible. However, such longer event chains are more unlikely.

3.2. Combinations of correlated events

Two or more events, at least one of them representing a hazard, do occur as a result from a common cause initiator. The common cause can be any anticipated event including external hazards. The two or more events correlated by this common cause could even occur simultaneously. Examples are landslide and a high energetic components failure, both induced by a seismic event, or an internal explosion (at one component) and a fire (at another component) correlated by a meteorological impact.

3.3. Combinations of unrelated events

An initial event, for example, an external or internal hazard occurs independently from but simultaneously to a hazard without any common cause. Typical examples are external flooding and independent internal fire or explosion, seismic event, and independent internal fire.

For each of these groups of event combinations it has to be systematically checked which types of internal or external hazards can result from such combinations with fire events. Possible combinations have been identified within the OECD/NEA FIRE Database Project and are listed in Table 1.

Table 1. List of the combinations of fires and other events observed in the FIRE Database (OECD/NEA, 2021)

Combination Category	Events observed in the FIRE Database
Combinations of consequential events	*Event and consequential fire:* Meteorological hazards (lightning, precipitation) => fire Biological hazards (ingress of leaves by animal) Internal flooding => fire HEAF => fire Internal explosion => fire *Fire and consequential event:* Fire => fire Fire => flooding Fire => HEAF Fire => explosion *Event chain of more than two events:* Seismic hazards => HEAF => fire Hydrological hazards (external flooding) => fire Fire => HEAF => fire HEAF => fire => flooding HEAF => explosion => fire Missiles => fire => flooding
Combinations of correlated events	Two fires correlated by a common cause initiator
Combinations of unrelated events	External riverine flooding and fire

Event combinations from all three combination categories provided in (IAEA, 2021) have been observed. However, other combinations can be expected to occur, particularly fires and other events being induced by a variety of common causes which cannot be excluded to occur.

4. Screening of combined fire hazards

In order to systematically address all types of combinations of hazards, including combinations of fires and other anticipated events, a semi-automated hazards screening approach has been recently developed and successfully validated by GRS (Röwekamp et al., 2020; Mayer et al., 2020). This approach is meanwhile supported by a software tool, called *Hazards Screening Tool* (HST), which enables the analyst to carry out for a single or for multiple installations at a given site a comprehensive hazards screening covering also hazard combinations (Strack et al., 2020).

4.1. Screening approach realized by the HST

In the following the hazards screening by the HST is briefly summarized, and two examples of the screening, the first one for a nuclear site with multiple reactor units and other nuclear sources, the second one for a site with only one nuclear installation are presented.

Basis for the hazards screening is a comprehensive compilation of the entire individual (single) hazards. Therefore, in a first step, the entire potential single hazards (external ones as well as internal ones) are identified for a given site and installation(s) to be investigated from the generic set of all hazards (*G*). The result is a generic set of all individual hazards (*I*) remaining for the screening. In a second step, a two-step qualitative (step 2.1) screening resulting in the *Qualitative Hazards Set A* and quantitative (step 2.2.) screening resulting in the *Quantitative Hazards Set B* of those single hazards identified in the first step, needs to be conducted. In the third step of the approach, all potential combined hazards of the different types of combinations as defined in (IAEA, 2021) are identified based on the results of the previous screening steps. The result serves as basis for the combined hazards screening to be performed within step 4 of the approach. For these hazard combinations, again qualitative (step 4.1) and quantitative (step 4.2) screening steps need to be consecutively conducted, applying the same screening criteria as for single hazards.

The stepwise approach is schematically outlined in Figure 1.

For screening of combined hazards of the category *subsequent hazards* the HST so far provides a tree structure of depth two (event chains of an initial event with subsequent first and second events) only. However, it is planned to further extend the depth, even if event chains of more than three subsequent events are extremely rare.

The HST is also able to generate combined hazards from the category *correlated hazards* based on correlation criteria defined by the analyst. However, the semi-automated generation of such combinations, followed by a tree-type screening, as well as the corresponding graphical output still need to be implemented in the software tool.

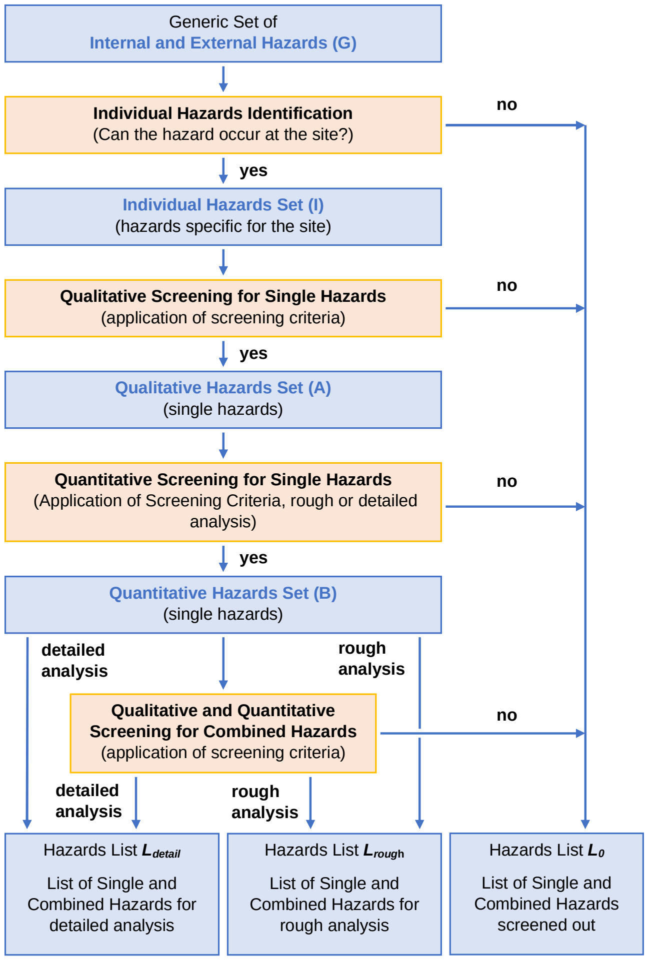


Figure 1. Hazards screening approach as realized in the software tool HST, from (Strack et al., 2020).

For screening of combined hazards of the category *unrelated hazards*, the tool provides a matrix structure, combining all single hazards remaining after the quantitative screening (Set B) with themselves. The screening is aided with a pre-selection of possible combinations based on the mission times of each single hazard. From the roughly estimated maximum mission time of each hazard a rough joint occurrence frequency of the hazards combined with each other is calculated. If this frequency exceeds the threshold value for screening out a single or combined hazard, it remains in the final list of hazards needing further in-depth investigation.

The following Figure 2 and Figure 3 show screening examples applying the HST for combined hazards of the categories *consequential events* and *unrelated events*.

4.2. Application of the hazards screening

For a German nuclear site with two reactor units and other non-negligible radioactive sources, the following nine single hazards including fire remained for further analysis after the individual hazards screening: the natural external hazards earthquake vibratory ground motion (A.1.1), riverine external flooding (B.1.2.2), local flooding due to precipitation (B.3.2), and extratropical cyclone (C2.1), the human induced external hazard aircraft crash in air traffic corridors (Z5.2), and the internal hazards fire (I.1), flooding (I.2), high energetic component failure (I.3), and explosion (I.7).

For the combined hazards screening a matrix of those single hazards remaining after the quantitative screening has been generated in order to analyse all three categories of combinations.

Figure 4 shows for the possible combinations of unrelated events how the result of the quantitative screening of these combinations (*Set B)* is imported and displayed providing for each hazard additional information including mission times categories (marked with red arrow) and the acquired attributes from the qualitative screening (blue arrow) needed for quantification.

The result of the screening of single and combined hazards for the exemplary nuclear site in Germany is provided in Figure 5.

Two combinations involving fire remained for the exemplary plant: seismic and consequential fire and aircraft crash and consequential fire. Due to the design of the installations collocated at the given site, fires and consequential events could be screened out. Fires and other events correlated by a common cause could not be excluded qualitatively but by low occurrence frequencies and extremely low damage frequencies, even under pessimistic assumptions. The only in principle possible combination of a fire and an independently occurring longer duration hazard, not screened out as single event, is a riverine flooding. Such a combination could be screened out by a suitable design of the site against external flooding, additional, suitable and reliable precaution measures, and highly reliable operational procedures for preventing any inadmissible damage resulting in negligible damage frequencies.

The screening approach was further successfully applied to different nuclear installations in Germany and abroad. The site characteristics as well as the design of these installations analysed are quite different from the above mentioned example, clearly demonstrating the broad applicability of the tool. One further example with different resulting spectrum of single and combined hazards to be analysed is briefly shown in the following.

For a larger research reactor facility, a complete probabilistic safety assessment covering also external and internal hazards (including hazard combinations) is being developed. In the fame of the qualitative screening of single hazards, 18 hazards could not be directly screened out. Quantitatively, this number could be further reduced to only five hazards remaining. As a result of the combined hazards screening, all combinations of unrelated hazards could be finally screened out.

As a result of the combined hazards screening outlined in Figure 6, the following four combinations of consequential hazards remained for detailed probabilistic assessment: an explosion occurring due to a pipeline accident in the near vicinity of the plant (Z.2.1) with subsequent internal fire (I.1), accidental military aircraft crash (Z.1.3.1) or accidental civil aircraft crash in the nearer vicinity of an airport (Z.5.1), both with consequential fire, and a fire with consequential flooding (I.2) (marked in green). Further nine combined hazards (again the above mentioned three external hazards, all with consequential internal flooding or internal high energy component failure (I3, mainly from HEAF), internal flooding with consequential fire or HEAF, and HEAF and consequential fire, all marked in yellow in Figure 6) only need a rough probabilistic assessment.

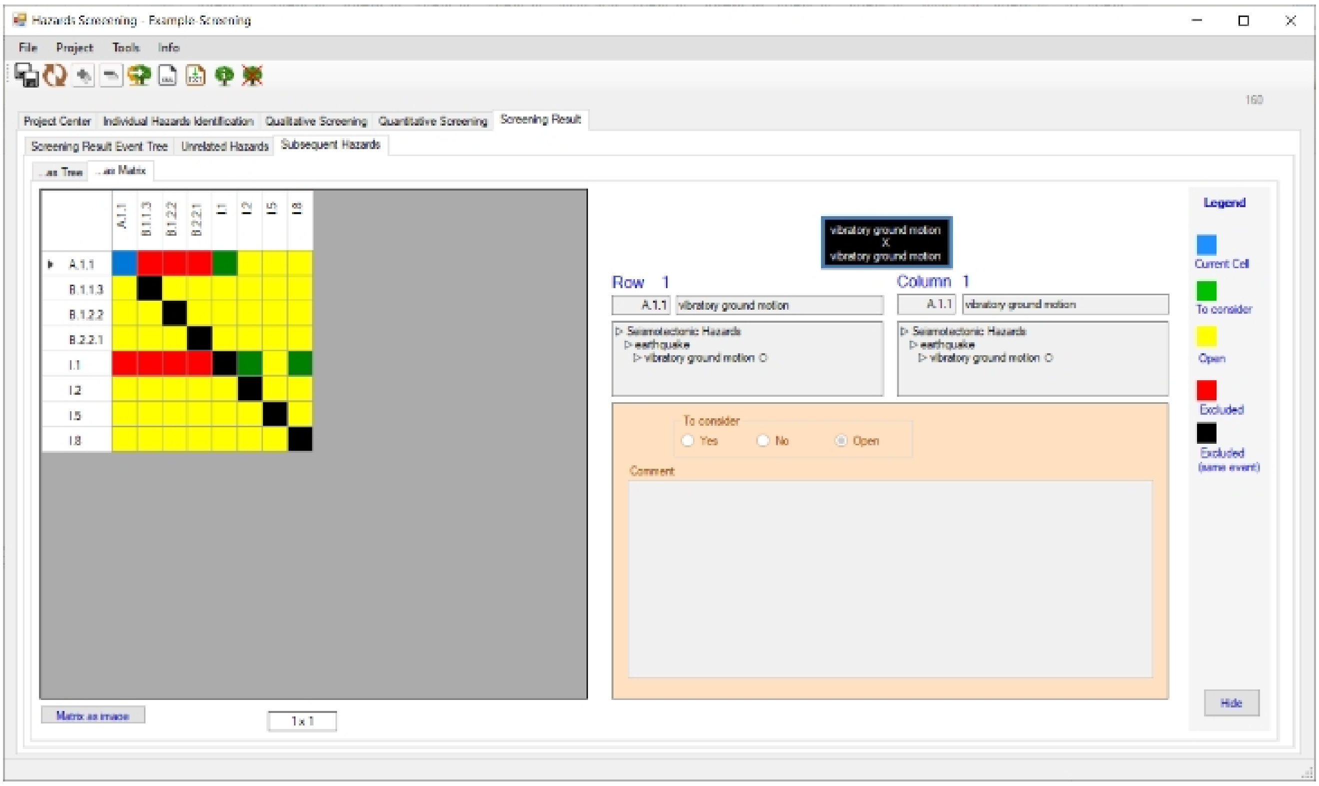


Figure 2. Example for the screening of combinations of subsequent events, from (Röwekamp et al., 2020).

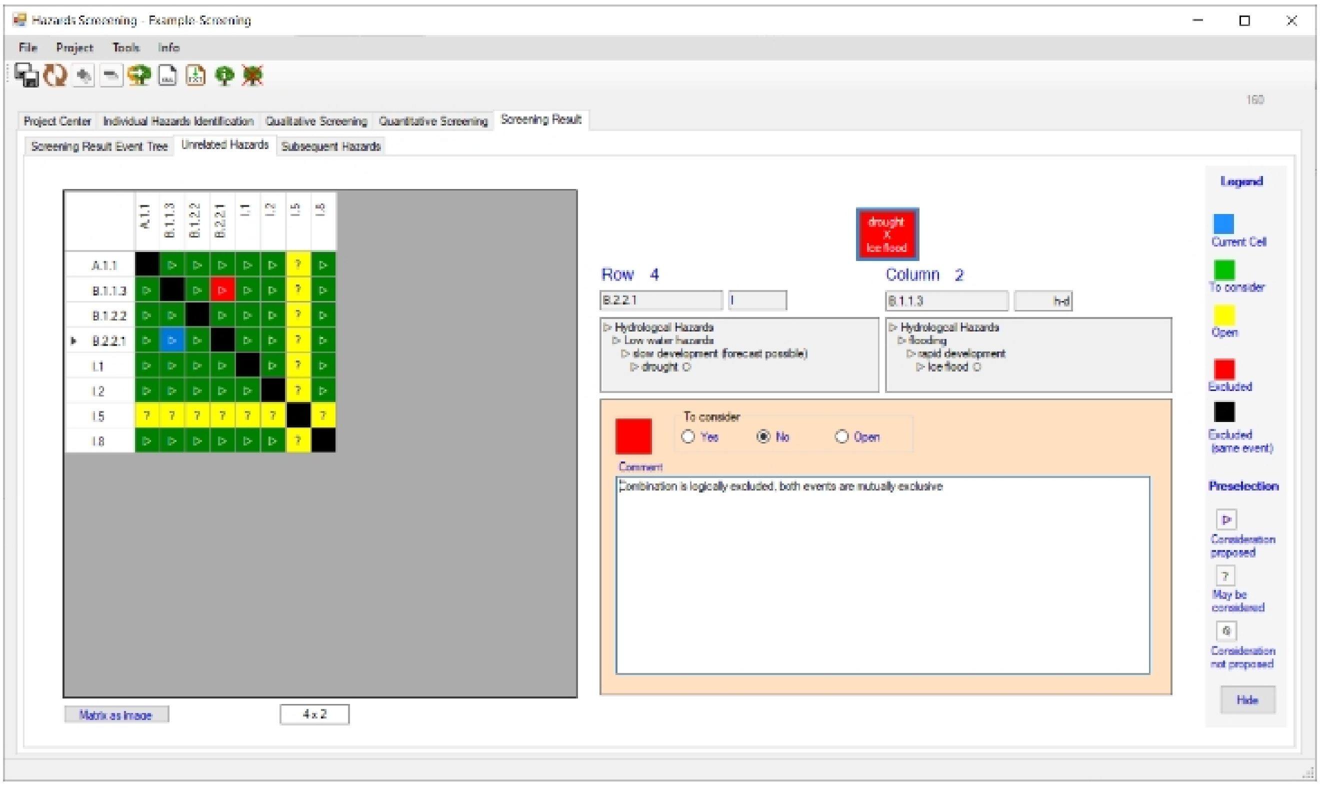
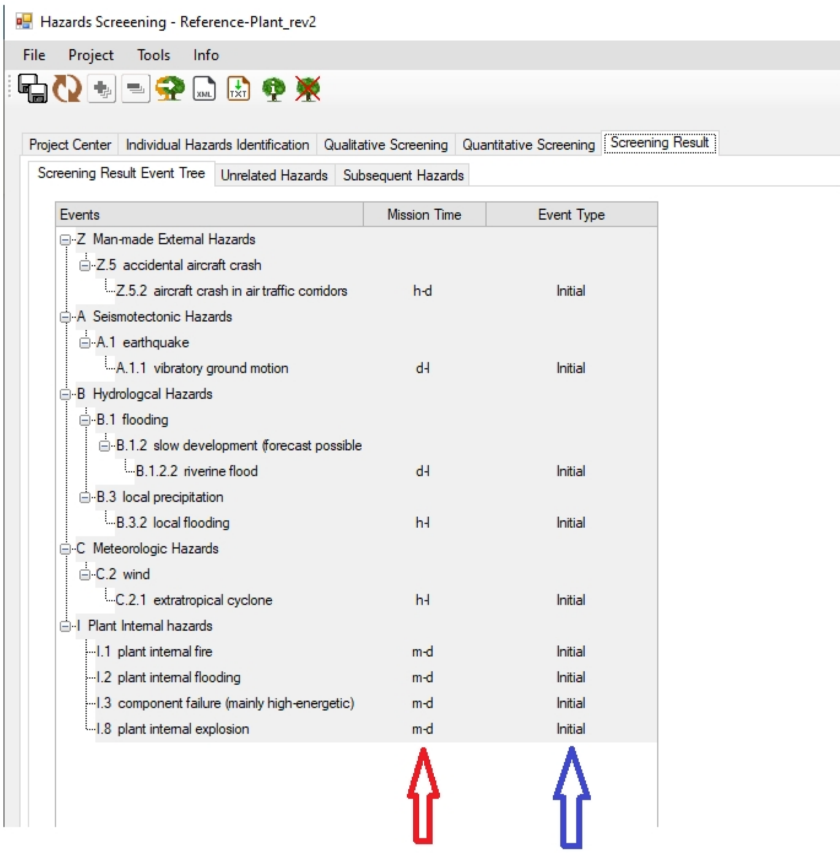


Figure 3. Example for the screening of combinations of events occurring independently of each other simultaneously (so-called unrelated events), from (Röwekamp et al., 2020).



Legend: m – minutes, h – hours, d – days, l – longer

Figure 4. *Quantitative Hazards Set B* displayed in a tee-type structure with additional information for each hazard including hazard mission time periods; from (Strack et al., 2020).

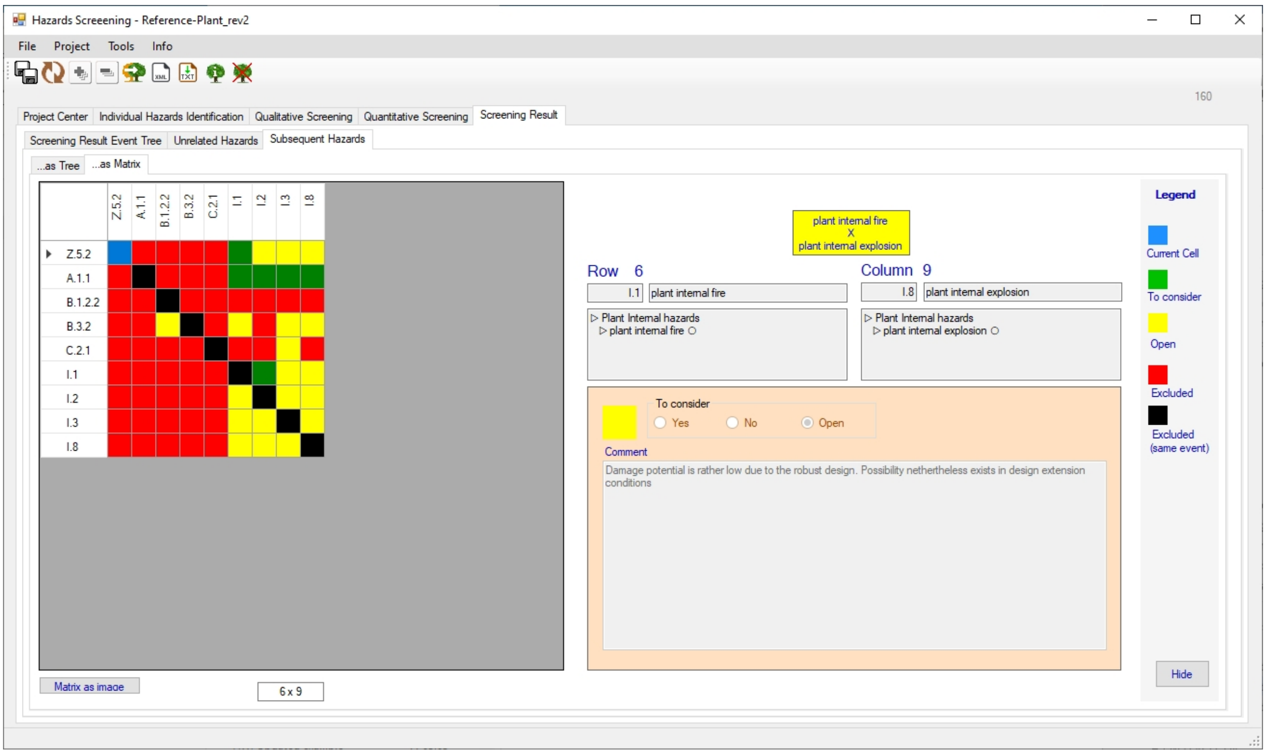


Figure 5. Result of the single and combined hazards screening for combinations of subsequent events as provided by the HST; from (Strack et al., 2020).

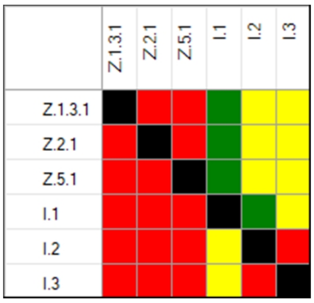


Figure 6. Result (graphical output) of the hazards screening for single and combined subsequent hazards for a single reactor facility in Germany.

The hazards screening so far carried out has clearly demonstrated that fires are a main contributor to plant damage. This also includes combinations of fires and other hazards not screened out for the facility being investigated. The in-depth analyses for these combinations remaining after screening are ongoing and may provide insights for plant improvements that could enhance the plant safety.

5. Operating experience feedback regarding combined fire hazards

In the following, some more recent examples from process industry as well as nuclear industry on the importance of fire event combinations are presented.

5.1. Recent operating experience from process industry

Cascading or domino effects provide an important safety related aspect in process and chemical industry (Zhu et al., 2020). As an example, the ammonia process production involved (flammable) natural gas with high temperature and high pressure in the process and has therefore been investigated in more detail (Lestari et al., 2019; Yue et al., 2020).

In January 2020, an explosion and subsequent fire occurred in an industrial estate near Tarragona, southern Catalonia (Spain). The event started with an explosion in a reaction tank of propylene oxide which caused a flame and a vertical column of smoke. This resulted in a second explosion at an industrial voltage transformer. The fire was not yet out 24 h after it had started.

Another explosion resulting in a fire occurred in June 2020 in a chemical plant in Porto Maghera in the area of the Venice lagoon. The fire spread over an area of about 930 m^2 after the explosion.

A third remarkable fire event combination occurred in Belle, West Virginia in the United States of America in December 2020. An initial explosion with subsequent fire occurred. There was a *massive explosion* at the site releasing metal debris onto an interstate and across the river. Chlorine and methanol were involved in the explosion. A 4540 l metal dryer became over-pressurized during a chemical product drying operation.

One of the most severe event combinations occurred on August 4th, 2020, when a fire broke out in a warehouse of the port of Beirut (Lebanon), where 2,750 t of ammonium nitrate was stored under highly inadequate conditions. The first explosion, likely triggered by fireworks stored in the warehouse, released a large cloud of smoke and a crackle of bright firework flashes. This explosion severely damaged the building structures of the warehouse. A second explosion, occurring approximately 35 s later, was even more severe. This second, huge explosion resulted in shaking of civil structures of the entire city of Beirut, shattering of glass and causing extensive damage to buildings and infrastructure within a radius of 3 km. More than 200 humans were killed, and approximately 6,000 ones injured. The homes of many residents were destroyed or severely damaged by the blast, leaving about estimated 300,000 inhabitants without adequate shelter. The Beirut port explosion also severely damaged two of the city's five hospitals – one of which was a dedicated COVID-19 facility (IRFC, 2020). The initial fire resulting in the subsequent explosions was finally extinguished the next morning.

The most recent combined event occurred in February 2021 in the Bharuch district of Gujarat (India). A boiler explosion resulted in a massive blast at the United Phosphorus Limited (UPL) company's agrochemical plant, and a huge fire broke out following the blast. Due to this event two people died and 26 were injured.

These more recent accidents have clearly demonstrated the need for in-depth investigations and assessments of credible combinations of fires and other hazards, not only for a single industrial facility but for the whole site and/or industrial park (Saloua et al., 2019). In that context, domino and cascading effects pose particular challenges for risk management to prevent industrial accidents (Zuccaroa et al., 2018).

5.2. Recent operating experience from nuclear industry

The OECD/NEA Fire Database represents a repository for fire related operating experience from nuclear power plant sites worldwide covering also combinations of fires with other anticipated events occurred so far in the fourteen member states (from Europe, North America and Asia) participating in this Database Project.
Figure 7 provides an overview on those event combinations involving fires observed in the operating experience of nuclear power plants in the member countries participating in the FIRE Database Project.

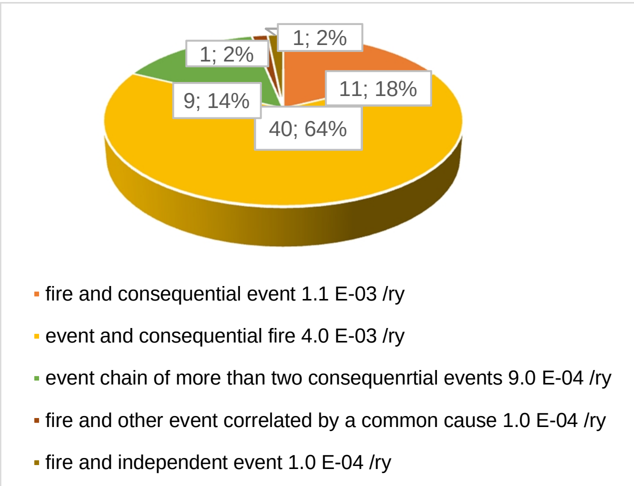


Figure 7. Event combinations of fires and other anticipated hazards in the OECD/FIRE Database (OECD/NEA, 2021).

Combinations of different anticipated events and consequential provide the dominating contribution of nearly 64% of all fire event combinations observed so far in (OECD/NEA, 2021). While only one event each has been observed for the combination categories *correlated events* and *unrelated events*), it is remarkable that nine out of 62 combined events (nearly 15% of all combinations) are event chains of more than two consequential events involving at least one fire. The different types of the 60 combined fire events in the FIRE Database of the category *consequential events* are schematically presented in Figure 8.
HEAF fire events also provide a remarkable share of all fire events in the FIRE Database. As mentioned in (Röwekamp et al., 2021), 65 out of 556 events are HEAF fires, 37 of these combinations involving both, HEAF and fire. Figure 9 demonstrates the significance of Combined HEAF and fire events. More than 75% of these combinations are HEAF and consequential (ensuing) fires with a non-negligible occurrence frequency of nearly 3 E-03 /ry.

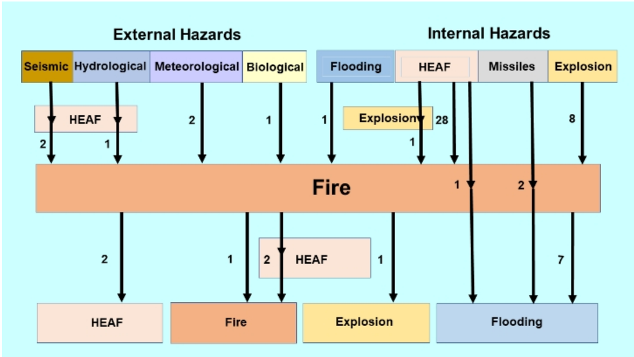


Figure 8. Combinations of consequential hazards involving fires included in the OECD/FIRE Database, from (Röwekamp et al., 2021).

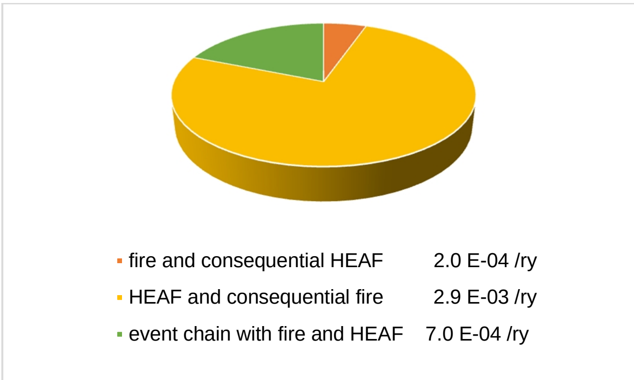


Figure 9. Combinations of fire and HEAF events in the OECD/FIRE Database (OECD/NEA, 2021).

Conservatively, the resulting generic core and/or fuel damage frequencies can be assumed to be in the order of E-06 – E-05 /ry. Combined HEAF and fire events therefore need further analysis and will require modifications at least in some nuclear installations for reducing their risk.

6. Summary of results

6.1. Nuclear installations

In nuclear industry, the increasing number of events reported from nuclear industry shows that the amount of combined events is non-negligible and their investigation is beneficial for identifying the needs for improvements of operating nuclear power plants as well as for the design of new plants in an suitable manner taking conservatively into account sites as well as installation type specific conditions.

About 12% of the entire fire events recorded in the most recent version of the OECD/NEA FIRE Database (OECD/NEA, 2021) have been identified as event combinations of fires and other events. 37 out of these 62 event combinations observed are fires consequential to HEAF, seven of these represent event chains, Thus, HEAF events resulting in fires provide the most important contributors to event combinations, among them HEAF at electrical breakers in cabinets, bus ducts and transformers representing the highest contributions.

The experience from event combinations in nuclear installations also clearly demonstrates (OECD/NEA, 2021) that only a few explosions caused a consequential fire and that most of these did not result in a change of the plant operational mode indicating that the plant design against internal explosions has already considered the possibility of such consequential fires and their potential effects on plant safety. This is in contrary to experiences from process industry (Zhu et al., 2020) as outlined in Section 6.2. A possible explanation is the strict design of nuclear power plants in FIRE member countries against explosions (Melly et al., 2020) including the mitigation of their consequences to prevent any nuclear risk.

It has been clearly recognized that all types of combinations of fires and other hazards do occur and may threaten nuclear safety. More recently, the observations have underpinned that combined hazards involving HEAF component failure events and fires belong to the most significant combined hazards. The hazards screening results from different nuclear sites and facilities support this observation and indicate that there is a need for more in-depth investigations how HEAF events with subsequent ensuing fires can be better prevented.

Experimental activities for getting more insights in HEAF induced fires in typical arrangements are ongoing. From the results of these experiments, additional analytical efforts and probabilistic safety assessment it may be possible to enhance nuclear plant safety through modifications in the plant design and operation.

Already started activities for getting more and better insights from the events stored in the OECD/NEA FIRE Database by analysing apparent and root causes of the events in more depth maybe also beneficial for reducing the number of combined fire events, at least of those with non-negligible consequences for the installation safety.

6.2. Process industry installations

Chemical plants consisting of hundreds up to sometimes thousands of hazardous installations located next to each other are usually characterized by high complexity and interdependencies (Zeng et al., 2019). These installations which store, transport, or process hazardous (e.g., flammable, explosive, toxic) substances in large quantities are usually operated under high temperature and pressure conditions.

In the chemical industry, multi-hazard (toxic, flammable and explosive) materials such as acrylonitrile are stored, transported, and processed in large quantities. A release of multi-hazard materials can either simultaneously or sequentially lead to acute toxicity, fire and explosion. The development of hazards over space and time may also result in cascading effects. A dynamic methodology called “Dynamic Graph Monte Carlo” (DGMC) has been developed in order to model such multi-hazard accident scenarios and to assess the vulnerability of humans and installations exposed to them (Chen et al., 2021).

The ammonia industry is one type of industry that is classified as a major hazard. Major hazards generally consist of fires, explosions and chemical leakages. Fires are the most alarming hazards endangering process plants with the highest occurrence frequencies compared to other major hazards (Lestari et al., 2019). Typical sources of fires and explosions in the ammonia industry are raw combustible materials in the form of natural gas, which is flammable, and its process units use high temperatures and pressures. Therefore, simulations of single or combined fire hazard event sequences in an ammonia production plant can be beneficial for improving the plant safety and production availability (El Moneim et al., 2018).

Due to the observation of a large number of events in the chemical industry, these events have been investigated in more detail, e.g. for China and Iran.

According to available statistics, the study for process plants of the chemical in China is based on 1653 hazardous chemical accidents and 500 fatalities in this country in 2019. It was also indicted in this study that leakages and explosions of hazardous chemicals in the production and storage were more likely result in severe consequences occurring almost every year (Chen & Reniers, 2020).

The study for chemical industry in Iran aimed at exploring causal factors of occupational accidents. In total, 1322 accidents reports were gathered from 22 plants in chemical industry for the time period 2007 to 2016. The results of the multiple linear regression analysis showed that human and organizational factors, health, safety, and environment training, risk management, unsafe acts and conditions as well as the type of accident occurrence played the most important role in occupational accidents (Derakhshan Jazari et al., 2021).

Understanding fire and explosion hazards, their likelihoods and consequences, protection techniques and the need of an effective safety management systems will enable plant operators to provide the best combination of protection means and capabilities necessary to reduce the risk to an acceptable level. Corresponding studies have performed to support this effort (Ji et al., 2018; Wang et al., 2020).

7. Conclusion

The significance of event combinations involving fires is underpinned by recent accidents. Cascading/domino effects are not only an important aspect in process and chemical industry, as recent accidents have also demonstrated. The operating experience feedback has indicated that investigations and risk assessment of combined fire hazards are relevant not only for a single industrial installation but for the whole site and/or the respective industrial park. In that context, domino and cascading effects may pose challenges for risk management in order to prevent industrial accidents.

Industrial facilities and critical infrastructure are vulnerable to the impact of hazards that can generate cascading effects. If vulnerabilities overlap and interact, escalation points are created that may induce secondary effects with higher impacts than those from the primary event.

Therefore, a complex multi-hazard assessment needs to be performed for determining the occurrence frequency of different hazards either occurring at the same time or following each other within a very limited time period, because of being directly causally related, correlated by a common cause, or merely threatening the same elements at risk without any chronological coincidence.

The operating experience from nuclear and chemical installations worldwide has shown that combinations of fires and other anticipated events, in particular external and internal hazards, do occur during their entire lifetime. This is also valid for other process industry installations. As a consequence, in the recent past years national and international activities have resulted in updates of the respective regulations and standards in order to adequately address event combinations.

However, these aspects are not only important for the nuclear and chemical area.

More generally, for exceptional events of natural or anthropogenic type, the elements at risk (people, buildings, infrastructures, economy, etc.) are often hit by sequences of *cascading events* as a function of time and space caused by the triggering event (seismic, landslide, volcanic eruption, fire, electrical failure, etc.). From a theoretical point of view the modelling needs and the main issues to be taken into account in the development of simulation tools aiming to include cascading effects analyses to effectively support decision-makers in their preparedness and disaster mitigation strategies in the framework of emergency planning at local, national and international level (Zuccaroa et al., 2018).

Economy and society in the globalized world are increasingly dependent on a reliable availability of essential goods and services provided by technical and socioeconomic infrastructures. Affected by single or multiple hazards, such interdependencies extend the affected area and increase damages. Climate change also gives rise to the increase in the frequency, intensity, spatial extent, and duration of extreme events (Zharikova et al., 2020).

Another aspect is that disasters are inherently a social phenomenon rooted in the social structure and reflecting the processes of social change. These dynamics may have different types of development, which are usually non-linear and cyclic. The framework also emphasizes the major role of information and social learning in these dynamics (Mizrahi, 2020). Moreover, it is discussed that all these events and their consequences may further lead to socioeconomic disruptions, such as business interruption, social unrest, healthcare degradation, and economic crisis. The most recent example of such consequences is the COVID-19 pandemic (Mignan & Wang, 2020).

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