Lessons Learned Bulletin No. 16

Chemical Accident Prevention & Preparedness

Learning from incidents in warehouses

The aim of the bulletin is to provide insights on lessons learned from accidents reported in the European Major Accident Reporting System (eMARS) and other accident sources for both industry operators and government regulators. JRC produces at least one CAPP Lessons Learned Bulletin each year. Each issue of the Bulletin focuses on a particular theme.

This 16th issue of the Lessons Learned Bulletin (LLB) focuses on industrial accidents which took place in warehouses as a follow-up on the Beirut explosion in 2020. For this study, the JRC analysed 38 reports of chemical incidents that occurred in independent warehouses. The study focused on accidents involving warehouses, distribution, and transportation centres accommodating non-stationary storage where warehousing was the main activity. Accident investigations on warehouses are frequently incomplete since the level of destruction prevents investigators from conducting an extensive causal analysis. Therefore, the study includes only accidents that have sufficient information to identify lessons associated with prevention and mitigation management.

Please note:

The accident descriptions and lessons learned are reconstructed from accident reports submitted to the EU's Major Accident Reporting System at

https://emars.jrc.ec.europa.eu

as well as other open sources. EMARS consists of over 1100 reports of chemical accidents contributed by EU Member States and OECD Countries.

The bulletin highlights those lessons learned that the authors consider of most interest for this topic, with the limitation that full details of the accident are often not available, and the lessons learned are based on what can be deduced from the description provided.

Case 1 – Explosion and fire of hazardous chemicals storage hangar

Sequence of events

An explosion followed by fire took place at a chemical storage hangar following the release of sodium chlorite from metal drums. The facility, registered as an upper-tier Seveso establishment, handles the wholesale, storage and distribution of various chemicals, including sodium chlorite, sodium persulfate, sodium nitrate, and chromic acid in various quantities. According to the preliminary investigation, the release of sodium chlorite occurred when a containment drum got punctured during an erroneous forklift operation.

The explosion, triggering a domino effect involving other drums and bags containing hazardous chemical products present in the hangar, caused its collapse due to the pressure wave. The collapse of the structure caused the death of one employee crushed by the debris. The pressure wave injured a second employee who was hospitalised and dismissed later the same day. The adjoining solids storage hangar was also affected by the explosion, causing the partial collapse of the structure and some small fires due to sparks projection. Neighbouring communities were also highly alerted and instructed to remain indoors. The cost, including material damage and loss of stored products, exceeded 4,000,000€.

Important findings

- The explosion and fire occurred in the storage area of combustible substances, where the two employees were present. Due to an erroneous operation of a forklift operated by one of the two employees, the forks punctured the metallic drum causing the release of sodium chlorite.
- The post-accident investigation identified the presence of incompatible substances in the storage hangar, particularly peracetic acid in the explosion area. A 1000L storage tank of peracetic acid at 15% was present outside of the storage hunger, while the operator argued that the presence of peracetic acid in the explosion point could be justified by the extinguishing water used by the emergency services.

Figure 1. Explosion and fire at agrochemicals warehouse, 6/8/1996
(Source: https://www.estrepublicain.fr/)

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(Continuation of Case 1)

- Since peracetic acid can cause an explosive reaction when contacting sodium chlorite, it is suspected that the same forklift could have been used to transfer peracetic acid or simply operated in the area between the two incompatible chemicals.
- The management failed to show acknowledgement of all substances present in the hangar and the hazards associated while substances present in the hangar had not been documented in the inventory list. During the post-accident investigation, certain out-of-specification products were found while no record in the inventory list of the storage hangar was present. Among the substances found some presented clear risks, hazards and incompatibilities.

Lessons Learned

Hazard identification and risk assessment. An inadequate risk assessment appeared to be an underlying cause in many warehouse incidents studied for this bulletin. In this case, the operator had failed to identify the hazards associated with the stored substances resulting in an insufficient risk assessment.

The hazard assessment should lead to identification of reference accident scenarios, taking into account:

- The hazardous properties of all possible substance types e.g., (flammable, explosive, toxic), as well as uniquely hazardous substances and their quantities (usually defined in the permit)
- The routine operations and activities taking place such as loading, unloading, transferring substances between containers, removal of released hazardous substances, etc., and what can go wrong with them
- Non-routine activities with possible elevated risk, such as maintenance operations or hot work
- The layout and configuration of the warehouse and its proximity to other structures, activities and land-uses
- Climate and weather extremes, security risks, and any other potential external threats
- The likelihood of explosive atmospheres and the need for hazardous area classification (EU Directive 2014/34/EU - ATEX)

As with any other hazardous site, the likelihood and potential impacts should drive the design and implementation of prevention and mitigation measures necessary for safe warehouse management. The warehouse should have competence in chemical process safety to manage the risk assessment process and to develop and oversee the implementation of safety protocols derived from the assessment.

Establishment of a storage plan to reduce risks. The risk assessment should drive the development and implementation of a storage plan that allocates different substances and substance types to assigned areas according to their hazardous properties, sensitivities (e.g., light, temperature, water reactive), and that ensures segregation of incompatible chemicals. For example, certain substances are vulnerable to decomposition or degradation if light and temperature conditions are not respected. In addition, the placement of incompatible hazardous substances in close proximity to each other that, in the event of cross-contamination, may cause an unwanted chemical reaction, generating a dangerous release, fire or explosion.

The storage plan should address the potential for escalation of an accident. As an example, oxidising agents will greatly increase the severity of flammable liquid fire. In addition, the placement of incompatible hazardous substances in close proximity to each other that, in the event of hazardous substances jointly should only take place if this does not increase the risk. Separate storage areas for different hazards and substances can be achieved in some cases by establishing sufficient distances, or as necessary for example with flammable substances, by installing physical barriers (e.g., walls, cabinets made of non-combustible materials).

The storage plan should be used by employees of the warehouse to determine which substances and amounts can be stored where and by emergency responders to guide response actions. It should contain information related to specific restrictions associated with storage sectors: height limitations (due to ventilation ducts, or sprinklers), load capacity restrictions, presence of ignition sources in the vicinity, and areas affected by direct sunlight. The storage plan may also include access restrictions to unauthorised personnel, restrictions concerning equipment (i.e., forklifts) that can be used in the designated storage class, or restrictions related to storage conditions such as temperature and humidity control.

Inventory management and processing of incoming material. In the case study, the operator failed to acknowledge the substances and preserve a detailed list of those, and the quantities associated Warehouses are typically characterised by frequent inventory changes, whether stock balance adjustments due to incoming and exiting quantities or changes in the substances handled or their grade. Such variability can lead to incompatible substances stored together, degraded substances introduced into the warehouse or misperception of the quantities under storage (i.e., storing excessive quantities).

There should be a Control and Acceptance process that takes place in a dedicated area and includes

- *Verification of documentation.* This process involves checking of the documentation accompanying the shipment (e.g., purchase orders, SDS, packaging labels, etc.), to verify that the delivery, both volume and quantity, is consistent with what was agreed with the client.
- *Verification of integrity of the packaging and product.* The documentation accompanying the delivery should provide information on packaging and proper storage conditions. Control and Acceptance should include a routine examination of the consignment to verify that it fulfils these requirements and there is no evidence of contamination or tampering. Documentation, labelling and packaging are normally governed by the prevailing international standard based on the transport mode (rail, road, inland or international water, air), with possibly additional national requirements, as adapted to align with the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).
- *Problem resolution process.* If there are any errors that arise in the verification process, they need to be resolved with the client prior to acceptance or the delivery must be rejected.
- *Registration in the inventory control system.* Upon acceptance, the product should be registered in the inventory control system, with all information necessary for safe handling and storage, including proper identification, quantities, hazardous properties and sensitivities, specific storage requirements, and storage location. Restrictions on the time period that substances can stay within the storage facility should also be noted. The inventory list should be easily accessible to employees, contractors and emergency responders.

(Continued on page 5)

Chemical accident risk management in warehouses
Prevention & Preparedness

Warehouses and distribution centre accidents can cost money and lives

Warehouses and distribution centres have always been one of the key elements in supply chain management to accommodate the commerce demands of manufacturing facilities as well as end users. Many advancements in warehouse management have been reported in the past decades, involving automation, artificial intelligence applications, utilization of drones, etc. However, recent accidents such as the explosion in the ports of Tianjin and Beirut, in 2015 and 2020 respectively, demonstrate the need to strengthen current safety practices, since the immense effects of warehouse and distribution centres accidents have resulted in numerous fatalities, excessive environmental pollution and tremendous financial losses.

The Major Accident Hazards Bureau (MAHB) of the European Commission's Joint Research Centre studied reports of more than 100 chemical incidents occurring in warehouses, distribution and transportation centres, available in eMARS and other open sources. The aim of the study was to understand typical causes of loss of containment, how it can lead to a major accident, and to identify practices to prevent such incidents and mitigate their effects. The findings were analyzed to provide lessons learned to support risk assessment and risk management decisions for chemical warehouse operators and inspectors. For this study, 38 cases were included in the analysis, where warehousing was the main activity (including distribution and transportation centres). Production warehouses, used for the storage of raw materials, semi-finished products and finished products were not included, since they follow a different business model and operations and activities upstream and downstream of storage may also differ substantially.

Types of facilities

The majority of the accidents in the study (30 or 79%) took place in independent warehousing and storage facilities (see Figure 2), where products from different suppliers are received, stored and prepared for transport to clients. These mainly involved:

- Agrochemicals and fertilisers
- Explosives and fireworks
- Other chemicals classified as hazardous (i.e., acids, oxidisers, etc.)

Eight accidents (or 21%) took place in handling and transportation centres, such as ports and marshalling yards, including a variety of substances such as oxidisers, nitrates and end-consumer products (i.e., garments).

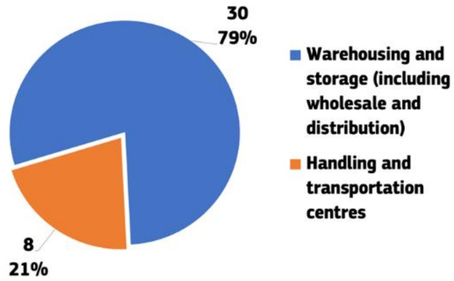

Figure 2. Facilities involved in the study (N=38)

Impacts and the risk of escalation and domino effects

The accidents in the study collectively resulted in 495 fatalities and at least 8,500 injuries, including members of the public and emergency responders. Four cases alone were responsible for the death of nearly 150 emergency responders. The earliest accident covered in the study dated back to 1977 while the most recent accident occurred in 2022.

By their nature, warehouses can be more prone than other types of hazardous facilities to escalation of an initial event due to large quantities of hazardous substances present in the same location and internal domino effects. There were a number of accidents in the study that appeared to demonstrate this tendency. The study included five disasters that took place in the past decade representing the majority of the fatalities and injuries counted in the study (see Figure 3), including the explosions and subsequent fires in port warehouses in Lebanon, China and Bangladesh as well as warehouses specialised in the storage of fertilisers in the United States and South Africa.

Accidents occurring in warehouse facilities can have greater potential for severe consequences offsite, and emergency responder and business impacts (see Figure 3). Throughout the study, it was quite common for warehouses to be claimed as almost or completely destroyed leading to excessive property damages, material losses and significant restoration costs. It is not uncommon for the entire stock of the warehouse to be lost as the result of such an event. Damages resulting from Tianjin and Beirut, have been estimated to be more than 5 billion euros, including also government sanctions. In these two cases, only some costs were borne by the operator, with a vastly greater portion imposed on surrounding communities and businesses in addition to the government.

Offsite impacts can also be significant causing considerable damage to residential buildings, local shops and businesses . as well as offsite injuries in surrounding areas. In more than 40% of the events (17) the community suffered substantial disruption because of evacuation or shelter-in-place imposed on a large portion of the population, or due to having services, such as water, electricity, or road access out of order for several hours or even days. As a case in point, a warehouse fire in France led to the confinement of over 38,000 people for 8 hours in 1987. More recently, in 2013, an accident in a fertiliser warehouse in West, Texas, USA, wreaked substantial damage on the city's infrastructure, including a public school and a nursing home.

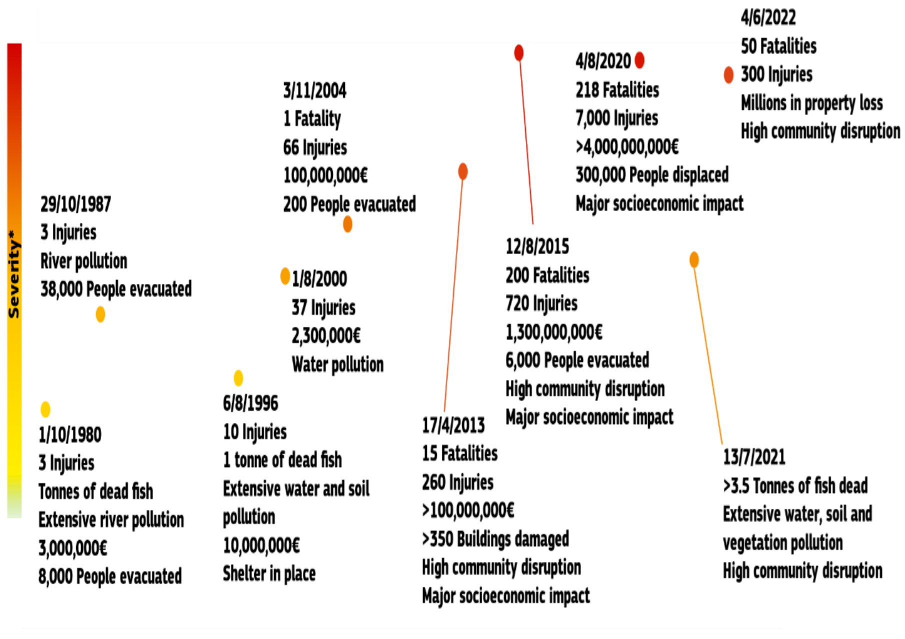

Figure 3. The 10 most devastating chemical accidents in warehouses (1977-2021)

Significant environmental pollution can also result from chemical accidents in warehouses, or either the release of hazardous substances or the firefighting operations due to uncontained firefighting water mixed with hazardous substances reaching the soil or the water basins, as was noted in 9 events in the study. The size of some warehouse fires means that emergency operations can prolong the exposure of emergency personnel to incident effects from several hours to days. Environmental impacts also tend to increase when the firefighting effort is long and drawn out. Firefighting mediums mixed with the hazardous substances, if not controlled, can enter and contaminate waterways requiring cost-intensive clean-up and restoration.

Initiating events in warehouse accidents

Chemical accidents in warehouses, like chemical accidents in other activities, are often caused by procedural errors. In the JRC study, such a mistake was the most common starting point of a chemical accident event, recorded in roughly a quarter of the reports in the study (see Figure 4). Errors were in large part associated with the mishandling of forklifts while manoeuvring (7 cases). In addition, accidental releases also occurred when a container was dropped from a certain height (2 events), also when manually transporting a product, and once because of improper positioning and stacking. Other initiating events include:

- Autoignition from cross-contamination between incompatible substances and/or decomposition of hazardous material due to improper storage conditions. In certain instances, elevated temperature or humidity led to products reaching their kindling point, igniting spontaneously, and initiating self-sustained combustion, before evolving into a facility-wide fire
- Lightning strikes in two cases caused the ignition of hazardous substances. Flooding also resulted in loss of products and damaged facilities in three events
- Malicious acts, such as arson
- Hot work in the vicinity of hazardous products during maintenance operations. In two of those cases, employees were performing welding on the roof and entrance gate prior to the fire
- Electrical sparks from non-ATEX forklifts and electrical equipment

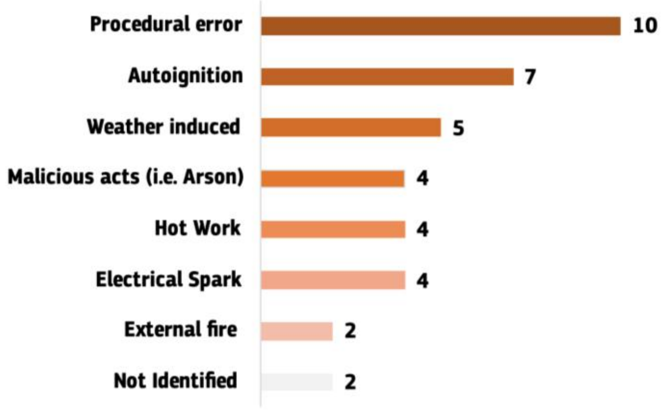

Figure 4. Initiating events in warehouse accidents (N=38)

Underlying causes and escalating effects

In more than 50% of the cases studied, emergency arrangements and response planning were found inadequate (see Figure 5). Notably, in almost half of those cases, emergency responders were among the fatalities and injuries resulting from the event. Several issues related to emergency management were identified such as:

- Insufficient communication and coordination between operators and emergency responders
- Delayed notification of emergency responders
- Poor design of firewater containment systems leading to environmental pollution
- Poor design of venting of storage areas, to reduce smoke volumes in case of fire and to facilitate safe evacuation and emergency responders operations
- Lack of sufficient firefighting capacity
- Lack of fire detection systems

Insufficient training was attributed as an underlying cause in several cases (32%). These were mainly incidents associated with the mishandling of forklift operations where employees were lacking appropriate training. The lack of adequate security against external risks was identified in five events including arson and one case of accidental fire by people who had unobstructed access to the facility. For four events, the accident sequence was initiated while employees were performing maintenance operations and more specifically hot work, introducing ignition sources in the vicinity of hazardous combustible products.

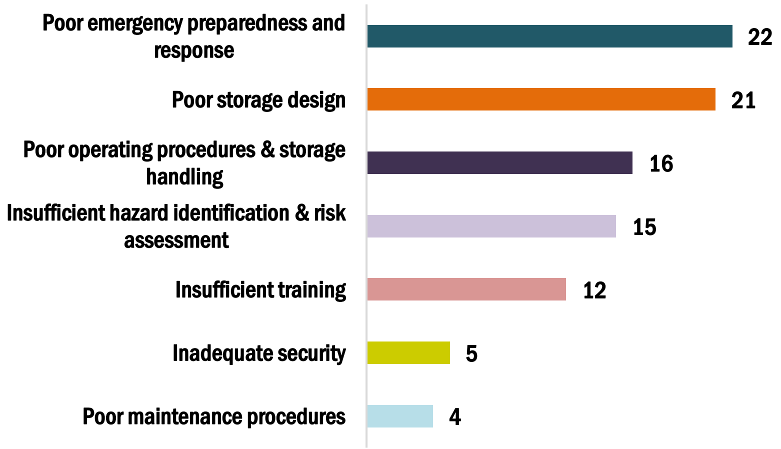

Figure 5. Underlying causes of warehouse accidents (Some cases are represented in more than one category) (N=38)

Other factors that were shown to contribute to propagation, escalation and intensity of a chemical accident in a warehouse include the structure and design of the warehouse, poor operating procedures, and inadequate inventory management. In little over half of the events, warehouses were not appropriately designed to accommodate hazardous substances. More specifically, as shown in Figure 6, design shortcomings acted as aggravating effects in the accident sequence due to:

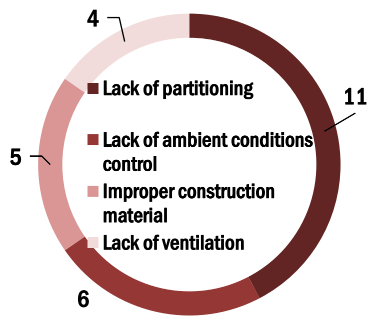

Figure 6. Most common issues related to poor storage design (Some cases are represented in more than one category) (N=20)

- Lack of segregation elements (firewalls), partitioning of stored quantities or unsafe distances among hazardous quantities
- Lack of controlling mechanisms to regulate storage conditions such as temperature and humidity.
- Lack of ventilation systems and smoke control systems
- Improper structural material (i.e., wood) or lack of fire-proofing

Poor operating procedures and mishandling of stored substances were associated mostly with:

- Stacking and positioning of products against good practices
- Storing of excessive quantities of hazardous material over the allowed or documented inventory,
- A complete lack of inventory management and classification of hazardous substances resulting in storing incompatible substances in close proximity

Almost 40% of reports Indicated poor management practices for hazardous substances in storage, suggesting that hazard identification and risk assessment may also not have been sufficient. Shortcomings identified include:

- Obsolete compatibility analysis of chemicals in storage
- No awareness of appropriate storage requirements per substance
- Poor or missing assessment of potentially explosive atmospheres (ATEX)
- Inadequate or nonexistent storage plan
- Inadequate site or land-use planning
- Insufficient awareness of flood risk

(Continuation of Case 1)

- *Allocation to an appropriate storage location.* In accordance with the conditions specified on the SDS, and taking into account the existing warehouse inventory and the storage plan, the product should be allocated to an appropriate area of the warehouse.
- *A rejection procedure.* If a product is rejected, the operator should initiate a process to contact the client and arrange to have the products removed safely. The products should not enter the main storage area.
- *Verification process for products confiscated by authorities.* There should be particular attention to confiscated chemical products that are brought to the warehouse for storage. The warehouse disaster in Beirut in 2020, that killed at least 218 people and injured more than 7,000, is a devastating example of a failure to assure safe storage of confiscated material. If the product cannot be identified and classified within a reasonable time frame, or stored safely at the warehouse, then the operator should arrange with the authorities to have the product removed.

Attention to loading and unloading risks. Many chemical accidents occur while handling dangerous substances during loading and unloading. Warehouses by their nature are particularly exposed to this type of risk. Specific safety measures to avoid loading and unloading incidents include:

- *Safe handling of forklifts.* Preventing incidents involving the transfer of hazardous substances within the warehouse is essential to reducing the accident risk. At least 7 accidents in the study began with a forklift manoeuvre. Among the cases, accidents occurred due to:
  - Mishandling during forklift operation
  - Carrying incompatible substances with the same forklift
  - Use of non-explosion-proof forklifts in explosive atmospheres (failure to comply with ATEX)
- *Proper handling of pallets and intermediate bulk containers (IBCs).* Pallets can be vulnerable to breakage either during loading itself or if stacked improperly. They should not be loaded beyond capacity, and they should be stacked flat with weight distributed equally across the surface. Notably, when IBCs containing combustible and flammable liquids are stored in large quantities they pose a high risk for pool fires. They melt quickly in fires, allowing large pools of liquid to spill and rapidly spread the fire. IBCs are also prone to damage from forklifts.
- *Special attention to manual transportation.* When manual transportation (e.g., lifting and carrying by hand) of packaged substances cannot be replaced by power equipment, management should make sure that procedures are in place to protect employees by providing the proper protective equipment and training.

Training and safety awareness. Storage operations should include awareness and safety training for prevention of incidents that could lead to serious accidents as well as correct behaviour in the event of a release. Training should include instruction on visual identification of defects in packaging and how to inspect a container for potential leakages. The training should cover risks associated with certain activities, including hot work, loading and unloading, forklift manoeuvring, and other activities.

The workforce should be trained to read and decipher the SDS and package labelling so as to guide them in inventory control, proper handling and storage conditions. They should also know the procedures and authorisations necessary for working in areas in the vicinity of hazardous substances and the emergency procedures and remedial actions to follow in case of a release.

Source: eMARS No. 000976

Case 2 – Fire at warehouse occupied by various operators

Sequence of events

A fire broke out in a 9,600 m2 warehouse storing various chemical substances, such as arsenic trioxide, phytosanitary products, and cotton wool cellulose. The warehouse, registered as an upper-tier Seveso establishment, was divided into eight cells rented by four operators (see Figure 7). The employees noticed the fire in a cell where one of the renters stored bales of cotton wool cellulose used to manufacture napkins, tablecloths, and paper for sanitary use. They initially attempted to address the blaze using the internal hose station network. However, 20 minutes later, and following the partial collapse of a cell-separating wall, a neighbouring cell that housed agro-pharmaceutical products also caught fire. Emergency services managed to put out the fire two hours later. During the firefighting operations, 30 firemen were affected by the overwhelming smoke while 7 more required hospitalisation.

According to the investigation, more than 100kg of arsenic trioxide were released. The fire caused extensive property damage, exceeding €2,000,000, while only a part of the warehouse was salvaged. The underground water basin, including the soil and the rainwater network, was contaminated by the extinguishing water, mixed with pesticides, detergents, and soaps. Restoration and water treatment operations extended over an 11-month period.

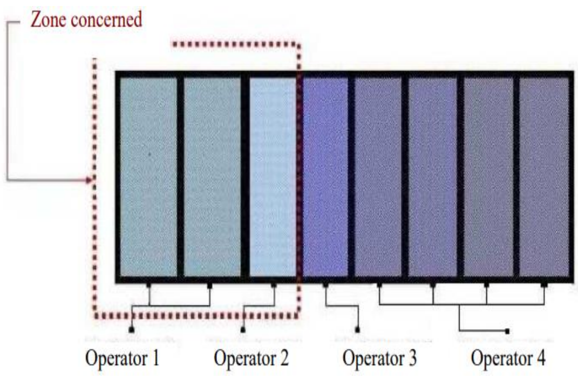

Figure 7. Multiple operators' warehouse layout (Image source: French Ministry of Environment)

Important findings

- Most probably the fire was initiated during hot work operations being carried out on the roof of the warehouse. Employees were conducting maintenance using a blowtorch to repair damages done to the roof during winter major storms.
- The design of the warehouse, including the roof and cell partitioning, as well as the quantities stored, were considered aggravating factors in the fire propagation. Various chemicals and other products owned by the four operators were stored without adequate partitioning while good construction practices had not been followed.
- The firefighting water was collected in a non-hermitic basin.

Thus, the soil, as well as the rainwater/sewage network, were polluted leading to a long, vigorous and cost-intensive process of restoration.

Lessons Learned

Safe execution of maintenance operations in warehouses. As with all hazardous sites, warehouses must follow appropriate protocols to prevent dangerous events stemming from maintenance operations. In particular, cutting blowtorches, welding and other hot work are common initiators of chemical accidents on many hazardous sites, including warehouses, and most notably as a probable initiator of the 2020 Beirut disaster. It is important that only qualified personnel who have received proper instruction and training and fully understand the hazards should carry out maintenance operations. A permit-to-work system should be used to control the maintenance operations, stating the requirements of the maintenance work prior to commencing and identifying all associated risks along with necessary preventive and mitigation measures.

Building construction. Design and construction of the buildings housing hazardous substances should allow a high level of structural integrity, mitigate any possible fire scenario by incorporating fire retardant insulation and prevent debris from projecting into the surroundings in case of explosion or complete collapse. Quite commonly, burning debris from the warehouse fire propagates fires in the surroundings, damaging neighbouring commercial or residential buildings, and sometimes even leading to fatalities. Improper construction materials, such as wood or non-flame-retardant insulation foam, should be avoided because they can intensify and spread the fire. An inbuilt store within a warehouse, with proper fire protection and insulation, may also be used to store highly flammable liquids and gases, aerosols or peroxides.

Considerations in building construction should also include:

- **Protection against weather.** Flooding, lightning, earthquakes and other natural hazards should be considered in the design and construction of warehouses where applicable. Flooding can be particularly dangerous when products in storage are water-reactive.
- **Ventilation and smoke control.** Dangerous concentrations of flammable vapours but also smoke and soot released during a fire require adequate ventilation of the warehouse. Measures to address ventilation can include fixed permanent openings in external walls and mechanical ventilation. Smoke control systems within warehouse buildings should be in place to facilitate emergency evacuation but also to assist the emergency responders in firefighting operations. (Equipment selection should take account of the potential presence of explosive atmospheres.)
- **Protection against malicious acts.** Warehouses are particularly vulnerable to arson and trespassing, that intentionally or unintentionally, have been known to cause accidents in warehouse facilities (including 4 cases in the JRC study). Good practice includes the installation of locks, fencing, alarms and security patrols. It also requires routine maintenance to ensure the integrity of construction elements, such as fixing damaged external walls and windows.

Design of firewater containment systems. Unburned toxic substances and firefighting mediums during firefighting operations can create a hazardous mixture that needs containment and treatment to avoid the pollution of water basins. A containment system is often required to contain firewater mixtures and to prevent them from escaping into the wider environment. These systems include, but are not limited to, tank dikes, curbing around process equipment, drainage collection systems, firewater lagoons, interceptor pits or tanks. The design of containment should also take into account the need to minimise the risk of adverse reactions of released substances due to exposure to water or incompatible substances in retention basins.

Depending on the procedures in place, firefighting water may require containment and treatment on-site or off-site contracting external services, sometimes for long periods until the restoration process commences.

Coordination of preparedness with emergency responders. There have been several disasters in the recent past, including West, Texas, USA (2013), Tianjin, China (2015), Beirut, Lebanon (2020) and Sitikunda, Bangladesh (2022), where emergency responders have been injured and killed responding to chemical accidents at warehouses storing dangerous substances. In these particular cases, the responders appeared to be unaware of the dangerous contents of the warehouses. In each case, the warehouse operator evidently had little or no exchange with the local responders about the hazards at the site, potential accident scenarios, and appropriate intervention measures. They also were not sufficiently aware of their own risk from potential escalation and from inappropriate or inadequate containment strategies, particularly in the case of ammonium nitrate fertilizers, a uniquely dangerous substance that was involved in 3 of these disasters.

These tragedies clearly indicate that operators have a primary responsibility to have ongoing and robust collaboration with local emergency responders about potential accident scenarios and the emergency measures in place for mitigation and response. Good practice includes among other things, sharing the hazardous substance inventory (and significant updates) and providing information on likely and worst-case scenarios. Information on firefighting measures is available in section 5 of SDS documents for example, which can be made available to the emergency services. On this basis, emergency services can receive proper training on the appropriate HAZMAT response for any hazards likely to be present in the warehouse. Moreover, establishing crisis communication protocols, and arranging emergency response exercises involving the local response community and employees, will enhance emergency preparedness.

Emergency procedures for all potential scenarios. As with all hazardous activities, there should be an internal emergency plan in place that is implemented at the earliest stage of an incident. Among other things, these procedures should take into account the hazardous properties and quantities of the potential substances that may be stored in the warehouse at any time. Emergency response should be designed with the warehouse structure and storage plan in mind, defining effective containment strategies as well as alternative escape routes for different scenarios.

Source: ARIA N° 18379

Case 3 – Fire at a refilling and distribution centre for liquefied and compressed gas cylinders

Sequence of events

During a period of extreme heatwaves, consisting of bright sunlight and ambient temperatures exceeding 36°C, several explosions followed by fire took place at a bottling plant.

The facility fills and distributes liquefied and compressed gas cylinders, rents welding machinery, and sells welding supplies. During normal operations, it has about 30,000 compressed gas cylinders containing oxygen, nitrogen, propane, propylene, acetylene, carbon dioxide, helium, and other speciality gases onsite, employing around 70 people. A technician retrieving cylinders from an outside storage area saw a three-meter-high flame coming from a cylinder and activated the fire alarm. As workers and customers evacuated, the fire spread to adjacent cylinders. After 4 minutes, the fire covered most of the facility's flammable gas cylinder area and chain explosions took place.

With explosions propelling cylinders in all directions inside and outside the facility, firefighters set up a perimeter, evacuated local residents, directed a water stream on the fire, and extinguished secondary fires started by burning cylinders and projectiles landing offsite. The fire was finally controlled following a 5-hour intervention. Damages included a burned-out empty commercial building, burned cars, a one-meter hole in the wall of one residential building, broken windows, and other destruction to residential and commercial buildings. Cylinder parts travelled as far as 250 meters from the area of the explosions. The fire plume spread asbestos from ruptured acetylene cylinders approximately over a 1,5km wide area, while one resident experienced a severe asthma attack and died. The facility was extensively damaged by the fire and the extinguishing water while about 8,000 cylinders were also destroyed.

Important findings

- Direct sunlight, as well as radiant heat from the asphalt, heated the propylene cylinders, while high ambient temperatures limited any natural air-cooling. Moreover, the returned cylinders, where the fire started, contained less gas than full cylinders, started heating up at an elevated rate. As the cylinder wall temperature rose, the internal pressure increased, causing the relief valve to open and vent propylene. Probably due to an electric spark or discharge, the released propylene was ignited.
- Temperature of the nearby cylinders rose, as the heat from the fire was supplementary to the heatwave, releasing more propylene into the fire. As a result, the liquefied petroleum gas (LPG) area of the facility became fully involved in the fire.
- Barriers to limit the spread of fire and explosion, deluge systems or fixed fire nozzles to cool cylinders in case of a fire as well as gas and fire detection systems that can activate alarms and fire mitigation systems were lacking.

Lessons Learned

Implementation of required storage protocols for hazardous materials. A critical principle of safe storage of hazardous goods is the strict adherence to safety protocols associated with the substance in question. In this particular case, the substance consisted of propylene and propane cylinders. Standard practices for storing cylinders are well-known and include maintaining recommended safety distance between cylinders, organising full and empty cylinders in separate locations, separating storage compartments for cylinders from any potential heat sources, and distancing them from flammable and combustible liquids that could easily ignite.

Packaging and storage standards for different types of hazardous substances typically address a number of elements, including the type of container and its composition, the degree of isolation or distance to be respected from other types of materials, temperature conditions, bonding and grounding of static electricity, and other parameters. For example, flammable substances should generally be stored only in dry, well-ventilated areas that are not exposed to heat or direct rays of the sun, or lightning. Special attention may be required for specific substances, such as ammonium nitrate, whose unique properties require particular handling and storage conditions. Measures should also include any controls necessary to combat climate and weather extremes of the location, for instance, potential excess humidity in port locations.

Handling and storage guidelines for dangerous substances with all hazardous properties, e.g., flammability limits, water reactivity, etc and optimal storage conditions (i.e., temperature and humidity) are available through the SDS which should be consulted before substances are sent to storage. If the correct storage conditions cannot be met for particular dangerous substances, then they should not be permitted in the warehouse.

Detection mechanisms and mitigation systems. Warehouses should adhere to recommended practices for detecting liquid and gas releases, changes in temperature, or other warning signs specific to the range of substances stored in the warehouse. Detection systems are often coupled with automated safety systems that are programmed to trigger alarms and mitigation measures (e.g., deluge systems) when parameters are exceeded. For example, for gas cylinders, detection of flammable gases should be in place to dissipate the gas before ignition, reducing the likelihood of uncontrolled fires. Fixed fire protection such as fire monitors, deluge, or sprinkler systems can immediately cool cylinders reducing the likelihood of additional cylinder releases, fire spread, and off-site consequences.

Firefighting medium (water, foam or other agents) should be used according to the hazard classification of the substances in storage avoiding any reaction between the firefighting medium and hazardous substances. The SDS contains all relevant information on suitable firefighting mediums as well as advice for firefighters.

Internal site planning. The placement of hazardous substances and the location of storage units should also consider domino effects of potential accident scenarios involving the dangerous materials in storage. For example, burning cylinders and fragments, acting as projectiles, can strike people and property both onsite and offsite, sometimes causing significant harm. They can even cause an escalation in the accident sequence if they hit another hazardous substance container, which then may also explode or release noxious gas or fluid. In this context, warehouse operators may consider storing hazardous substances under reinforced structures to mitigate the effects of an explosion as well as assess the facility's segregation policy.

Land use planning. Potential offsite consequences on urban areas should be thoroughly assessed, considering appropriate safety distances from residential buildings and the warehouse structural design elements that can minimise the possibility of impacts offsite. The high potential for domino effects, when mitigation measures are inadequate to control the event escalation, can represent a very high risk for offsite populations and structures. In this particular case, the projectiles from the explosion of gas cylinders reached an area of 250m from the epicentre of the main explosion. The Tianjin, China warehouse fire (2015) and the fire and explosion of a fertiliser warehouse in West, TX, USA (2013) are both examples of the excessive danger that serious warehouse fires and explosions pose to their surroundings due to expulsion of projectiles, massive overpressure, and the propagation of fire to nearby objects and structures.

Source: *United States Chemical Safety and Hazard Investigation Board, Praxair Fire*

Motto of the year

"Try to change situations, not people…"

T. Kletz ("An engineer's view of human error" ,1985)

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European Commission

When lessons learned from the past are applied

On May 27, 1987, a massive fire took place in a paint warehouse, in Ohio, U.S. The facility was storing over five million litres of paints and other chemicals and was located over the aquifer area which provided water supply to more than 400,000 people. Only two minor injuries were reported, but the property loss exceeded 32 million dollars. Notably, a fire a year earlier in the Sandoz Chemical plant in Switzerland chemicals and firewater run-off caused excessive pollution. of the Rhine in at least 250km area, soil pollution (at least 25,000 tonnes), prohibition on water consumption and fishing for six months. In contrast, the emergency incident command in Ohio decided not to apply water on the fire to avoid contamination from firefighting run-off, precluding a threat to the aquifer and the city's water supply, and preventing a major catastrophe. According to the official report, this decision was highly regarded and consistent with the lessons learned from the Sandoz accident. Ohio officials reported that "the decision not to apply water to the warehouse fire resulted in far less contamination to the groundwater and little if any difference in property loss".

Source: United States Fire Administration

Recommendations for checklist questions

- Has a hazard identification been conducted by taking into account the substance authorisation in the permit, along with operations at the warehouse and its physical features?
- Has the need to apply the ATEX directive been assessed with arrangements subsequently updated in regard to infrastructure, equipment, electrical components, and motor-assisted vehicles requirements?
- Is there a warehouse plan that assures safe and stable storage of all types of substances and appropriate segregation for incompatible materials?
- Is each container of hazardous chemicals in the workplace labelled, tagged or marked identifying the chemical it contains and the appropriate hazard warnings?
- Is there an inventory control process for controlling and accepting incoming shipments, assigning and transferring them to storage, and documenting and registering them in the inventory management system?
- Are there protocols in place that include criteria for rejecting consignments, and a process for either rectifying or as necessary, returning nonconforming consignments, including the availability of safe interim storage space for the goods until the situation is resolved?
- Have appropriate control procedures been instituted for hazardous materials, including safe handling practices for transferring substances and loading and unloading?
- Does the facility implement specific practices for safe operation of forklifts, including proper certification and training of operators, and documented procedures for forklift operation, with design and layout?
- Are there regular training sessions for management and employees to raise awareness of risks associated with the handling of hazardous substances, including contamination and incompatibility hazards, and particular activities, such as hot work and loading and unloading?
- Are there specific procedures, such as a permitting system, in place to address maintenance operations safely?
- Is structural integrity able to withstand fires, flame heat or explosion pressure weaves preventing the collapse of warehouse buildings?
- Are segregation elements fire-insulated to minimise fire propagation, where applicable?
- Are there systems in place to provide protection against malicious acts, including alarms and fencing?
- Are external construction elements (i.e., external walls, fencing) routinely checked and maintained?
- Are the firewater containment systems designed and maintained appropriately to accommodate the inflow of firewater mixtures in case of emergency?
- Is the inventory of all substances, including stored quantities and associated hazards, available to employees contractors, and emergency services?
- Is there ongoing and routine exchange with emergency responders on potential accident scenarios and emergency planning, including joint exercises?
- Has the need for specialised training (i.e. HAZMAT) on specific substances for emergency teams been assessed as part of the emergency planning?
- Are there safety protocols in place to ensure safe storage conditions, taking into account appropriate ambient conditions (i.e., temperature, humidity) per hazardous substance?
- Are there detection mechanisms and mitigation systems in place to address the potential release of flammable or toxic substances?
- Has the location of storage units onsite been thoroughly assessed (i.e. segregation, safe distancing from establishments boundaries), taking also into account the potential for domino effects, as part of the internal site planning?
- Have possible offsite consequences been assessed, particularly in highly urbanised areas, as part of the land use planning?

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