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On the Effects of a Triple Aggression (Fragment, Blast, Fireball) on an LPG Storage

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A possible event during a domino effect escalation is the projection and impact of a fragment on a storage. The fragment can be a consequence of a previous industrial accident, or may originate from a terrorist action. If this previous event (triggering event) is an explosion, the fragment impact can be combined with others effects such as blast or fireball. Many papers can be found about the impact of a fragment, a blast or heat fluxes on a tank during a domino effect. But very few work focused on a combination fragment + blast + fire ball. An experimental work was performed in order to study that topic. Fragments were launched against tanks containing LPG. A pyrotechnic setup was used to generate a blast effect and a fire ball. The influence of three effects (fragment, blast, heat) on the tank is be presented and discussed in order to better understand the domino effect occurrence in chemical plants.

1. Introduction

Domino effects have been defined as a cascade of events in which the consequences of a previous accident are increased by following one(s), as well spatially as temporally, leading to a major accident. Such chains of accidents have a greater propensity to cause damage than stand-alone accidents. The probability of occurrence and adverse impacts of such 'domino' or 'cascading' effects are increasing due to increasing congestion in industrial complexes and increasing density of human population around such complexes. Due to the significance of this phenomenon for the process industry, the analysis of the main features of the domino effect is quite interesting for risk analysis.
Previous authors considered scenarios where domino effect followed a sequence type chronology. Clini et al. (2010) performed a study of 261 accidents involving domino effect. This study revealed that the most primary incidents for a domino effect sequence are fire and explosion. The most probable global sequence is an explosion followed by a fire, which occurred in 21 % of the accidents, followed by the sequence release-fire-explosion (15 %) and fire-explosion (14 %).
This study considers a primary explosion in a chemical plant. This event may be a previous accident, e.g. a BLEVE, or a criminal aggression (bomb). In the first case, rocketing of parts of the tanks can entail high velocity fragments flying on long distances. The second case is linked with terrorism, sabotage and other criminal acts (Baybutt and Ready, 2003). Plants that handle hazardous chemicals are potential targets for terrorists, saboteurs, criminals and even disgruntled employees. Prior to September 11, 2001, these plants rarely considered such risks. But such acts could result in large numbers of public fatalities, economic and environmental damage and cannot further be ignored.
Threats can arise internally or externally. Internal threats include sabotage and vandalism by employees, or others contractors with routine access to a facility. Actions taken in such cases are likely motivated by the desire to cause economic damage rather than injuries to people, although the latter may occur even though it may not have been intended. The principal external threat is from terrorist's intent on causing a large release of hazardous material, or damaging or shutting down the facility. Release of chemicals requires the process containment to be breached, including the use of explosives or projectiles. The breach can be done either by actions taken from outside the plant boundary or from inside. Typical actions

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include the use of vehicle-born IEDs (improvised explosive device), the use of projectiles such as rocket-propelled grenades. Internal actions include the placement of satchel or shaped charges.
Whether in the case of accidental or deliberate explosion, it is likely to observe the three following effects, which are called escalation vectors:

- Overpressure and/or blast waves (shocks)
- Heat load (fire ball, pool or jet fires)
- Projection of fragments

A domino effect escalation by either one of these physical effects has been studied separately in the literature, but no work focused on the simultaneous aggression of the three vectors.

2. Single aggression (fragment impact or blast or heat)

Many studies have explored how the three parameters contribute to domino effect. Cozzani et al. (2005) described the occurrence probability of domino accidents caused by the three escalation parameters above based on accumulation probability of normal Gaussian distribution. The consequences of each escalation vector taken separately will be considered first.

2.1 Fragment impact

A major cause of failure is the impact of a fragment on target storage. The fragment can impact the tank at a velocity depending on the emission mode, shape and mass of the fragment, and the distance to be covered by the missile. Several works focused on the ejection velocity of fragments from BLEVE of LPG tanks (Genova et al., 2008), pressurized vessels (Baum, 1991) or warheads (Lecysyn et al., 2008). The ejection velocities ranged from 10-100 m/s (BLEVE, pressurized vessels) to 1,700 m/s (war projectile).
Lecysyn et al. (2009, 2010) performed several experiments in order to characterize the consequences of the impact of a high velocity projectile on a tank. A hydrodynamic ram is generated in the liquid and may make the tank burst. Liquid is ejected with a high velocity and may experiment primary break-up end partial evaporation. A liquefied gas will flash and form a two phase cloud. The consequence of this escalation vector is a leak of commodity or a total loss of containment.

2.2 Blast impact

Both domino effect and voluntary threat may involve a blast wave. The assessment of damage to process equipment caused by blast waves may be carried out at different levels of detail, depending on the final aim of the analysis. The straightforward identification of possible damage following a blast wave is greatly enhanced by the availability of so-called damage threshold values, that is minimum overpressure values at which a damage is expected at a given ‘‘target equipment’’. It is also worth remarking that the availability of threshold values is of utmost importance to simplify risk assessment studies, because in alternative damage evaluations should be carried out for all the equipment present on site. Moreover, several simplified models for the assessment of damage caused by blast waves in quantitative risk analysis as well as many ‘‘safety distance’’ criteria adopted in technical standards and even in the legislation are based on threshold values (Cozzani et al., 2006,Dyer et al., 2012).

2.3 Fire impact

Finally, thermal effects can also impact the storage. The thermal aggression can be very short (a few milliseconds) in case of explosions (condensed explosive, vapour cloud explosions); longer in case of fireballs (tens of seconds) and very long in case of continuous fires such as pool or jet fires (up to hours) (Heymes et al., 2013). The damage probability to process and storage vessels involved in fires is often calculated by the use of arbitrary threshold values that do not take into account site-specific factors, as the possible mitigation due to effective emergency response. On the other hand, very complex and time consuming approaches are available for the detailed calculation of the time to failure (ttf) of storage vessels, requiring a detailed description of vessel geometry and other design data (Landucci et al., 2009).

3. Multiple aggression (fragment, blast, fireball)

All three escalation vectors will impact the target tank at a time depending on transmission velocity of the vector.

- For a heat flux, the transmission by radiative heat transfer will be immediate and will last as long as the fire will burn. This vector requires an unobstructed straight line view between primary explosion and the target. The level of impacting heat flux depends on distance and geometric considerations.
- The overpressure wave will then hit the tank. The velocity of overpressure waves depends on the level of overpressure, at lowest it will equal speed of sound in the acoustic hypothesis. The level of shock wave depends on the distance and geometric configurations (1D, 2D, 3D).

- Finally, fragments will follow approximately parabolic trajectories before hitting the tank. The shape of this trajectory depends on fragment characteristics and initial velocity. In case of strong explosions, fragments can be propelled at supersonic velocities and can hit a target before the overpressure wave. A same chronology may be found when the distance between donor and acceptor sites is small.

3.1 Chronology of events

Figure 1 shows the time needed for each escalation vector to hit the target tank, as a function of distance between explosion and the target. Thermal events are instantaneous; other times were calculated following ballistic considerations and by assuming that the overpressure will propagate at sound velocity. For example, at 50 m a projectile propelled at an initial velocity of 1000 m/s will impact the tank after 52 ms, the blast will impact after 147 ms (overpressure propagation velocity assumed to be 340 $m.s^{-1}$). On the right side of Figure 1 are reported typical durations for different phenomena (vapour cloud explosion VCE and explosions (0.1 s), BLEVE fireball (10 s), jet fires, pool fires, structure fires (>100 s)).

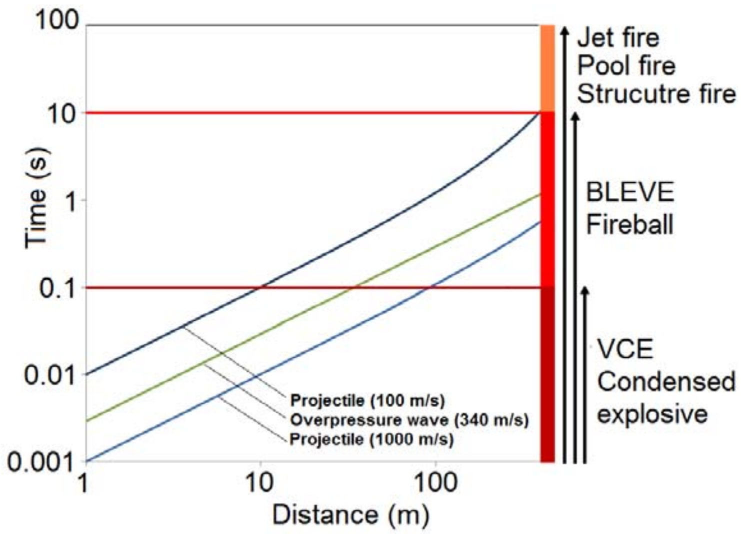

Figure 1: Chronology of aggression events on a target tank

Depending on the distance and the type of explosion, two scenarios can be considered:

- The overpressure comes first, damage the tank then the fragment hits the tank. At impact time, the tank remained quite cold since the heat exposure was too short to heat the wall.
- The fragment comes first. If a leak is created, the overpressure hits the damaged tank and interacts with the jet. At impact time, the tank remained quite cold since the heat exposure was too short to heat the wall.

In the first case, the overpressure wave may have weakened the tank which increases the probability to create a breach thanks to the fragment. The commodity release will follow dynamics as described in (Lecysyn et al., 2009). In the second case, the overpressure will hit a damaged tank; the probability to destroy the tank will increase too.

If the overpressure encounters a liquid jet, the interaction of both may lead to the break-up of the jet as reported in (Slangen et al., 2012). Depending on liquid characteristics, different behaviors are expected with typical breaking shapes like stripping, bag breakup or jellyfish. During the interaction with strong shock waves, drops will be atomized and will form a mist of micron-sized droplets. This is important parameter, since if a flammable commodity (such as gasoline) is atomized by the overpressure wave, a fuel-air explosion may occur.

3.2 Effect of fire during the triple aggression

The direct effect of primary fire on the tank depends on the heat transfer level and duration, but also on the presence of a breach or not in the wall of the tank. If a large breach was created, the internal pressure should remain low and no domino effect should be expected except the leak itself. If a small or no hole was created, the internal pressure could increase sufficiently to lead to another explosion (BLEVE, pressurized tank rupture). This explosion should be less severe because the damaged tank will burst at a lower pressure.

Another possible effect of primary explosion is the ignition of the released liquid jet. Figure 2 represents a sequence with the following steps:

- Point 1: a large LPG storage is considered
- Point 2: an explosion takes place near the storage; a fragment hits the storage and perforates the wall
- Point 3: the liquefied gas is released in the direction of the source of explosion, the shock wave encounters the gas jet and interacts therewith
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Point 1 Point 2 Point 3

Figure 2: Investigated chronology of domino sequence

Two outcomes can be expected. The first outcome is the ignition of the flammable jet (Figure 3). This will create a jet fire, with little effect from a domino point of view if no target is impacted by the fire (Point 4), or with severe domino effects if another LPG tank is impacted by the fire (Point 5). It has to be noted that the jet fire will also affect the wall of the releasing tank itself.

Point 4 Point 5

Figure 3: Outcomes of considered domino sequence

The second outcome is that the released jet is not ignited by the primary fire. In that case, a flammable cloud will expand on the plant and may cause a dangerous vapor cloud explosion. It is likely that the initial released jet will ignite and may create a jet fire and other domino effects.

3.3 Experimental results

The ignition of the flammable jet depends on many physical aspects such as LPG or oxygen concentrations in the released cloud, the ratio of both liquid and gas phases in the cloud; the ignition mechanism depending on the fire characteristics. Considering the well-known flammable limits is not sufficient since the primary fire area will be depleted in oxygen. The limiting case was assumed to be a condensed explosive as primary scenario. The combustion of such explosives is very short (much shorter than 1 s) and the area around the fireball is depleted with oxygen thanks to post combustion of the chemical reactants. Since the fire duration is very short, the LPG jet has to come quickly in contact with the fire before its extinguishing.

Figure 4: Release of LPG

A first set of experiments was performed in order to understand the propagation velocity and flammable concentrations of the LPG jet (Figure 4). Data about the contents of the tank, fragment velocity, type and mass of explosive are kept confidential in this paper.

A modelling of propagation of released cloud was used to understand in which conditions the LPG could ignite. Figure 5 presents the dynamics of the scenario. At time 0, the explosive is ignited. A blast, fragment and fireball are produced. The fragment covers the distance between the explosion and the tank. An LPG jet is created (point 1). The jet moves towards the fireball. If the distance is too great, the jet reaches the fireball when it is extinguished (point 2). If the distance is smaller, the jet is formed earlier (point 1') and can reach the fireball before extinction (point 2').

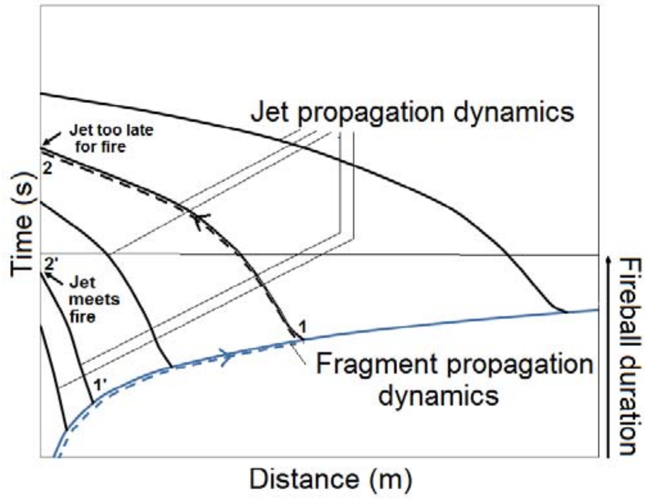

Figure 5: Chronology of events during the considered scenario

This description of the process was checked experimentally. Various distances and explosive quantities were investigated. It was proven that a condensed explosive can ignite the LPG jet (Figure 6). Consequence of this ignition is a jet fire which should be considered carefully. As reported by Casal et al. (2012), jet fires can be very dangerous because of the further accidents that they can originate if there is flame impingement on some equipment or if, due to a short distance, there is a strong radiation. In 50 % of the jet fires reported in accident data bases, an additional event with severe effects also occurred. In this case, the failure can occur at any moment from the beginning of the fire, the time to failure being very difficult to predict.

Figure 6: Ignition of LPG cloud

4. Conclusions

The objective of this work was to assess the consequences of combined aggression (fragment, overpressure, heat load) on a chemical storage to check for possible domino effects. Many experimental tests aimed to evaluate the perforation mechanisms, the hydraulic ram in the tank and the bursting of thereof, the liquid jet ejection, the fragmentation of the drop thanks to the overpressure wave.

Field experiments of combined aggressions were performed to evaluate the possible domino effects from the triple aggression of a LPG tank. It has been shown that in some cases, the LPG jet can be ignited by a condensed explosive. This result is worthwhile in domino effects studies considering global safety scenarios.

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References

Baum, M.R., 1991. Rupture of a gas-pressurized cylindrical pressure vessel: The velocity of rocketing fragments. J. Loss Prev. Process Ind. 4, 73–85.

Baybutt, P., Ready, V., 2003. Strategies for protecting process plants against terrorism, sabotage and other criminal acts. Homel. Def. J. 2.

Casal, J., Mares, M.G., Muñoz, M., Palacios, A., 2012. Jet Fires : a " Minor " Fire Hazard ? Chem. Eng. Trans. 26, 13–20.

Clini, F., Darbra, R.M., Casal, J., 2010. Historical analysis of accidents involving domino effect. Chem. Eng. Trans. 19, 335–340.

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., Zanelli, S., 2005. The assessment of risk caused by domino effect in quantitative area risk analysis. J. Hazard. Mater. 127, 14–30.

Cozzani, V., Gubinelli, G., Salzano, E., 2006. Escalation thresholds in the assessment of domino accidental events. J. Hazard. Mater. 129, 1–21.

Dyer, J.N., Raibagkar, A.P., Kolbe, M., Salzano, E., 2012. Blast Damage Consideratons for Horizontal Pressure Vessel and Potential for Domino Effects. Chem. Eng. Trans. 26, 87–92.

Genova, B., Silvestrini, M., Leon Trujillo, F.J., 2008. Evaluation of the blast-wave overpressure and fragments initial velocity for a BLEVE event via empirical correlations derived by a simplified model of released energy. J. Loss Prev. Process Ind. 21, 110–117.

Heymes, F., Aprin, L., Birk, a. M., Slangen, P., Jarry, J.B., François, H., Dusserre, G., 2013. An experimental study of an LPG tank at low filling level heated by a remote wall fire. J. Loss Prev. Process Ind. 61, 100-107.

Landucci, G., Gubinelli, G., Antonioni, G., Cozzani, V., 2009. The assessment of the damage probability of storage tanks in domino events triggered by fire. Accid. Anal. Prev. 41, 1206–15.

Lecysyn, N., Bony-Dandrieux, A., Aprin, L., Heymes, F., Slangen, P., Dusserre, G., Munier, L., Le Gallic, C., 2010. Experimental study of hydraulic ram effects on a liquid storage tank: Analysis of overpressure and cavitation induced by a high-speed projectile. J. Hazard. Mater. 178, 635–43.

Lecysyn, N., Dandrieux, A., Heymes, F., Aprin, L., Slangen, P., Munier, L., Le Gallic, C., Dusserre, G., 2009. Ballistic impact on an industrial tank: study and modeling of consequences. J. Hazard. Mater. 172, 587–94.

Lecysyn, N., Dandrieux, A., Heymes, F., Slangen, P., Munier, L., Lapebie, E., Gallic, C. Le, Dusserre, G., 2008. Preliminary study of ballistic impact on an industrial tank: Projectile velocity decay. J. Loss Prev. Process Ind. 21, 627–634.

Slangen, P., Aprin, L., Heymes, F., Munier, L., Lapébie, E., Dusserre, G., 2012. Overpressure wave interaction with droplets: time resolved measurements by laser shadowscopy. Proc. SPIE.