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A study of caprolactam storage tank accident through root cause analysis with a computational approach

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ABSTRACT

In Taiwan, the rapid development of the petrochemical industry over the past four decades has resulted in economic progress and technological advancement. However, this success has been accompanied by pollution and sporadic accidents. Numerous accidents related to crude oil and its derivatives have resulted in a loss of life, employee injuries, environmental and property damage, economic decay, social outcry, and even political turmoil. This study investigated a caprolactam storage tank accident through root cause analysis with a computational approach. The previously described approaches returned findings that indicated causes similar to the real cause of this caprolactam accident. The four summarized descriptions of false conditions of the caprolactam explosion can serve as a reference for other investigations into the causes of petrochemical accidents. Reason of the caprolactam storage tank accident was determined by root cause analysis accompanying with a computational approach.

1. Introduction

The development of the petrochemical industry has been a major source of economic prosperity in Taiwan and has driven the progressive development of associated industries over the past four decades (Chen et al., 2014). After the completion of the crude oil refining process, a variety of chemicals are conserved in storage tanks in chemical plants and refineries for further commercial usage. These contents are usually hazardous and flammable (Bai and Liu, 1995; Chang and Lin, 2006), and the accidental release of these chemicals can exert devastating effects regarding lives lost, employee injuries, environmental and property damage, economic decay, social outcry, and even political turmoil. According to Chang and Lin (2006) and Wang et al. (2013), petroleum refineries are the most frequent locations of these accidents. According to previous studies (De La Fuente et al., 2014; Jonsson et al., 2015; Marucci-Wellman et al., 2015), even a small accident can result in a few days of production interruption, employee injuries, and property losses as high as USD 1,000,000. A large accident may lead to lawsuits, company bankruptcy, or stock devaluation (Chang and Lin, 2006). Examples from the previous decade include the Buncefield Oil Storage Depots disaster of December 11, 2005 (MIIB, 2008); a massive tank fire at Caribbean Petroleum Refining on October 23, 2009 (U.S. CSB, 2009); a devastating vapor cloud explosion that occurred in a large fuel storage area at the Indian Oil Corporation Depot in Jaipur, India on October 29, 2009 (Sharma et al., 2013); and an explosion that occurred at Xingang Port in Dalian, China on July 16, 2010 (Zhang et al., 2013).

Strategic petroleum reserves help sustain the demand for continuous and steady oil growth, and as a result, storage tanks play an increasingly critical role in the petrochemical industry (Bai and Liu, 1995; Shi et al., 2014). The most common type is the atmospheric storage tank, which is a convenient and lockable form of on-site oil storage (Bai and Liu, 1995). However, oil storage tanks and floating roof storage tanks are usually used to conserve crude oil and other products that have been subjected to the fractional distillation process, rendering them highly flammable and at high risk of exploding. The fault tree analysis (FTA) and why tree analysis (WTA) are therefore often used to analyze failure probability values during the oil conserving process and determine potential risks (Chi et al., 2014; Dong and Yu, 2005; Ejlali and Miremadi, 2014; Hu et al., 2014).

When investigating the root causes of accidents (Baysari et al.,

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2008; Chauvin et al., 2013; Li et al., 2008; Naderpour et al., 2014; Olsen and Shorrock, 2010; Patterson and Shappell, 2010; Schröder-Hinrichs et al., 2011), the deductive principles of FTA and WTA are broadly employed in graphical form to discover the logical functional relationships among components and subsystems of a system (Shi et al., 2014; Ejlali and Miremadi, 2014). This format helps clarify the direct and indirect causes of system failure and, in FTA, evaluate the probability of an event occurring (Ejlali and Miremadi, 2014; Zemva and Zajc, 2005). FTA and WTA have an extensive range of applications, such as to oil and gas transmission (Dong and Yu, 2005), railway systems (Svedung et al., 2008), electric power (Volkanovski et al., 2009), bio-energy production (Hu et al., 2014), nuclear power (Purba et al., 2011), man–machine robot systems (Lin and Wang, 1997), the aerospace industry (Ale, 2006), the petrochemical processing industry, the management of crude oil storage tanks (Wang et al., 2013; Lavasani et al., 2015), and the construction industry (Dong and Yu, 2005).

These forms of analysis can demonstrate the possible sequence of events following oil storage tank explosions. However, the distribution of stress during the explosion process is not factored into FTA or WTA. ANSYS computational fluid dynamics software is available to simulate this particular aspect of the explosion process.

Numerous studies have delved into the causes of chemical explosions, but few have focused on the causes of physical explosions. Therefore, this study combined WTA and ANSYS to investigate the physical causes of oil storage tank accidents, specifically those involving caprolactam (CPL). The results of this study contributed to the understanding of the physical aspects of oil storage tank explosions as well as standard operating procedures (SOPs) for oil derivatives storage, which can be used as a reference for inherently safer design of oil-derivative storage systems.

2. Case study of a CPL accident

2.1. Personnel interview record

This study involved a storage tank located at a plant in Taiwan. The top cover collapsed in the explosion, deforming the top portion as well as destroying the feed piping. The storage tank contained approximately 164.72 tons of CPL, which has a melting point of 69.0 °C, specific gravity of 1.05, vapor pressure of 0.1 mmHg, explosion limit of 1.4–8.0 vol% (LEL–UEL), vapor density of 3.9, and vapor flash point of approximately 100.0 °C.

The storage tank was fabricated of SUS304 stainless steel. A floating top design was completed in June 2000, and the storage tank was modified with a fixed top design in 2003. The storage tank was enclosed by thermal insulating material embedded with hot water piping and a zinc-coated metal plate, which maintained the temperature at 80.0 °C. The volume of the storage tank was approximately 2500.0 kL. There were connected auxiliary features such as a CPL feeding and discharging pipe, backflow gas pipe, hot water pipe, low-pressure vapor pipe, trace oxygen analyzer, storage tank, nitrogen purging system, thermocouple, level meter, pressure transmitter, flow meter, loading system, hot water pump, filter system, hot water tank, and hot water recycling system. In addition, there was a fire hydrant system, sprinkler system, cooling sprinkler, rain water discharge valve, vapor cooling system, bridge pipe support, measuring port, sampling port, oil fence and stairs, ground wire, and purging nitrogen supply, as shown in Fig. 1a and b.

The design and construction of the storage tank was produced following the API Standard 650 (API, 2013). The storage tank was equipped with three 4-inch pipelines on the external wall: One for unloading material from a ship, another for releasing pressure through vents connected to the ship, and another for nitrogen blanketing. After the storage tank was modified in 2003, the venting pipe leading toward the ship was sealed, and a new 3/4 inch pipe was constructed on the ground surface. Nitrogen was introduced through a 4-inch pipeline into the storage tank. In the new design, the venting pipe was connected to the storage tank.

CPL tank operations personnel in charge of the operation at the time of the explosion were interviewed about two weeks later at 10:40 a.m. on Friday, June 05, 2009. The storage tank explosion occurred on May 15, 2009 at approximately 2:00 p.m. The head of operations stationed in the control room informed on-duty staff that a pressure alarm had sounded for the storage tank (the alarm pressure value was set at 600.0 mmH_2O, normal pressure value was 500.0 mmH_2O, oxygen concentration was 10.0 ppm, and the system was purged with nitrogen).

After this notification from the control room, the on-duty staff immediately inspected the storage tank. The target storage tank near the main storage tank was vented, causing the tank pressure to decrease to 100.0–200.0 mmH_2O (below the normal working supply pressure of 350.0 ± 250.0 mmH_2O); after reaching this low point, the tank continued to vent. The function of the target storage tank is to release abnormally high pressure in the main storage tank through connected piping. The water in the main storage tank (smaller water seal vessel) is maintained at a certain level, and the pressure limit is set at 550.0 mmH_2O. If the pressure exceeds this limit, then the venting process automatically activates.

On June 5, 2009 at approximately 2:10 p.m., the on-duty staff arrived on the scene and conducted a recovery procedure to replenish and release water. However, this procedure was unsuccessful, and the pressure of the storage tank fluctuated at approximately 100.0–200.0 mmH_2O. As a result, a second operation was performed manually by opening the water-replenishing valve, releasing a small amount of gas from the storage tank. A large explosion occurred at approximately 2:30 p.m. Because of the sudden rise in pressure in the storage tank, the explosion ripped through the thermal insulating materials, including calcium silicate boards and insulation wool, and scattered them near the tank. After the explosion, the staff immediately turned off the power to the tank as well as the heating device, and further emergency response measures were initiated. The on-site interview results for the accident and the determined causes are summarized in the investigation records as follows.

2.2. On-the-scene investigation record

The pressure waves (p-waves) generated at a location near the explosion center are suspected to have been caused by the caving-in of the interior wall of the storage tank and the bending of the fence on the top-cover weld seam (the weakest point of the storage tank). The resulting pressure waves were centered at the explosion point inside the storage tank and expanded outward spherically. The wave surface area increased as the radius of the storage tank enlarged. Moreover, air gas pressure changed substantially and rapidly over time. Because of the aforementioned factors, the top cover of the storage tank was unable to withstand the largest pressure wave during the sudden and continuous rise and fall in pressure (ΔP), leading to the explosion.

The fractured surface had a dull metal color that did not show any sign of corrosion along the weld seam between the body and top cover, as depicted in Fig. 2a and b. Furthermore, the lifting hole installed on the tank body for the purposes of relocation also showed damage near the weld seam. Deformation of the weld seam was clearly observed on the fractured surface between the lifting hole and tank body.

CPL crystals and CPL blockage inside the pipes were noted on the interfaces between the vertical and horizontal hose pipes and pressure releasing pipes. A false signal was sent to the nitrogen