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Kaohsiung Vapour Explosion - A Detailed Analysis of the Tragedy in the Harbour City

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On the midnight of July 31st, 2014, a catastrophic vapor explosion occurred in the downtown of Kaohsiung city. The incident was initiated from a leak of an underground pipeline transporting pressurized propylene liquid. Analysis of pipeline operation logs and pipeline break release modeling suggested that at least 90,000 kg of propylene leaked, entered the underground trench and spread into the trench 4.5 km in distance before meeting an ignition source some three hours later after the leak. The ignition caused a significant vapor explosion which blew out the road above the underground trench, damaged more than one hundred vehicles on the road with thirty two fatalities and more than three hundred injuries. This article takes an in-depth look at the explosion incident covering the events leading to the explosion, explosion damage, cause of the leak, spread of the leak, and identification of a probable ignition source. Lessons learnt and recommendations are given to prevent and mitigate the occurrence of similar incidents.

1. Introduction

Vapour cloud explosion (VCE) is one of the most destructive events in the chemical process industries (Crowl and Louvar, 2011). Vapour cloud explosion is normally initiated by leak of a large amount of flammable vapour, dispersion of the vapour cloud in air, and finally ignition of the cloud leading to combustion, flame propagation and generation of overpressure. The destructive nature of vapour cloud explosion has been documented in well-known incidents such as Flixborough explosion in 1976, Pasadena explosion in 1989, and more recently the BP Texas City explosion in 2005 (Crowl and Louvar, 2011; CCPS, 2010).

In 2013, a devastating confined vapour explosion occurred in storm drains in Qingdao, China, which resulted in 62 fatalities and 136 injuries (Zhu et al., 2015). The explosion was resulted from a leak of a crude oil pipeline with about 2,000,000 kg of crude oil spilled into the city storm drains and spread several kilometres upstream and downstream. A larger but less documented incident was the gas explosion in Guadalajara, Mexico, in 1992 (IRB, 1996) in which gasoline was leaked into sewer through a corroded pipeline. There were 252 fatalities and more than 1500 injuries. Key factors contributing to the large number of fatalities and injuries in these two incidents are due to the very large quantity of flammable mass leaked and they occurred near or inside the well-populated communities in addition to the confinement in the sewer or drain. With growing process industries and city development, confined vapour explosion will be the major hazard that must be carefully assessed when process industries interact with the city.

In the present work, we described a confined vapour explosion occurred in the downtown of Kaohsiung City, Taiwan, on the midnight of July 31st, 2014. The incident was initiated from a leak of a corroded underground pipeline transporting pressurized propylene. The leak entered the underground storm water trench, spread more than 4.5 km, and finally met an ignition source some three hours later after the leak. Although this incident bears similarities to the Qingdao explosion and Guadalajara explosion, there was a subtle difference in that the present case was a leak from a pressurized, flashing liquid which would vaporize completely upon

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leak into ambient environment while the later cases dealt with flammable liquids with only partial vaporization. Challenges and recommendations are given to prevent and mitigate the occurrence of similar incidents.

2. Event leading to the explosion

The pipeline related to the incident is a high-pressure line connecting the LCY Chemical Corporation Tashe Plant and the harbour terminal company, China General Terminal & Distribution Corporation (CGTDC). It is a four inches pipe buried about 1 m below grade with a total distance of about 27 km solely devoted to transporting liquid propylene. Its route was planned in 1986 and operation started in 1993. A total of three underground pipelines, one 8-in ethylene line, one 6-in propylene line, and one 4-in propylene line, were built at the same time by Taiwan CPC Corporation and the 4-in line was transferred to LCY after the erection. Initially, the 4-in line was connected to the Taiwan CPC Corporation Cianjhen terminal. Subsequently, an extension line to CGTDC terminal was built as a second supply source. Although the pipeline route had carefully avoided the major downtown residential area, 25 years later most part of the pipeline is now surrounded by commercial and residential buildings.

On 20:46 July 31st 2014, an unknown white fog was reported to come out intermittently from manholes of the storm trench beneath the junction of Ersheng 1st Road, Kaixuan 2nd and Kaixuan 3rd Roads. Fire fighters from Kaohsiung City Fire Bureau arrived the site on 20:50, secured the area and began spraying water on the fog. An incident command post was also setup in the foot path of the road junction. Efforts were made to identify the leak materials and leak source but were in vain. By 21:50 with conflict information on the leak source and unknown leak gases, the on-scene commander from Fire Bureau decided to call EPA Southern Environmental Incidents Specialist Team, which is operated by Southern Centre of Emergency Response of Toxic Substances, National Kaohsiung First University of Science & Technology, for on-scene analysis.

On 22:20, a small explosion in the manhole of storm water trench occurred about 1 km away from the initial leak scene. The explosion did not escalate. Around 22:35, the EPA Specialist Team arrived the site. Efforts were made to identify the gas and find the leak source. Around 22:50, a major white smoke was found coming out from nearby light rail construction site underground trench opening. EPA Specialist Team entered the light rail construction site to perform gas sampling and analysis. This opening was considered as the source of the leak and the site was considered as the hot zone with restricted entry. An online Fourier Transform Infrared (FTIR) spectroscopy was also setup about 100 m from the command post in Kaixuan 3rd Roads to identify the unknown gases. Air samples were also taken back for FTIR analysis. Unfortunately, explosion occurred before the air sample was fed into FTIR which blew up not only the FTIR spectrometer but also the vehicle and injured five EPA Specialist Team members. Thus, there was no clear conclusion regarding the leak gas, the leak source and the source owner before the explosion. Formal confirmation of the leak gas to be propylene was delayed to 6:30 am the following day by another FTIR spectrometer from EPA Specialist Team on the intact storm water trench in Ersheng 1st Road.

Investigation after the explosion revealed the pressure transmitter on the side of Taiwan CPC pipeline connected to LCY pipeline recorded a sudden drop of pipeline pressure from 4.2 MPa to 1.37 MPa on 20:43. Both CGTDC and LCY Tashe Plant did not installed pressure transmitter on their side of pipeline. Only pressure gauges and flow meters were installed. Subsequently, LCY Tashe Plant operator found in the control room that the pipeline flow meter indicated zero flowrate. LCY operator phoned CGTDC operator in CGTDC control room. CGTDC operator found that the flowrate from the pump was abnormal and reached 33,000 kg/hr, well above the normal flow rate of 23,000 kg/hr. The operator also found that the pumping pressure was dropped from 4.0~4.5 MPa to 2.7 MPa and further dropped to 1.8 MPa, while the electric current for the pump motor rose from 120~130 amperes to 180 amperes. The operator then shut off the pump and pipeline isolation valve. The pipeline pressure dropped to 1.3~1.35 MPa after the shutoff. The engineers of the two sites discussed and decided instead of carrying out a pressure test at pumping pressure, a static pressure test with isolation valves at both sides of pipeline closed was carried out. The pipeline pressure maintained at the propylene vapour pressure of 1.3~1.35 MPa. By 22:00, LCY manager demanded to start pumping again. By 22:15 pumping restarted but CGTDC pipeline flow meter indicated a flowrate of 24,500 kg/hr yet LCY operator found that their flow meter indicated a flowrate of 6,000 to 7,000 kg/hr. Engineers of both companies agreed that such flowrate discrepancy should be resolved later. On 23:23, a CGTDC foreman for the next shift smelled propylene near Kaixuan 3rd road on his way to work. He suspected that it could be a leak from their pipeline and thus he rushed to CGTDC plant. He arrived 10 minutes later, expressed his concern to control room operator and ordered the shutdown of the pump. By 23:57, explosion occurred. Neither companies informed the Kaohsiung City Fire Bureau or any government agencies regarding the flow rate and pumping pressure abnormalities even after the explosion. Clearly, the slow response and negligence of operators in combined with production oriented plant manager were the major contributing factors for the catastrophic explosion.

3. The Explosion and the damage

Without any warning, an explosion occurred near the command post on 23:57 July 31st. The explosion was occurring beneath the road surface with a smoke erupting out from the storm water trench manhole, followed by road surface crack, and a large fire erupted out. The road surface was blown out and pushed upwards all vehicles and personnel on the road and then collapsed to the trench. Figure 1 shows the explosion affected area, the distribution of causalities and the pipeline route. The explosion propagated along the Kaixuan 2nd road to the north and Kaixuan 3rd road to the south along the storm water trench. At the end of Kaixuan 2nd road, the explosion propagated towards Sanduo 1st road and its junction to Wuqing 2nd road. A total of 4.5 km road were blown out.

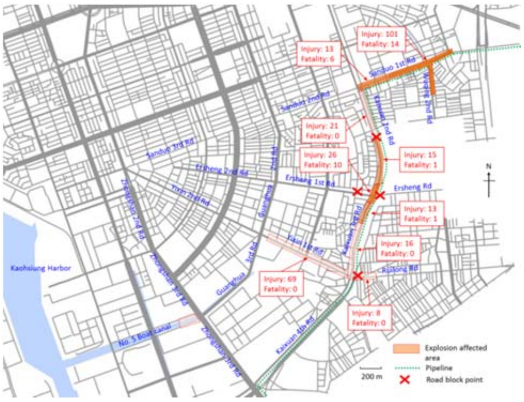

Figure 1: The explosion affected area, the distribution of causalities and the pipeline route.

Figure 2 shows photos of explosion damage at different roads. The junction of Sanduo 1st road and Wuqing 2nd road suffered the largest fatalities and injuries as indicated in Figure 2(a). Wuqing 2nd road is famous for many midnight snack shops. A total of fourteen civilian were killed by the blast wave and fire ball while more than one hundreds were injured. Another factor contributed to the significant fatalities in this area is that the road surface covering the storm water trench was only about 0.5 m which is very thin comparing with the 1 ~ 2 m in other roads. The explosion not only blew out the road surface but also shattered the road into small fragment and debris. Causalities were most caused by the debris impact and the explosion flame.

The second largest fatalities were occurred in the junction of Kaixuan 2nd road, Kaixuan 3rd road, and Ersheng 1st Road which centred around the incident command post. Fire trucks that parked on the Kaixuan 2nd and 3rd roads and were overturned by blown out road as shown in Figure 2(b). More than twenty fire fighting trucks were damaged along with three emergency response vehicles from EPA Specialist Team. Seven of the ten fatalities on this road junction were fire fighters. The explosion damage on the south side of Kaixuan 3rd road and Yixin 1st Road was less severe compared with other area as shown in Figure 2(c). It is likely that most explosion energy was dissipated by the thick road surface on top of the storm water trench. The explosion on the Yixin 1st road continued through the storm water trench near Guanghua 3rd road eventually vented through the No. 5 boat canal and blown out the canal terminal.

(a) (b) (c)

Figure 2: Photos showing the explosion damage near (a) the junction of Sanduo 1st road and Wuqing 2nd (b) the south side of Kaixuan 3rd road and (c) Yixin 1st.

4. Analysis of leak

4.1 The leak point

After the explosion, a large jet fire developed near the junction of Ersheng 1st Road and Kaixuan 3rd Road as shown in Figure 3(a). This was the largest fire after the explosion and it lasted till 6 am the following day. As the fire diminished gradually, it can be seen clearly that the fire was coming out from a branch of storm water trench as indicated in Figure 3(b). Clearly, this would be the source of leak.

(a) (b)

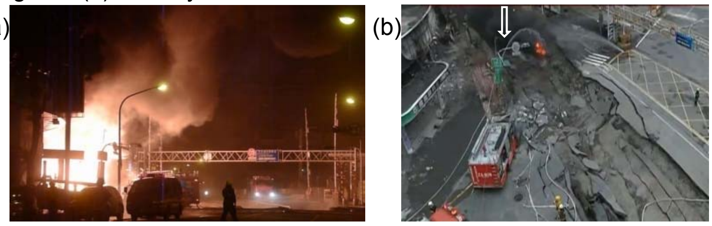

Figure 3: Photos of the fire after the explosion on the north side of junction of Kaixuan 3rd road and Ersheng 1st road. Time of the photos: (a) 12:00 am (b) 06:00 am.

Subsequent inspection of the trench branch with jet fire revealed that there were three pipelines passing through the trench. The 4-in line was completely exposed in air and had a break opening of 4 cm by 7 cm as shown in Figure 4. The 6-in and 8-in lines were located next to the 4-in line, partially exposed in air, and remained intact. Inspection of the leaked pipeline also showed pipeline wall thickness greatly reduced from its original 6 mm to less than 1 mm by corrosion from the humid ambient environment in the trench.

Figure 4: Photos of the storm water trench, the 4-in propylene pipeline and the break.

4.2 Amount of the leak

It is important to estimate the leak rate and amount of leaked in order to assess the potential damage and evacuation zone. The leak rate was dominated by leak opening and the pipeline pressure. Figure 5(a) shows the pipeline pressure recorded at Taiwan CPC Cianjhen terminal which is a branch line to the CGTDC and LCY pipeline. As the Taiwan CPC Cianjhen terminal was close to CGTDC pumping station, the recorded pressure can be a good approximation of the upstream pressure of the leak. As the boiling point of propylene is far below the ambient pressure, the leak from the pipeline may or may not flash depending on the upstream pressure. If the upstream pressure is higher than the saturation vapor pressure, the propylene may leak out as a liquid before flashing (Crowl and Louvar, 2012). If however the upstream pressure is close to the saturation pressure, flashing is expected and the typical two-phase flashing flow across an orifice may be used (Crowl and Louvar, 2012).

(a) (b)

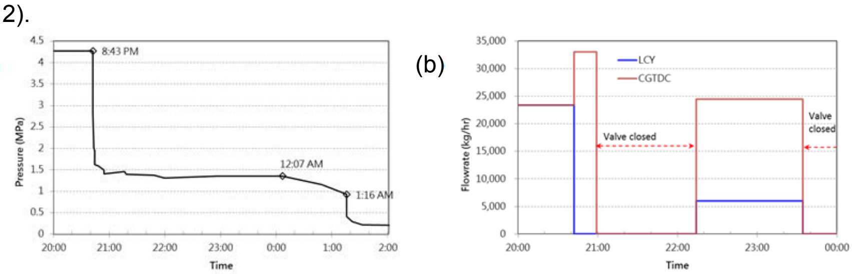

Figure 5: (a) Pipeline pressure recorded at Taiwan CPC Cianjhen terminal, a branch line to the CGTDC and LCY pipeline. (b) Recorded flowrate on CGTDC and LCY side

As Figure 5(a) indicates that the pipeline upstream pressure after the break was very close to propylene saturation pressure, flashing two-phase flow will be the dominant mode of leak. Although more detailed modeling can be done for the two-phase pipe flow, Chen et al. (1995) showed that the liquid dried out is expected to occur in about 10 s for a 100 m pipeline containing pressurized propane and butane. In the present case with very long pipeline and long leak time of more than 1 hr, liquid dry out was also expected near the break and the vapor choked flow equation (Crowl and Louvar, 2012) can be a good estimation of leak rate.

Figure 5(b) showed the recorded flowrate on CGTDC and LCY side. The area difference between the two records will be the amount lost during pumping and mostly in liquid form. Direct integration gives 34,000 kg. For the valve closed period, a total of 97 min, the loss is calculated to be 56,800 kg from the vapour choked flow equation and 160,000 kg from the flashing flow equation. The latter is far larger than the possible pipeline inventory of 100,000 kg based on the 27 km of pipeline volume and propylene density. As expected, the value from vapour choked flow calculation is considered a more realistic value compared with that from flashing flow equation. Thus, a total of 90,000 kg propylene was estimated to leak before the ignition.

4.3 Spread of the leak

Although the source of the leak was confirmed, it is important to know how the leak in the trench was spread to cause such a large damage. Subsequent investigation revealed that there were two storm water trench branches, one being directly beneath the Ersheng Road but is only 7 m in length and sealed in the other end, the other being about 10 m north of the dead ended branch and housed the pipelines. The later was then connected to the trench beneath Ersheng Road. Figure 6 put up a schematic diagram showing all the trenches and trench openings. The trench branch that housed the pipeline had a manhole upstream which was the manhole with the suction sound. As the pipe break was facing towards the main trench, the break leak would form a jet and entrained significant air from upstream and thus the manhole. Thus, the direction of the leak is in consistent with the finding of suction sound in the upstream manhole. It is also consistent with the fact that there was virtually no damage in Ersheng road.

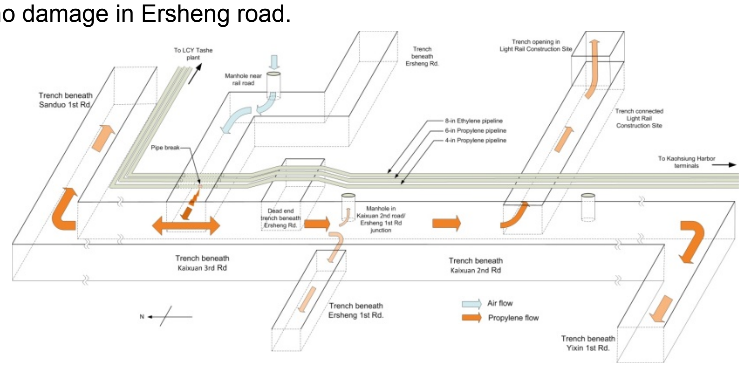

Figure 6: Schematic diagram of storm water trench, the pipeline, and the spread of the leak propylene.

In addition, the leak jet entered the main trench and spread both sides to Kaixuan 2nd and 3rd roads. This is in agreement with the fact that the manhole on the junction of Kaixuan 2nd road and Ersheng 1st road was the initial spot of vapour spread out of the trench to ground. Furthermore, a branch on the Kaixuan 2nd road was connected to the light rail construction site with a very large opening of 3 m by 3 m. This opening provided the least resistance for propylene vapour to escape to the ground and was considered the major source of leak before the explosion. Interestingly, the opening also provided a vent during explosion which reduced the explosion overpressure in that branch and therefore the ground above the branch was intact.

As the main storm water trench beneath Kaixuan 2nd and 3rd roads were connected to Sanduo 1st road and Yixin 1st road, respectively, majority of the vapour spread along Kaixuan 2nd and 3rd roads and then to Yixin road and Sanduo 1st road where the entire road surface above the trench was blow out. The trench beneath Sanduo 2nd road was however not connected to the trench beneath Sanduo 1st road and thus remained intact. The trench beneath Ruilong road was connected to the trench beneath Yixin 1st road but suffered only minor damage owing to its smaller dimension. Finally, the damage on the Ersheng 1st road was also minor as compared with those of Kaixuan 2nd and 3rd roads with road surface remained intact. This was again caused by the smaller trench dimension and reduced branch flow. In fact, all the branches connected to the main trench were mostly intact without road surface blow out.

In summary, the spread of the vapour flow in the trench was in consistent with the damage of the road. The spread of the leak vapour in the underground trench was governed by the flow resistance which is in turn affected by trench dimension, branched flow and trench opening to ground. Finally, the area with most vapour escaped do not necessarily corresponds to the leak source but rather depends on the size of opening to ground. These findings will be useful for all incident commanders dealing with underground pipeline leak incidents provided that all underground trenches are well documented and available during the incident. Unfortunately, the lack of information on the complicated trench network in the present case has prevented the on-scene commander from making a proper judgment regarding the leak source and potential evacuation zone.

5. Analysis of ignition source

An additional factor contributing to the vapour explosion is the ignition source. It is crucial to identify the exact ignition source so that a better site control in any future incident can be taken. As the ignition occurred more than three hours after the leak, it is difficult to determine the exact ignition source owing to very wide dispersed release. Several available videos from road surveillance cameras, vehicle driving records, and reporter cameras were used to review the direction of fire and explosion propagation. All videos pointed to the junction of Ersheng and Kaixuan Roads as the initiation location. In addition, a video taken by a journalist near the command post captured the explosion sound, a white smoke erupting out of a manhole on the road junction. This is the only video captured the moment before and after the ignition and thus confirmed that the junction of Ersheng 1st road and Kaixuan Road was the area with the first ignition.

As the area were blocked for traffic, the only available ignition sources were the fire trucks which remained running to provide firewater. In fact, there was a fire truck near the junction of Ersheng 1st road and Kaixuan Road as shown in Figure 3(b). Further investigation revealed that the fire truck was sit on top of an electrical cable junction box cover. The electrical cable junction box is not sealed but usually drained to nearby storm water trench. It is very likely that the vapour in the storm water trench spread out into the junction box, and eventually escaped the cover to meet the truck engine and ignited. The analysis suggests the importance of strict control of ignition source during a flammable release. In fact, the only safe outcome of such a large release of flammable vapour into a confined space is a slow dilution to below flammability limit. Either premature ignition or recovery of flammable vapour is extremely difficult and risky to do.

6. Conclusions

This article presents the first reported incident with leak and explosion of pressurized, flashing liquid in a storm water trench. The present case provided numerous lessons learnt and recommendation for preventing similar incidents in the future.

Firstly, a flammable leak into an underground trench is an important scenario and should not be overlooked in risk assessment of underground pipeline transporting flammable liquids or gases. Secondly, correct information on the underground pipeline and trench is crucial for the on-scene emergency regarding such leak. The spread of the leak vapor in the underground trench was governed by the flow resistance. A detailed storm water trench plot plan with all manhole opening is needed to identify the vapor spread dynamics.

Thirdly, the impact volume of a flammable leak into an underground trench is equivalent to the gas diluted into its flammability limits with the UFL being the realistic case and LFL being the conservative case. With known trench cross-sectional area, the impact length can be estimated from the leak rate and the UFL and LFL. For a pressurized, flashing liquid flow, the mass leak flow rate can be estimated from vapour choked flow equation.

Finally, the only safe way for disposing a flammable vapour leak in an underground trench is to allow the vapour being dispersed to concentration below the flammable limit. This would take significant time and thus the control of ignition source is crucial.

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