Anatomy of a domino accident: Roots, triggers and lessons learnt

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A B S T R A C T

On July 24th, 2010, several explosions and fires devastated a hydrocarbon processing plant in Kharg Island, Iran. Four workers were killed and many others were severely injured. The plant became out of service for 80 days. The way the accident happened and its sequence was representing as a domino accident. In this paper, events leading up to the disaster have been analyzed in details. Graphic presentation techniques such as Fish Bone Analysis and Event Sequence Diagram (ESD) have been utilized to enhance the understanding of the accident mechanism. Finally major lessons learnt from this domino accident have been addressed.

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1. Introduction

Petrochemical complexes are major hazardous installations which process large quantities of different substances. Large amount of flammable substances, intense temperature and pressure conditions make these installations potential sources of severe accidents. Due to the complexity, congestion and level of interaction among subsystems in petrochemical plants, the accidents that usually have occurred were not standalone. There is a high potential of domino accident occurrence in those plants meaning an initial accident can trigger more and more accidents making the consequences worse (Khan and Abbasi, 1998, 1999a).

The Middle East has probably the most important influence on the global petrochemical industry today and will remain so for many years to come. The region’s unparalleled production cost advantage and the willingness of its governments to diversify their oil-based economies have fostered exponential growth of this industry (Khoshrou, 2003). However, rapid growth of industry in this region had another undesirable consequence; more accidents. A survey done by authors has shown that both the number and the fatalities of domino accidents are decreasing in developed countries while these statistics are rising globally. At the moment, the share of developing countries from past domino accident is around 28% but it is growing year by year. That study has revealed that 12% of the total past domino accidents belongs to Middle East region (Abdolhamidzadeh et al., 2011). One of the latest domino accidents which has occurred in this region has taken place in Kharg Petrochemical plant. This plant is located in Kharg Island, 25 km off the coast of Iran and is producing mainly propane, butane and methanol.

Similar to many past domino accidents, the material which has been involved in this accident was a mixture of propane and butane. Based on a comprehensive analysis of 225 domino accidents, LPG has the highest share (26.7%) among all the chemicals involved in past domino accidents (Darbra et al., 2010). Table 1 shows some of these accidents.

Although the hazard associated with light hydrocarbons such as propane and butane has been repeatedly pointed out, there are still accidents happening with these components involved. It seems that in spite of the importance of these components, industry still needs lessons to be learnt in this regard. Some of these lessons can be learnt by reviewing past accident. So in this paper, Kharg accident has been selected for study and analysis.

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Table 1 – Some of the past domino accidents with LPG (propane/butane) involved.

<table>
<thead>
<tr>
<th>No.</th>
<th>Year</th>
<th>Location</th>
<th>Plant/unit/chemical</th>
<th>Deaths</th>
<th>Injuries</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1951</td>
<td>Port Newark, USA</td>
<td>LPG storage/propane</td>
<td>0</td>
<td>14</td>
<td>Lewis (1993)</td>
</tr>
<tr>
<td>2</td>
<td>1954</td>
<td>Lake Port, USA</td>
<td>Storage area/LPG</td>
<td>4</td>
<td>–</td>
<td>MHIDAS (2009)</td>
</tr>
<tr>
<td>3</td>
<td>1966</td>
<td>Feyzin, France</td>
<td>Refinery storage tank/propane</td>
<td>18</td>
<td>81</td>
<td>Mahoney (1990)</td>
</tr>
<tr>
<td>4</td>
<td>1972</td>
<td>Rio de Janeiro, Brazil</td>
<td>Refinery/storage area/LPG</td>
<td>37</td>
<td>53</td>
<td>Mahoney (1990)</td>
</tr>
<tr>
<td>5</td>
<td>1984</td>
<td>Mexico City, Mexico</td>
<td>Storage tank/LPG</td>
<td>650</td>
<td>6400</td>
<td>Lewis (1993)</td>
</tr>
<tr>
<td>6</td>
<td>1984</td>
<td>Romeoville, USA</td>
<td>Refinery/absorption column/propane, butane</td>
<td>17</td>
<td>31</td>
<td>Lewis (1993)</td>
</tr>
<tr>
<td>7</td>
<td>1986</td>
<td>Petal, USA</td>
<td>Pipeline/LPG</td>
<td>–</td>
<td>12</td>
<td>MHIDAS (2009)</td>
</tr>
<tr>
<td>9</td>
<td>1997</td>
<td>Visakhapatnam, India</td>
<td>HPCL refinery/LPG</td>
<td>60</td>
<td>–</td>
<td>Khan and Abbasi (1999b)</td>
</tr>
<tr>
<td>10</td>
<td>2000</td>
<td>Texas, USA</td>
<td>Tanker truck/propane</td>
<td>2</td>
<td>1</td>
<td>Acusafe (2009)</td>
</tr>
<tr>
<td>12</td>
<td>2009</td>
<td>Viareggio, Italy</td>
<td>Freight train/LPG</td>
<td>15</td>
<td>&gt;50</td>
<td>Landucci et al. (2011)</td>
</tr>
</tbody>
</table>

Nowadays, accident investigation/analysis are widely recognized as an important part of a comprehensive and efficient process safety management. A detailed and systematic analysis of an accidental event, allows to identify not only its immediate (primary) cause, but also the whole set of so-called root causes whose combination led to the failure of the system and to the occurrence of the corresponding harmful consequences (major accident), or to an unplanned temporary hazardous condition (near miss). Through reporting the results of the analysis, and through communicating and disseminating the report to other facilities/companies/organizations, the adoption of appropriate changes to similar existing installations or the introduction of preventive measures in the design of new systems will avoid the recurrence of similar events or, at least, reduce their frequency of occurrence (CCPS, 1992).

Another reason that makes analyzing of this accident important is that, despite the importance of domino accidents, little attention has been paid to this phenomenon. Moreover, there is no widely accepted definition for domino accidents and in different references up to 13 dissimilar definitions have been reported (Reniers, 2010). A reason of this un-uniformity can be lack of comprehensive analysis of domino case histories.

In this paper, roots and causes which led to the accident have been analyzed thoroughly. In this regard, graphic presentation techniques such as Fish Bone Analysis and Event Sequence Diagram (ESD) have been utilized. Finally, some corrective actions are proposed as this paper aims not only to clarify the mechanism and sequence of this particular domino accident but also to prevent similar accidents from occurrence by reviewing the lessons learnt.

2. The accident

2.1. Sequence

At about 7 p.m., on July 24th, 2010, a leak occurred due to gasket failure of a flange installed on the inlet line of a Preheater (Chemical Notebook, 2010). This exchanger warms up the feed entering to Deethanizer column by exchanging heat with its own hot effluent. Deethanizer column is a part of separation process that is being performed to extract propane and butane from the plant feed. In Deethanizer column, methane and ethane are separated from the top of the column while propane and butane are extracted from bottom and sent for further separation.

A schematic diagram of the leak position and its location in the plant layout are shown in Fig. 1(a) and (b), respectively.

The leak caused a hot liquid release immediately followed by a flash. A vapor cloud mainly consisted of propane and butane was seen by one of the shift supervisors. Four operators were sent there to isolate the exchanger by closing some manual valves that was not a safe order. However, the expanding vapor cloud soon found an ignition source and a terrible vapor cloud explosion (VCE) occurred. All the four operators were killed. The cloud was most likely ignited by the hot exhaust pipe of adjacent compressors that is shown on the plant layout in Fig. 1(b).

Unfortunately, this explosion was just the initiator of a chain of accidents. Fire flashed back to the release point and due to the high pressure inside the column, a jet fire happened. On the other hand, a part of the vapor cloud entered an empty space of the column skirt through a manhole. Although after the first explosion the plant was shut down and all of the feeds were cut off, the confined gas ignited causing a second VCE. The blast displaced the column and it collision to neighboring air fans and pipe rack led to more line rupture and subsequently more fires (Naftnews, 2010).

Meanwhile, the jet fire flame was impinging on the inlet line of Deethanizer column which was still filled with hydrocarbons. As inlet valves were closed, liquid hydrocarbon was trapped inside the inlet pipe and was heated continuously; these conditions gave rise to the occurrence of one of the most fearsome process accidents: BLEVE (boiling liquid expanding vapor explosion) (Abbasi and Abbasi, 2007, 2008). Finally, BLEVE followed by a tremendous fireball, occurred at the feed section. After three hours of effort, bravery and by getting help from neighboring companies, fires were brought under control at around 10 p.m. Finally at 6:30 a.m., fires were totally ceased (NIPC, 2010).

For the sake of better illustration, an Event Sequence Diagram (ESD) has been developed for this accident and as shown in Fig. 2. The Event Sequence Diagram method is a simple and
powerful modeling tool for developing possible scenarios. It enables visualization of the logical and temporal sequence of causal factors leading to various states of any system (Transportation Research Board, 2008).

A domino accident is defined as “An incident which starts in one item and may affect nearby items by thermal, blast or fragment impact, causing an increase in consequence severity or in failure frequencies” (CCPS, 2000). As it can be seen from Fig. 2, the sequence of this accident clearly meets the definition of a domino accident. The unique point about this mishap is that the cascade of accidents has expanded in two parallel pathways, both with severe consequences.

2.2. Causes

Typically, large scale accidents occur because of unexpected interactions among multiple failures. One component’s failure triggers failures in other components or subsystems (Shaluf et al., 2003). In Kharg accident, same as many other process catastrophes; a single cause cannot be pointed out as the main reason. There were a nested collection of roots and causes that led to this accident. These causes ranged from straightforward ones like mechanical defects to more fundamental roots such as managerial flaws or poor safety culture in the organization. In order to illustrate the role played by all of these causes, a Fishbone diagram has been developed for the accident. The Fishbone diagram (also called Ishikawa diagram or cause and effect diagram) was invented by Ishikawa and Lu (1985) and it is used to summarize the causes that create or contribute to a specific effect. In this method, causes are usually grouped into major categories to identify these sources of variation. This method usually works well when there are many causes involved in the occurrence of an accident. After a lot of investigation, interview, documentation checking and analysis, major causes of this accident have been categorized under six topics as it is shown in Fig. 3.

It can be seen that the number of sub-causes under the Equipment and Management categories are more than the other categories. If the quality of the gasket was better, the initial leakage would not happen ever. In case of leakage, if there have been gas detectors in that area to alert the operators or if there have been Remote Operated Shut-off Valves (ROS0V) to isolate the exchanger quickly, the extent of the accident would not be that large. Even after the occurrence of initial fires, the subsequent damages would be prevented; if there were deluge system and fireproofing coats. By a simple survey, it was revealed that as the plant was an aged one, there were a lot of shortcomings regarding hardware. This is called as lack of Mechanical Integrity in terms of safety standards such as Process Safety Management (PSM) standard (29 CFR 1910.119) (OSHA, 1991).

On the other hand, some of these shortcomings were rooted from lack of proper hazard identification in the plant. In case of performing a comprehensive HAZOP study, some of

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**Fig. 1** – Release point (a) and Layout (b) of the plant.

**Fig. 2** – ESD diagram of the accident.
the early causes might have been removed. It should be mentioned that there is a theory that the exchanger which was the source of release was not properly located. This exchanger was not a part of the original design and was added just a few years before the accident happened, in order to save more energy. Hence, in its layout adjustment, safety was overlooked and just operational feasibility was taken into account. This negligence was due to the lack of concern to the Management of Change (MOC) in the company.

Many other causes such as availability of ignition sources, lack of suitable training and poor safety culture have catalyzed the occurrence of the accident. These are shown in details in Fig. 3.

2.3. Consequences

Like other domino accidents, the consequences worsen after toppling of each domino block leading to a huge destruction. All of the equipment in the separation unit were damaged. Some of these equipment, such as Deethanizer and heat exchangers, were totally destroyed while the others experienced partial damages. More than 150 instruments and meters of control cables were totally destroyed. Plant was shut down for 80 days. More importantly, four skilled operators lost their lives as it was mentioned before. Fig. 4 shows sample of the huge destruction made.

It should be highlighted that the extent of damage could be much greater. But due to mobilization of several fire fighters and cooling of equipment affected by thermal radiation, the consequences were limited to those mentioned above. However, if the problem was accelerated to the scenario of LPG storage tanks rupture or release of H2S which was present in neighboring equipment, the accident could be turned to a regional crisis.

3. Lesson learnt and recommendations

Several lessons can be learnt by analyzing this accident. Occurrence of this accident once again indicated that even a minor change in process can have vast consequences. The change that was implemented to save energy by adding a pre-heater had led to the tragic consequences outlined above.

That is why Management of Change (MOC) is drawing more and more attention toward itself nowadays. In addition, by implementing a MOC system in a company, every single change will be reviewed in a holistic approach; not only design or operational benefits will be checked. It should be mentioned that MOC is one of the recommended elements of PSM standard.

Like many other past accidents, the present one has also happened after plant start-up. History of process accidents shows a very high potential of accident occurrence in the early stages after a plant start-up. Even the PSM standard has allocated a single element to: Pre-startup Review. Any incident investigation recommendations, compliance audits or PHA recommendations need to be reviewed to see what impacts they may have on the process before beginning the startup (OSHA, 1991).

A quick glance at the developed Fishbone (Fig. 3) can reveal the role of insufficient hardware safeguards or faulty equipment in this accident. Level of mechanical integrity was not satisfactory in that unit of the company. Several API standards dictating safety measures had been neglected while each of these measures might prevent the domino blocks from toppling. If deluge system had been installed based on API 2030, accident consequences would have been lower. If
the major structural supports had been properly fire proofed, there would have been fewer consequences. Although the level of required fireproofing against jet fires is still an unmet study and almost all of the practices just take into account the effect of pool fire. Moreover, by following API 2031, the plant should have installed more gas detectors and, again, lowering the extent of the accident. In Fig. 5, Swiss cheese model is showing how the lack of mechanical integrity led to the accident.

Hence, it should be emphasized that following the well-matured safety codes such as NFPA or API can have a huge effect on the safety level of each process plant. But merely following the codes cannot guarantee the accidents from not happening. There are several potential hazards that should be identified, where the associated risks of these hazards should be assessed and finally controlled. Therefore, it is vital for every process plant dealing with highly flammable and hazardous materials, to have a risk management plan. At least in this particular accident it seems that the implementation of OSHA PSM standard might have eliminated almost all of the causes leading to the accident.

4. Conclusion

Although the hazard associated with light hydrocarbons, such as propane and butane, is repeatedly pointed out, there are still accidents happening with such components involved. It seems that despite the hazard associated with these components, industry still have not learnt enough lessons on how to deal with these components in process plants. So digging for roots, causes and consequences of such accidents is still essential. Also, domino accidents need more attention and surveillance. Due to the fact that this accident happened in a domino fashion, with severe consequences and a lot of interacting causes, several lessons can be learnt by investigating the Kharg accident.

Fishbone and ESD techniques, which are both graphical methods with frequent use in accident investigation, showed benefits in describing the accident sequence and interaction of roots and causes. By performing an analysis based on the information gathered, the major roots and causes fall under two basic categories: Equipment and Management. By comparing the situation of the company with the elements of PSM standard, several deviations have been observed. It seems that the implementation of PSM standard or any other well-organized safety management system may lead to minimize the occurrence probability of similar accidents. On the other hand, integrity of layers of protection can prevent initial accidents to be cascaded.

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