Caribbean Petroleum VCE Case History

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A vapor cloud explosion (VCE) occurred at the Caribbean Petroleum site in Bayamón, Puerto Rico on October 23, 2009 shortly after midnight. An above-ground gasoline storage tank (Tank 409) was being loaded from a cargo ship shortly before the incident. Overfilling of Tank 409 resulted in gasoline discharge through elevated tank vents and the creation of a very large vapor-mist cloud, which extended off the plant site into surrounding areas of heavy vegetation. Approximately 5,000 barrels (210,000 gallons, 790,000 liters) of gasoline were released, creating a cloud with a footprint of roughly 3 million ft^2 (70 acres, 0.3 km^2). The over-fill was halted roughly 10 minutes prior to the VCE. The cloud was ignited at an electrical equipment enclosure outside the electrically classified area. The resulting VCE caused blast damage to both on-site and off-site structures. Fires were ignited in a number of other storage tanks within the tank farm, which burned for several days.

Based on comparisons with the damage observed by the authors both on- and off-site, it was concluded that the VCE preceded as a deflagration, with vegetation located outside of the tank farm representing most of the congestion responsible for the VCE. Contrary to some reports in the literature, which appear to have focused primarily on individual damage indicators within the vapor cloud, the results of this investigation indicated that the VCE did not precede as a detonation (i.e., a deflagration-to-detonation transition did not occur). Additionally, contrary to the findings of some of the other investigations of this incident, it was concluded that the flame did not propagate through the east-west sewers.

Background

The accident described in this paper occurred at the CAPECO facility located in Bayamón, Puerto Rico. The authors participated in the on-scene investigation, evidence collection and analysis of the data. Information presented in this paper is the result of the authors' investigation.

A satellite view of the overall facility layout is shown in Figure 1. The facility included a refinery, tank farm, dock, and truck loading rack. The refinery portion of the facility had been out of operation for several years prior to the incident and all process equipment was decommissioned. No operations or maintenance was taking place in the refinery area, so there was no fuel source for the VCE in the refinery portion of the facility.

The CAPECO facility was being operated as a terminal at the time of the incident. Fuel received by ship was offloaded at the dock and pumped to tanks in the tank farm through a 20-inch diameter import pipeline. The dock was about 2 miles from the north boundary of the facility.

The tank farm occupied a large percentage of the facility, as can be seen in Figure 1. A tank farm layout is provided in Figure 2. The tanks being filled from a ship just prior to the accident were tanks 405, 504, 411 and 409, in that sequence. Tank 107 was also scheduled to receive gasoline, but the incident occurred before flow was started to Tank 107.

The topography in and around the CAPECO facility influenced vapor and mist dispersion. The northeast portion of the tank farm where tanks 405, 504, 411 and 409 were located was a high point in the facility as can be seen in the topographical map in Figure 3. The ground sloped away outside of the dikes for the north group of tanks. The arrows in Figure 3 show the downhill direction from areas in the tank farm.

The area to the north and downhill from the facility was a heavily vegetated public wetlands area. Only one onsite unpaved perimeter road separated the north dike wall from the wetlands. To the east of the facility was a public roadway across which was Fort Buchanan. The perimeter of the Fort near the road also had heavy vegetation.

To the west of the north tank farm was the Waste Water Treatment plant, as shown in Figure 1, at an elevation below that of the north tank farm and comparable to that of the central tank farm area. An east-west roadway separated the north tank farm dike area from the central tank farm area, as can be seen in Figure 2.

Figure 1. Satellite View of the CAPECO Facility

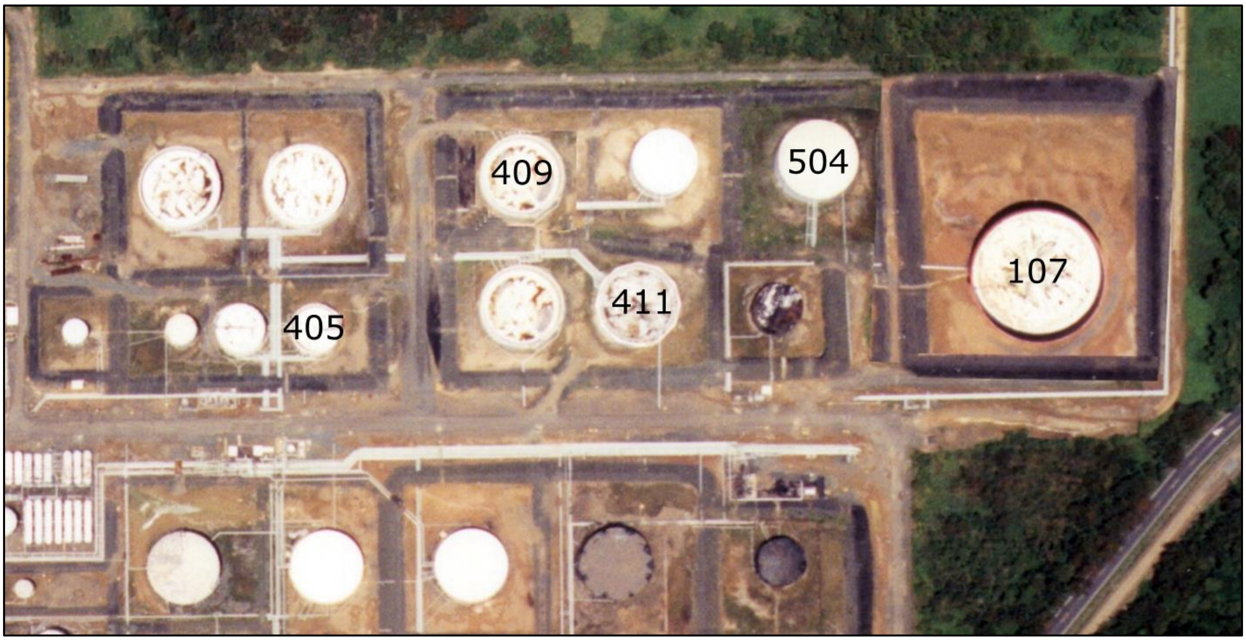

Figure 2. CAPECO North Tank Farm Layout

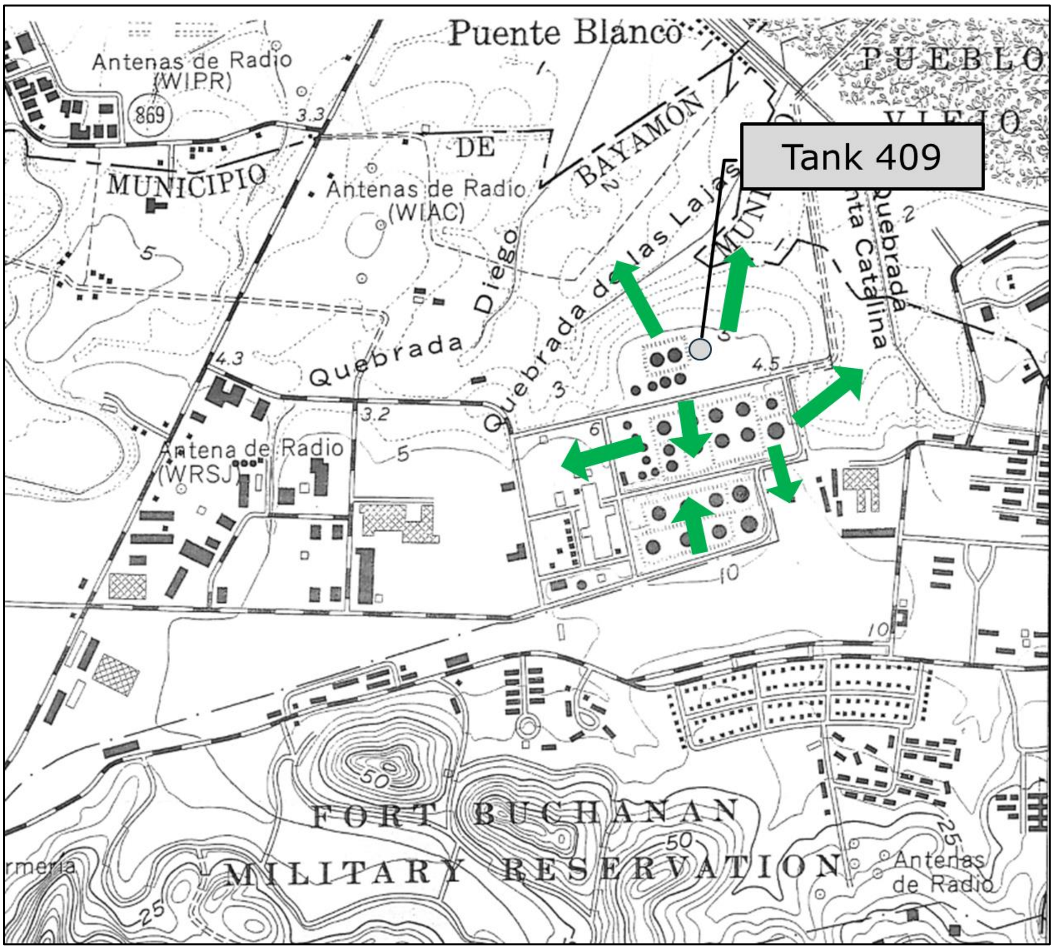

Figure 3. Topography at the CAPECO Facility

Sequence of Events and Witness Accounts

The sequence of events was developed from witness interviews, process data, inspector logs, ship logs, and surveillance video.

The VCE occurred during offloading of the tanker ship Cape Bruny on October 23, 2009 shortly after midnight. The ship arrived at the dock at 7:00 AM on October 21, 2009. Two independent inspectors arrived and gauged the ship cargo tanks. The inspectors then went ashore and gauged the tanks scheduled to receive gasoline. Inspectors also gauged tanks once they were filled and placed seals on the tank valves to "close" the tanks. The inspectors used their own tape measure to gauge the ship cargo holds and onshore tanks, not relying on ship or tank level gauging systems. The inspectors' notes therefore provide independent and accurate data on tank levels and fuel volumes transferred.

Four tanks were to be filled with gasoline (Tank 405, 504, 411, 409), with the remainder of the ship's gasoline cargo to be loaded into Tank 107. Switching of flow from one tank to another was done without stopping or slowing flow from the ship. The switching process was done by opening the inlet valve on the next tank in the sequence while continuing to pump to the tank which was being filled. The inlet valve on the tank which was being filled was then closed.

Unloading gasoline from the Cape Bruny began at 8:47 PM on October 21 into Tank 405. A pipeline purge and verification were first performed with the inspectors. Once verified, fuel was transferred continuously. Tanks 405, 504 and 411 were filled and "closed" before the accident occurred, with Tank 411 filling operations being complete around 10:00 PM on October 22. Tank 409 was the only tank receiving fuel for the reminder of the sequence until unloading was stopped at 12:12 AM on October 23.

The facility had a practice of "cracking" the inlet valve for the next tank in sequence when filling a tank, such that there was always a secondary flow path to protect against dead-heading a pump. However, this practice was not consistently followed. Most importantly, when filling Tank 409 (i.e., the tank which overflowed), the inlet valve to Tank 107 (i.e., the next tank to be filled) had not been cracked open. All flow from the ship was therefore being directed into Tank 409 when it was being filled.

The tank monitoring system was not communicating with the Tank 409 level transmitter, as will be discussed below. Operators were therefore making hourly rounds and manually checking the level using the index readings on the level housing located on the side of the tank. Based on these hourly readings, operators estimated that Tank 409 would be filled at 1:00 AM on October 23, at which time they planned to divert flow to Tank 107. The last time the tank level was read was 11:00 PM on October 22.

The last persons in the tank farm were the inspectors, who arrived at Tank 411 at 10:54 PM to close Tank 411. They sealed the valve and climbed to the top of Tank 411 to gauge it. Tank 411 was located diagonally across from Tank 409 as can be seen in Figure 2, and the inspectors had a clear view of Tank 409. They did not observe any problems in the tank farm, and did not observe any overflow from Tank 409. They also reported that it was a clear night with no wind. The inspectors left the tank farm at 11:23 PM.

Overflowing of Tank 409 began sometime between 11:23 PM and midnight on October 22. Three operators arrived at the tank farm shortly before midnight to make their rounds. They started walking from the Waste Water Treatment plant to the east into the tank farm along the roadway south of Tank 409. As they approached the tank farm, they observed a light “fog” illuminated by a street light. The fog was likely higher than the street light, but they could not tell how much higher due to lack of lighting. As they walked closer, they observed a dense layer of fog about waist deep and felt the fog on their bare hands. They had reached the propane bullets shown on the left (west) side of Figure 2. At that point they decided to turn back. The operators did not see or hear a tank overflowing or identify the source of the fog.

The operators radioed the ship to stop pumping, and then radioed other personnel on site to initiate an evacuation. Ship pumps are estimated to have stopped around 12:12 AM on October 23.

Other operators attempted to approach the tank farm in a car from the roadway on the east side of the tank farm. They observed a vapor cloud around Tanks 301 and 302. Fortunately, the cloud ignited before they reached the north tank farm area. They did not identify the source of vapors. As a result, no witnesses observed the overflowing tank.

CAPECO had been transferring other fuels by pipeline to an export dock on October 22nd. Jet fuel, diesel fuel, and fuel oil were transferred to a different dock than the one at which the Cape Bruny was docked. All fuel transfers were completed by 9:00 PM. The investigation revealed that there was no path through the terminal pipe system for the fuel transfers to the export dock to have affected the fuel unloading from the Cape Bruny and filling of Tanks 405, 504, 411 and 409. Unloading of the Cape Bruny was therefore found to be the only feasible means to overflow Tank 409.

Two vehicles were present on the public roadway on the east side of the plant at the time of the explosions. A sedan was headed north and had passed the northeast corner of the plant, and a dump truck was headed south and was southeast of Tank 107. The sedan is not believed to have been in the flammable cloud at the time of ignition. However, the dump truck was determined to have been in the flammable cloud when it ignited. Both vehicles were damaged but still operable, and the operators of both vehicles were able to drive away with minor injuries.

Tank 409 and Gauging System

Tank 409 was one of the newer tanks at the CAPECO facility. It was built in 2006, three years before the accident. The tank was 120 ft diameter and 63 ft high with a nominal capacity of 120,000 bbls. The tank had an internal floating roof. Figure 4 is a photograph of the tank taken at completion of construction. Visible in the photograph are two of the six overflow openings, each of which was 3 ft wide by 9 inches high.

Figure 4. Tank 409 Photograph

Tank level was measured with a mechanical level system, which used a float that ran on guide rods in a well in the floating roof of the tank. A metal tape connected to the float was routed through the roof of the tank through guide tubes to the gauge head. A spring actuated take-up reel wound the metal tape inside the gauge head. The gauge head was affixed to the side of the tank about 4 ft above ground level. The gauge had a manual index head that could read at the tank at grade level. It also had a transmitter to communicate with a computer that monitored tank level in the tank farm control room. CAPECO had a communication system problem, however, that prevented some tanks, including Tank 409, from being monitored in the control room.

The authors believe that the tank gauging system malfunctioned during filling of Tank 409, leading operators to incorrectly estimate the time required to fill the tank. There was no redundant high-level alarm. More information on the level gauge system can be found in the Chemical Safety Board report. [1]

Tank 409 Filling and Tank Overflow

The initial level of Tank 409 was 3 ft 2.6 inches, a level below that required to float the internal roof, which was initially resting on its legs. The available volume was 117,562 bbls of gasoline at ambient temperature.

The Cape Bruny had 12 centrifugal pumps available and was using six pumps during the unloading process. The ship could vary the pumping rate using combinations of pumps and pressure controls, and the ship pumping rate varied during unloading from about 10,000 to 11,400 bbls/hr. The pumping rate was estimated to be 11,369 bbls/hr at ambient temperature at the time Tank 409 overflowed. Ships typically pump at the fastest rate that the receiving facility can accept in order to minimize both the time the ship is docked and the associated expense. A hypothesis considered was that the ship may have increased the pumping rate in the final hour before the incident. Despite investigator requests, however, the Cape Bruny never produced pump rate data that could be used to evaluate that hypothesis.

Based on a detailed material balance, accounting for the material off-loaded from the ship and received at the facility, approximately 4,600 barrels (193,000 gallons, 731,000 liters) of gasoline overflowed from Tank 409. The overflow period duration was estimated to be about 24 minutes. Fuel transfer from the ship was stopped roughly 10 minutes prior to the VCE.

Weather Conditions

The weather was clear on October 22 and 23 with no precipitation. Plant personnel reported that the weather was mild. Weather reported in San Juan was a temperature of 82 °F (28 °C) at the time of the incident with calm winds. The two inspectors who were on top of Tank 411 about an hour before the accident stated that the weather was clear with no wind.

Gasoline Dispersion

Gasoline overflowed from the six overflow outlets arranged around the shell of Tank 409 about 60 ft (18.3 m) above grade (see Figure 4). The tank also had two wind girders that protruded 8 inches (20 cm) from the shell, fabricated from 8 inch × 6 inch (20 cm x 15 cm) angle steel with the open side of the angle facing down.

Gasoline that spilled from Tank 409 and reached grade level was collected in the dike, which had a drain pipe through the north dike wall that connected to a sewer that discharged into the wastewater pond. For environmental reasons, the plant had to keep drain valves closed. Rain water was collected in the dikes, sampled and tested, and then drained from the dikes. The dike drain valve was found closed, chained and locked after the accident. Plant personnel were ordered by government authorities to open the dike drain valve after the accident in order to check the valve. Weeks later in a subsequent check with investigators using water, the valve was not closed tight, and some water passed the valve. The authors believe that the dike valve was closed and not leaking during the accident. However, if the dike valve had been leaking, gasoline would have flowed to the north sewer and discharged into the wastewater pond, which the authors inspected. This north sewer did not connect to any other plant sewers. Gasoline discharged into the wastewater pond therefore could not account for the flammable cloud footprint.

The flammable cloud formed by a combination of gasoline vaporization and mist formation from falling gasoline impacting surfaces (i.e., tank wind girders, ground, etc.) and atomizing in air. The momentum of the vapors and mist carried the cloud outside of the dike. In the calm wind condition, the denser-than-air cloud spread in all directions from the tank, generally following the topography downhill.

The flammable cloud was about 1,000 ft (330 m) in diameter, and generally centered on Tank 409. Based on observed damage to vegetation and analysis of surveillance videos, the flammable cloud area was roughly 3 million ft^2 (70 acres, 0.3 km^2).

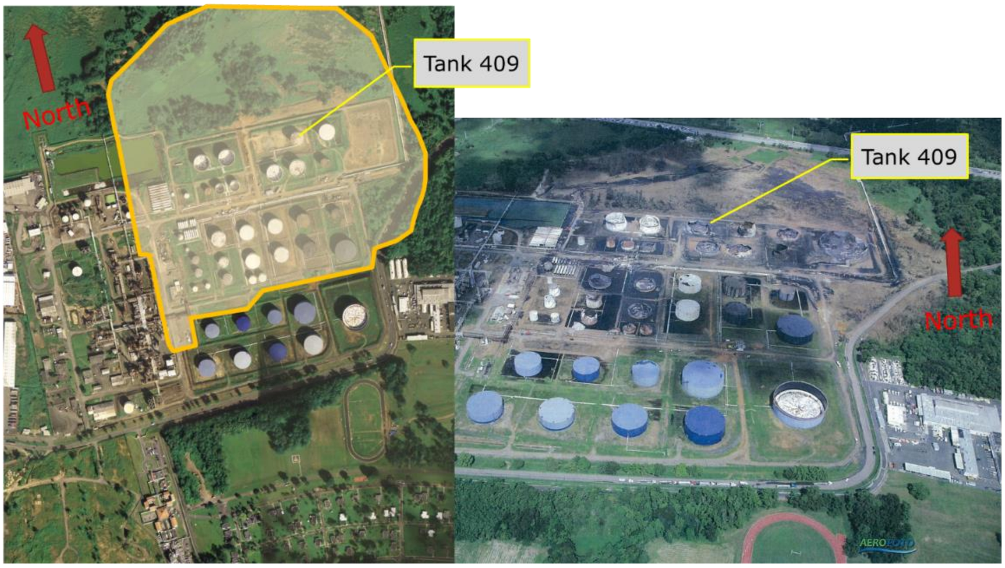

Figure 5. Flammable Cloud Overlaid on Before Photograph and Compared to After Photograph

Ignition Source

Ignition occurred about 34 minutes after Tank 409 began overflowing. The initial ignition source was on the western fringe of the flammable cloud, as depicted in Figure 5. CCTV cameras were located at northwest corner of the site (rotating) and on a column in the refinery (fixed). The ignition of the vapor cloud was not captured directly by either CCTV camera. However, the general location of the ignition source was deduced by examining CCTV footage and noting the object (e.g., tanks, vessels, etc.) surfaces that were first illuminated. This allowed the general area of the ignition source to be isolated to the dotted rectangle shown in Figure 6; the edges of the site lines for each CCTV camera are denoted as yellow lines in this figure. The most likely ignition area based on the reflections is shown as a red circle in Figure 6. The only identified potential ignition source within this circled area is an electrical equipment enclosure that housed pump switch gear, which is shown Figure 7. The white arrows in Figure 7 show the direction of illumination of the tanks from ignition at the electrical equipment enclosure. The metal panel siding for the enclosure was blown off the enclosure frame, consistent with flammable vapors entering the enclosure and being ignited within.

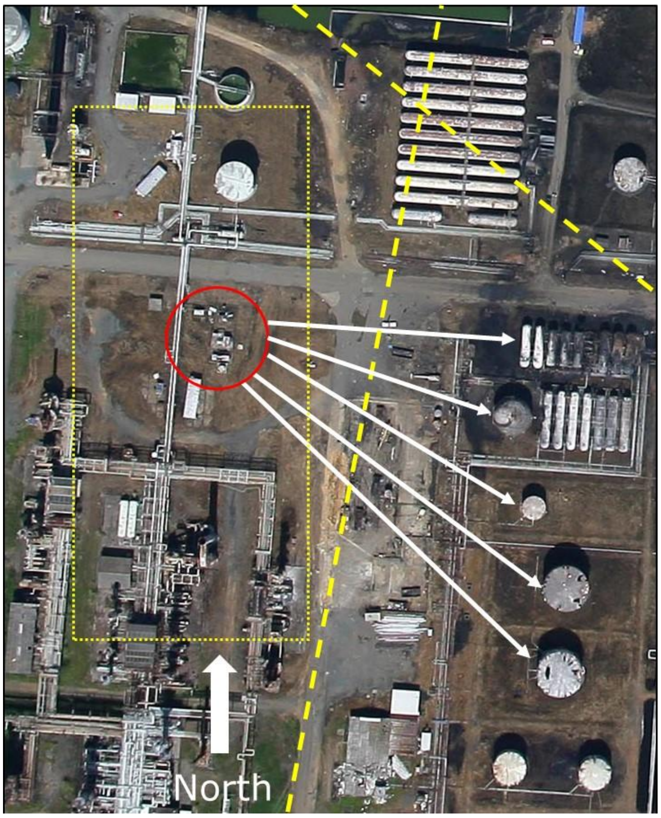

Figure 6. Location of Ignition Source

Figure 7. Ignition Source (Electrical Equipment Cabinet)

A secondary ignition is evident in the CCTV video roughly to the southwest of Tank 107 (i.e., flame appears in this area ahead of the main flame front), as shown in Figure 8. The hypothesis that this secondary ignition was a flame propagating through a sewer and jetting from a sewer opening southwest of Tank 107 was investigated in cooperation with the CSB. However, the only nearby storm sewer opening was a sump that always had standing water controlled by a level switch to keep a submersible pump submerged. In order to have reached this opening, the flame had to have been forced to propagate in the upstream direction through a check valve and the flooded pump. Inspection of this equipment did not indicate damage consistent with internal flame propagation. Process sewer pipes were also investigated and found to be liquid filled with no indications of internal blast pressure loading. The hypothesis of a flame jet originating from a sewer was therefore not borne out. Also, careful triangulation of the video placed this secondary ignition in line with an electrical equipment enclosure, not a sewer opening. The electrical equipment enclosure is shown in Figure 9. The panels forming the enclosure were all displaced in a manner consistent with internal pressurization; the circled items in Figure 9 are sections of this enclosure.

Figure 8. Frame from CCTV Showing Secondary Ignition

Figure 9. Secondary Ignition Location (Electrical Equipment Enclosure)

Vapor Cloud Explosion

VCE blast loads were evaluated using two approaches:

(1) A deflagration using the Baker-Strehlow-Tang (BST) VCE blast load prediction method [2,3] based upon a flammable cloud consistent with the outline shown in Figure 5, and

(2) A detonation based on the cloud predicted using the HSL methodology [4,5] for a gasoline overflow.

The BST VCE blast load predictions were developed assuming a 10-foot cloud height, which was a reasonably consistent average based on observations at the site and witness accounts. Confinement and congestion were mapped by BakerRisk investigators while on-scene both in the plant and the vegetated areas. The HSL cloud was modelled as being a 1-meter high, cylindrical-shaped cloud, consistent with the HSL guidance. The radius of the HSL cloud was 1,510 ft (461 m), about 50% greater than the observed damage radius. Coincidently, the flammable cloud volume with both these approaches was 23×10^6 ft^3 (6.5×10^5 m^3); that is, the only significant differences between the two flammable clouds considered was the height and lateral dimensions.

The response of structural components (i.e., damage indicators) was compared to the predicted blast loads for the VCE scenarios considered. Damage indicator information was gathered for buildings and structures on and near the site. Examples of the types of structural damage indicators include corrugated metal panels, cold-formed metal girts, open-web steel joists, wide-flanged steel roof girders, steel plate covers of firefighting equipment, and glass windows. The damage indicators were analyzed to determine the blast load that would result in the observed damage using the single degree of freedom (SDOF) and empirical pressure-impulse diagram methods.[6] Indicators that did not experience any observable damage served as upper bounds (i.e., an upper limit to the blast loads above which damage would have occurred). Indicators that had observable damage were used to determine blast load estimates.

The structural damage analysis indicated that a vapor cloud detonation using the cloud size indicated by the HSL guidance significantly over-predicts the VCE blast loads. On average, the detonation scenario over-predicted blast overpressures as compared to the blast damage indicator pressure asymptote values by a factor of approximately 40 (i.e., more than an order of magnitude). The detonation scenario gave blast overpressure predictions that were 5 to 300 times the damage indicator pressure asymptote values.

Blast load predictions for the deflagration of the same cloud volume using the BST method with a medium reactivity fuel, which is representative of gasoline vapor/mist mixtures, matched the structural damage indicators reasonably well. Neglecting the congestion present in the heavily vegetated areas significantly under-predicts the required blast loads, while accounting for only the vegetated areas still yielded reasonable agreement with the observed damage; this is expected since roughly 90% of the flammable cloud was located in the vegetated areas.

These analyses indicate that the flammable cloud did not undergo detonation, and that the deflagration blast loads predicted using the BST parameters yields reasonable agreement with the observed damage. The vegetated areas were found to drive most of the blast load predicted using the BST method. It is noted that, unlike the Buncefield incident [7], buildings were not present within or near the edge of the vapor cloud, and hence the observed building damage was not as dramatic as at Buncefield.

Damage observed at the facility was consistent with a deflagration and not a detonation. There were no locations of high airblast damage that would occur in a detonation. Extensive fires caused considerable secondary damage, some of which has been mistakenly used by others to conclude that a deflagration to detonation occurred, such as a bent hand rail and a buckled tank. The authors investigated these damage indicators on site and found that fire sources caused the observed damage. In addition, other nearby damage indicators did not suffer damage consistent with a detonation (e.g., a hand rail on the other side of the stairs from the one that was significantly bent).

Secondary Fires

Secondary fires were immediate and covered an extensive footprint. The surveillance videos showed that vegetation throughout the flammable cloud footprint was promptly ignited. This is an unusual situation in that the vegetation was very moist in the tropical environment and hence not particularly susceptible to prompt ignition. Nearby tanks and dikes were also quickly involved in the fire. It is believed that mist from the overflowing tank was a significant contributor to fire spread. Wetting of vegetation, tanks and other equipment by gasoline mist that ignited is suspected to be the reason for the abundance of fires throughout the area covered by the flammable cloud. Most of the damage in the facility was due to secondary fires, fed by a loss of containment from other tanks and vessels during the fires.

Conclusions

The following conclusions were drawn from the investigation.

- The VCE at CAPECO was the result of overfilling of Tank 409 during gasoline unloading from a ship.
- The volume of fuel estimate to have spilled was 4,600 barrels.
- The vapor-mist cloud dispersed in all directions in the calm wind conditions due to the momentum and density of the vapors and mist, with the cloud spread generally following the topography. The cloud width was approximately 2,000 ft (610 m).
- The VCE was a deflagration. Thorough site inspection by the authors revealed no evidence of a DDT, even on a small, localized basis.
- Blast loads were consistent with a deflagration. By contrast, blast loads for the detonation of a flammable cloud size per HSL guidance for an overflowing gasoline tank were over-predicted by at least 5 times and by as much as two orders of magnitude. The over-prediction of the blast pressure was, on average, a factor of 40.
- Using a cloud volume consistent with the HSL methodology and applying the BST VCE blast load methodology would be expected to yield reasonable consequence predictions for similar events.
- Extensive secondary fires are suspected to have been rapidly ignited due to gasoline mist wetting vegetation, tanks and equipment. Such rapid fire spread is uncharacteristic of VCEs involving flammable gases.

References

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