Use a Bow Tie Analysis to Improve Emergency Response Plans at Terminals

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Abstract

Terminals storing hydrocarbon fuels and other flammable materials have a significant loss history of catastrophic fires despite the widespread availability of applicable Recognized and Generally Accepted Practices (RAGAGEP) and the best efforts of terminal emergency response teams, public fire departments, and private industrial firefighting companies. After an initiating event, usually involving a loss of primary containment, fires involving hydrocarbon fuels grow rapidly. The expanding fire size generates convective, conductive and radiative heat transfer, resulting in consequences that extend far beyond those of the initial event. This is known as the domino effect. Loss history tells us that the Domino effect has played a role in many catastrophic terminal fires.

The Bow Tie can be used as a tool by terminal operators to identify and analyze their Prevention and Consequence Mitigation Barriers. This paper demonstrates how a Bow Tie analysis can be used to improve a facility's emergency response plan by examining the Consequence Mitigation Barrier performance associated with the ITC Deer Park Terminal fire.

Introduction

Fuel terminals range in size from single storage tank locations to facilities with 200 plus tanks. Fuel terminals have a long loss history within the global energy industry. Well known losses include the San Juanico, Mexico Explosion of 1984 and the Buncefield Terminal Fire of 2005. These incidents started out as major loss of containment events that triggered explosions and ensuing fires. Most terminal fires; however, often start small and grow into catastrophic fires.

From a property damage and business loss standpoint, terminal fire and explosions are small events when compared to similar events at chemical plants and refineries. When fatalities, community impact and environmental damage are also considered, Terminal fire consequences can reach catastrophic levels. The ITC Deer Park and Marathon Garyville fires are examples of this type of event.

ITC Deer Park, TX (March 17-20, 2019) A naphtha pump failure with ensuing fire in a large tank farm destroyed all of tanks within the diked area. The secondary containment system(a dike wall) failed post-extinguishment. Massive amounts of contaminated effluent were released into the local waterway. Local residents and businesses were adversely affected by the incident.[1]

Marathon, Garyville, LA (August 25-28, 2023): A naphtha leak and ensuing fire in a large secondary containment area destroyed two storage tanks over the course of several days despite the rapid response of well-equipped firefighters.[2]

The domino effect potential inherent with storing large amounts of combustible fluids in a relatively small area makes flammable liquid tank farm fires very difficult to extinguish. Even the best emergency response organizations will struggle to extinguish these types of fires if they are the only effective line of defense (consequence mitigation barrier) in place. The impact of other well designed and maintained consequence mitigation barriers can greatly reduce the burden placed upon the emergency responders.

USA-Based References for Tank Farm & Terminal Fire Protection

There are few publicly available fire protection and prevention references ***specific to*** fuel terminal operations within the US. They are listed below.

- NFPA 30, Flammable and Combustible Liquids Code, Chapter 22[3]
- API 2350: Overfill Protection for Storage Tanks in Petroleum Facilities.[4]
- API 2610 (RP) Design, Construction, Operation, Maintenance, and Inspection of Terminal and Tank Facilities [5]
- API 2510A Fire-Protection Considerations for the Design and Operation of Liquefied Petroleum Gas (LPG) Storage Facilities[6]
- API 2001 (RP) Fire Protection in Refineries[7]
- LASTFIRE - Hydrocarbon Storage Tanks [8]
- Texas Administrative Code (30 TAC), Chapter 338- Above Ground Storage Vessel Safety Program.[9] (Implemented after the ITC Incident)

The OSHA 1910.119 standard, known as the Process Safety Management of Highly Hazardous Chemicals, does not apply to the storage of flammable liquids in atmospheric storage tanks that are kept below their normal boiling without refrigeration or chilling[10]. The use of, or compliance with, the above references is not mandatory on a federal level. The Texas Administrative Code (30 TAC) noted above has incorporated recommendations from the NFPA 30 Chapter 22 and API 2350 into regulations. These recommendations (requirements) go into effect in 2027.

Fuel terminals in the US are lightly regulated from a fire prevention and protection standpoint and, in this authors' experience, rarely have an emergency response plan that includes a reliable strategy for extinguishing fires that grow beyond an incipient stage level.

Emergency Response Planning

A standard emergency response plan (ERP) should identify the potential incident scenarios a facility expects to manage. These scenarios include fires, explosions, environmental releases, and personnel accidents. A comprehensive ERP will also provide guidance on how to deal with their worst-case credible incidents, such as major fires and explosions. This information is often included in a document called the "fire pre-plan."

As noted in Guidelines for Technical Planning for On-Site Emergencies, "Chemical process emergencies rarely involve a single event. A typical scenario can represent a spectrum of outcomes, depending upon the degree of failure and range of possible intermediate detection and response events."[11] Fuel terminals are much simpler than chemical processes and present fewer incident scenarios for evaluation.

For a tank farm storing flammable and combustible liquids, there are three basic types of fire scenarios (or credible incidents).

- tank fire (full or partial roof involvement)

- pool fire (inside diked area)
- pressure fire (from pump or piping)

The fire pre-plans should provide emergency response information on the fire safeguards in place and some level of guidance on each type of fire scenario. In reality, *most firefighting organizations lack the resources to manage simultaneous fire scenarios, such as multiple tanks on fire at once*. Therefore, the potential for domino effects / rapid fire escalation must be minimized to maintain the credibility of the fire pre-plans and the effectiveness of the emergency response actions.

Case Study - The ITC Deer Park Terminal Fire of 2019

Terminal Description

The ITC Deer Park Terminal is a bulk liquid storage terminal situated on the inlet of Tucker Bayou in the Houston Ship Channel. At the time of the loss, the ITC Deer Park terminal was a 265-acre facility equipped with 227 storage tanks, both rail car and tanker truck access, tanker berths, barge docks, and multiple pipeline connections.[1] The terminal is over one mile long. The property begins at the docks on the north side and extends south approximately 6000 ft. following the course of Tucker Bayou.

Most of the storage tanks are rated for low pressure (less than 15 psig) and store liquid petroleum products such as gasoline and hexane. The storage tanks are grouped into common operational areas known as “tank farms.” These tank farms are surrounded by concrete dike walls for spill containment. The distinguishing features of the ITC terminal are multiple tanks in a common dike areas and the arrangement of the tanks in rows more than two levels deep.

The incident occurred in the tank farm known as First and Second 80’s Tank Farm (Figure 1). This tank farm contained 15 low-pressure storage tanks with internal floating roofs. Each tank was rated for 80,000 barrels (3,360,000 US gallons) of product. The tanks contained a variety of petroleum products, most of which were highly flammable. Two of the tanks in the tank farm were empty at the time of the fire.[1] One tank, Tank 80-8, stored butane-enhanced naphtha, a gasoline blending stock.[12]

The tanks were 110 ft. wide and 48 ft. tall. They were spaced 36 ft. apart in three parallel rows. Each row contained five tanks, and each tank was assigned a pump. The pump was used to move products into and out of a tank and to recirculate its contents. The pumps were connected to the rest of the terminal by piping routed on low-level steel supports called “manifolds.” The dike walls enclosing the tank farm were roughly 730 ft. long and 430 ft. wide. Each storage tank had a semi-fixed firefighting foam system. The fire truck connection for the foam systems was located just outside the south dike wall.[1] Manually operated fire monitors surrounded the tank farm. Two pairs of fire monitors were installed in the center of the tank farm. They were connected to 4-inch lateral fire mains tied to a larger fire water main that supplied the perimeter fire monitors. There was one fire hydrant within 250 ft. of the tank farm. It was located on the south side of the tank farm.[12]

The terminal fire pumps are located at a marine dock about a mile to the north of the tank farm. A network of carbon steel fire mains connected the pumps to the rest of the terminal. A simplified schematic based upon the data in the CSB Investigation Report and the Terminal Fire Water Drawing[12] is provided below (Figure 1).

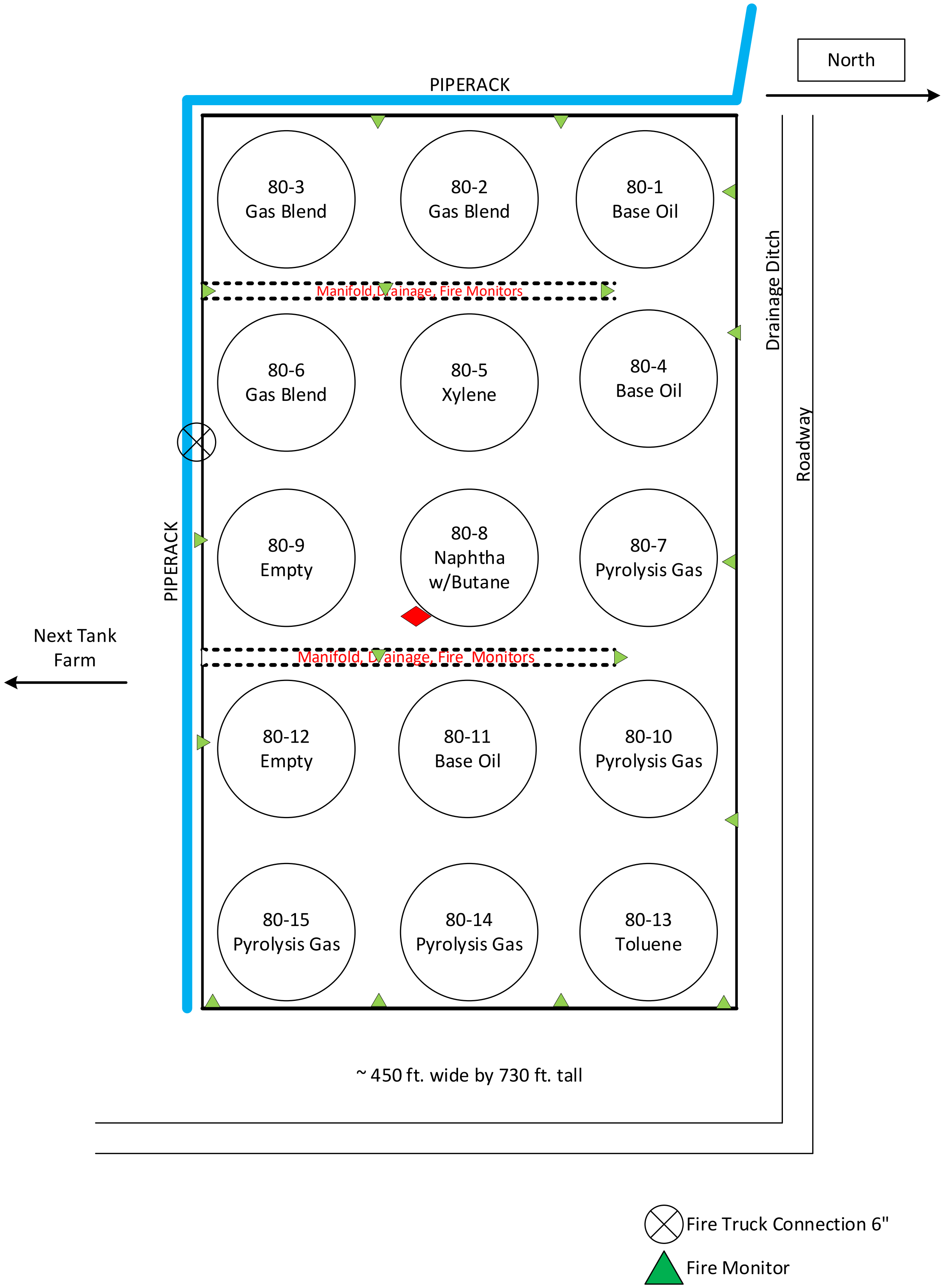

Figure 1 - First and Second 80's Tank Farm

Incident Summary

The initiating event at the ITC Terminal was the result of the mechanical failure of the pump serving Tank 80-8 at ~9:00 am Saturday morning, March 17th, 2019. The pump was recirculating a naphtha/butane blend in preparation for transfer to a shipping vessel when it failed.[13]

The pump released ~300 gpm of blended product for approximately 30 minutes into the secondary containment system. The process control system on the tank and the transfer pump did not send any emergency alarms to the control room prior to ignition.[13] The fire announced itself to site employees with a load roar and tall flame plume. Terminal personnel responded quickly, established command, assessed the scene, activated the emergency response team (ERT) and made emergency notifications. The centrally located fire monitors could not be used to directly cool the pump skid or Tank 80-8. The perimeter fire monitors also could not reach pump skid or Tank 80-8.[1] The pool fire spread across the diked area heating multiple storage tanks, starting with Tank 80-8.[13] The fire can be seen in Figure 2.

Figure 2 – Early stage of the fire[1]

The pump was not isolated from the tank despite the assistance Channel Industry Mutual Aid (CIMA) responders and the Deer Park Fire Department who arrived at roughly 10:30 am. The off-site emergency responders brought firefighting apparatus, portable fire pumps, large diameter hose and high flow fire monitors.[1]

Over the next two days (March 17th & 18th), emergency responders came close to extinguishing the fire several times. However, their efforts to isolate the Tank 80-8 leak or prevent other tanks from leaking into the fire and catching fire were unsuccessful. A private firefighting organization was contracted late on March 18th and arrived on-site the morning of the March 19th. Working with the terminal and mutual aid personnel, they applied massive amounts of water and foam. Final extinguishment was obtained on March 20th. By this time, all 15 storage tanks were effectively destroyed. [13]

The secondary containment system, consisting of 4 ft. tall by 8-inch thick concrete walls and a compacted crushed rock and earthen floor, failed on March 22nd, releasing several million gallons of effluent into a nearby ditch that ran directly into the local waterway. The wall was repaired the following day, March 23rd.[14] A view of the site after extinguishment and dike wall breach can be seen in Figure 3.

Figure 3 – Extinguishment Achieved w/Wall Failure[13]

Bow Tie Analysis

Methodology Overview

The Bow Tie methodology (also known as Bowtie) has been around since 1979 and has been used in various forms within the petrochemical and offshore industries since then (Figure 4).[15] A Bow Tie is a risk assessment tool that does not require P&IDs, detailed process information or probability data. Instead, a Bow Tie utilizes the expertise and experience of the team conducting the risk analysis to evaluate Prevention and Mitigation Barriers associated with a given scenario. Bow Ties are not designed to identify unknown failure scenarios, as a Hazard and Operability (HazOp) study does, but rather to illuminate how a failure scenario incident can occur and escalate into an event with catastrophic consequences. Bow Ties can evaluate industrial processes, storage facilities or operational activities. They are particularly useful when examining a fire scenario as a Bow Tie evaluates both fire prevention safeguards and fire protection safeguards.

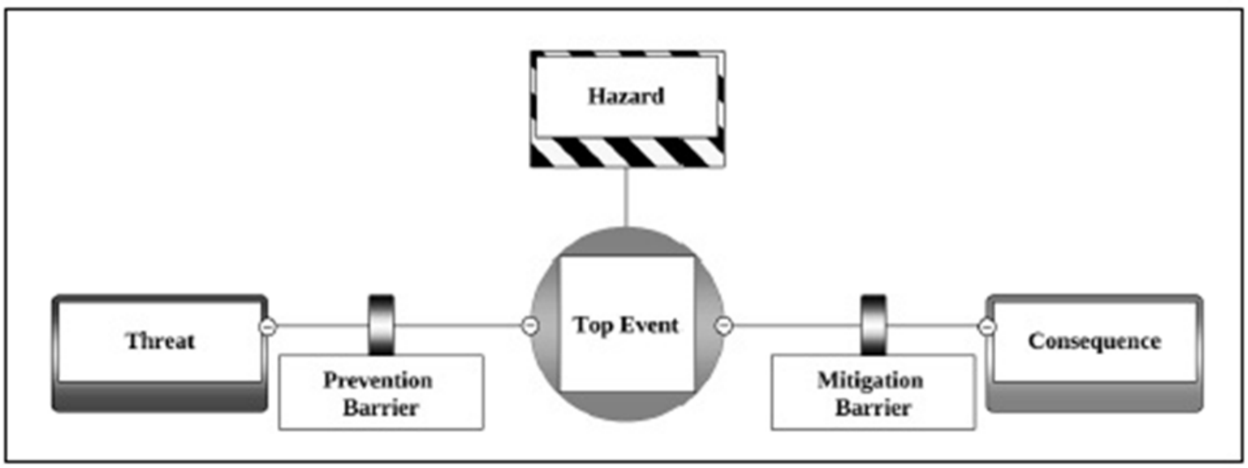

Figure 4 – Bow Tie Model[14]

Bow Ties are made up of six distinct features:[14]

Hazard: An operation, activity or material that is a potential source of harm.

Threat: The potential event that can result in a loss of control or containment of a Hazard

Top Event: The central event corresponding to the moment when there is a loss of control or loss of containment of the Hazard.

Barrier: A control measure that can prevent a Threat developing into a Top Event (Prevention Barrier) or can mitigate the consequences of a Top Event once it has occurred (Mitigation Barrier).

Consequence: The undesired loss (financial, personnel, environmental) that a Top Event may generate.

Any situation, condition, or error that compromises the proper function of a Barrier is a Degradation Factor. A Degradation Factor can influence more than one Barrier at a time.[14]

Consequence Mitigation Barriers for Tank Farms

This paper focuses on the escalation of Consequences following the Top Event. As such, only the Consequence Mitigation Barriers are evaluated for Degradation Factors, not the Prevention Barriers. The Consequence Mitigation Barriers that can be provided for a tank farm consist of Leak Detection, Remote Operated Shut Off Valves, Diking and Drainage, Fixed Fire Protection Systems, Emergency Response / Firefighting.

Leak Detection

This Barrier includes combustible gas detectors, pump monitoring, and tank level monitoring. Any system that will reliably alert the control room of a loss of containment qualifies as leak detection. Leak detection does not have to be interlocked with hardware, although it often is. Combustible gas detectors can be employed to detect leaks and send an alarm to the control room. These gas detectors are usually located near pumps, sumps, and other areas where vapors can accumulate. A process control system can also indirectly identify leaks by alarming upon

- Mechanical failure of the transfer pump, such as a seal leak.
- An unexpected drop in tank level.

If a product leak is detected early, operators may be able to isolate the leak before it ignites. The ERT can also construct dams to contain the product and apply firefighting foam to prevent ignition.

Remote Operated Shut Off Valves (ROSOV)

Flammable gas and liquid leak fires will burn until the fuel source is exhausted or is physically isolated by a valve. This is why a ROSOV can be such a valuable fire protection tool. A ROSOV must be ‘fire safe” to be reliable. This means it must work (usually close) and be reasonably leak-tight even when exposed to a fire for a short duration (15+ minutes). The valve does not necessarily have to be bubble tight. ROSOVs can be motor operated valves, spring actuated valves with fusible links and pneumatically actuated fail close valves. The valve should be operable from a safe location and be of a robust construction.

Diking and Drainage (Spill Control)

Diking and Drainage includes items such as tank farm area grading, drains, intermediate diking and secondary containment walls. These items can reduce the spread and control the direction of a spill and any ensuing fire. NFPA 30 Chapter 22 is the normal reference for this Barrier.[3] Note that firefighting-generated effluent is NOT included in NFPA 30 secondary containment requirements. As such, the ability to divert this effluent to a tertiary containment system is very useful to prevent overflowing containment areas. The facility Spill Prevention, Control and Countermeasure Plan, an US-Environmental Protection Agency requirement, may have helpful information on the tertiary containment system[16].

Fixed Fire Protection Systems

Fixed fire protection systems include items such as deluge water spray systems, foam chambers, and fire monitors. These systems can provide exposure cooling to at risk assets that will slow down the Domino effect or can offer extinguishment opportunities for tank and pool fires.

Emergency Response/Firefighting

An emergency response/firefighting Mitigation Barrier includes the Terminal Emergency Response Team and any mutual aid organizations who may respond. It also includes operators who can be trained to use handheld fire extinguishers and turn on fixed fire protection systems as well.

The goal of firefighting is to extinguish the fire as quickly as possible, with no loss of life and minimal property damage and environmental impact. The first objective of firefighting is to extinguish a small fire before it expands and becomes a large fire or to control a large fire and protect adjacent exposures until emergency response resources and staffing are sufficient to safely mount an aggressive suppression effort. A successful firefighting organization must be appropriately staffed, trained, and equipped. An incipient fire involving a storage tank or equipment attached to it can quickly escalate into a large or complex incident. The ability of the initial incident commander to quickly size up the situation and aggressively implement objectives for rescue, exposure protection, containment/control, extinguishment, and overhaul is necessary for control of a rapidly expanding incident.

Degradation Factors

The effectiveness of a Barrier can be compromised by Degradation Factors such as poor design or inadequate maintenance. The risk analysis team needs to identify, understand and characterize the nature of the Degradation Factors affecting each Mitigation Barrier. The firefighting water supply (pumps, mains and fire hydrants) can be a common mode Degradation Factor for fixed fire protection systems and firefighting efforts. A reliable firefighting water supply should be able to meet the combined water needs of both Barriers while surviving the failure of a key component such as a single fire pump.

Review of the performance of the ITC Terminal Consequence Mitigation Barriers.

As noted earlier in this document, the ITC fire of 2019 has been extensively reviewed by multiple parties, including this company. As such, there is sufficient information to conduct a review of the performance of the Consequence Mitigation Barriers used by Terminals / Tank Farms:

Leak Detection: **Not Installed**

- The tank farm was not constantly occupied.
- The tank farm process control system was not sophisticated enough to alert operations of the pump failure or the loss of tank level from a ~9,000 gallon leak.
- There were no combustible gas detectors installed in the tank farm.

RESULT: The spill grew to 9,000 gallons over a 30 minute time period.

ROSOV: Not Installed

- The local isolation valves were located between the pump and the tank. The valves could not be reached and manually closed by emergency responders.

- Motor Operated Valves (MOVs) were installed upstream of the pumps serving 12 other tanks in the tank farm (excluding Tank 80-8).[1] These valves were not activated during the incident. The power to the tank farm failed early into the incident.[1]

RESULT: The fuel load to the fire continually increased as the piping connections to other tanks failed.

Diking and Drainage:

- The tank farm drainage system was designed to route spills and effluent along the pumping manifolds and the south side of the tank farm.

- There was no intermediate diking provided between tanks.[1]

RESULT: The pool fire followed the pumping manifold system from tank to tank blocking access to the fire monitors and damaging the piping systems at other tanks.

- The containment area has a compacted earthen floor, surrounded by a 4 ft. concrete wall. The firefighting effluent could not be readily drained from the containment area to a safe location. [13]

- Saturated soil was identified as a significant risk in the wall failure.[14]

- Containment system design was a Degradation Factor that led to the mechanical failure of the wall.

RESULT: Dike wall failure released massive amounts of effluent into the local waterway.[1]

Fixed Fire Protection Systems:

- The pump and exposed tank walls could not be directly reached/cooled using the local fire monitors.[1]

- There was no deluge water spray coverage over the pump manifolds or on the storage tanks.[11]

- Inaccessible fire monitors and the lack of deluge water spray systems were Degradation Factors.

RESULT: Emergency responders could not effectively cool the exposed storage tanks or isolate the fuel leaks coming from the base of the storage tanks.

Emergency Response / Firefighting:

- The ability of the emergency responders to block in a pump fire is assumed to be a site expectation as no ROSOV was installed upstream of the transfer pump of Tank 80-8 or on the other 200+ low pressure storage tanks at the terminal. ROSOVs were installed between the high pressure storage tanks and pumps at the terminal.[1]

- The emergency responders were unable to manually isolate the originating pump fire or the product leaks that followed.

<u>RESULT:</u> The fire accessed all of the fuel in all of the storage tanks.

- No plans were made prior to the incident to contract a 3rd party for additional resources beyond that of the local mutual aid responders.[1]

<u>RESULT:</u> The final extinguishment of the fire was delayed until the arrival of the 3rd party emergency response provider.[1]

Holistic Analysis of the entire Bow Tie Consequence Mitigation Barrier System (Leg)

The Bow Tie diagram for the ITC Fire is shown below in Figure 5. The diagram includes the Cause Leg only as a visual aid

The lack of the first two Consequence Mitigation Barriers (Leak Detection and ROSOV) placed the burden of isolating the fuel leak on the Emergency Response Barrier. The remaining Consequence Mitigation Barriers provided limited assistance in cooling exposed equipment, and slowing the spread of the fire. As such, the fire grew as equipment heated up and additional fuel sources were added.

There were modifications that could have been made to the other Consequence Mitigation Barriers that would have reduced the growth rate of the fire and therefore better assisted the Emergency Response Barrier: For example:

IF the Fixed Fire Protection System Consequence Mitigation Barrier had included automatic deluge water spray coverage over the pump manifold areas, the pump and its isolation valves would not have been engulfed in flames. The fuel source isolation job would have been significantly easier and much more likely to be accomplished.

IF the tank farm secondary containment system had been provided with large, accessible drains capable of safely diverting effluent, the hydrostatic load on the dike walls would have been reduced.

IF, as noted in the CSB reports and recordings on the fire, a gas detection system and a ROSOV had been installed on Tank 80-8, the fire would not have significantly challenged the other Consequence Mitigation Barriers before it was isolated and extinguished.

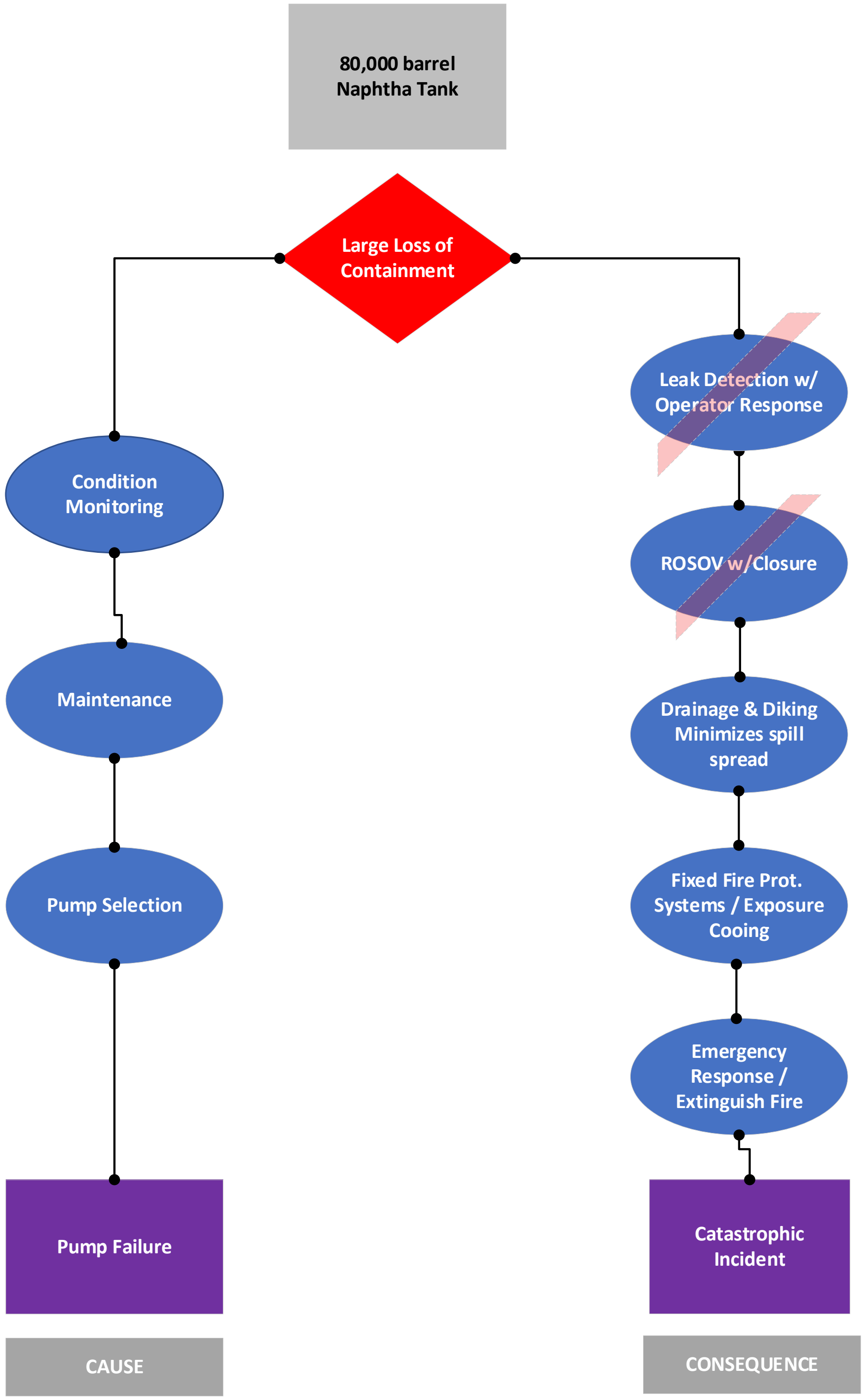

Figure 5 – Bow Tie for the ITC Fire

With only three of five potential Consequence Mitigation Barriers in place, the terminal needed each of them to be highly effective. Unfortunately, that turned out not to be the case, as each Barrier had some level of design and/or performance limitation. The rapid growth and sustained heat generation of the fire resulted in a catastrophic consequence.

Application of a Bow Tie to Emergency Response Planning

A Bow Tie can be a great tool to support the development of an emergency response or fire pre-plan for tank farms or even chemical process units, with a few modifications. For Example:

<u>Tank Farm Bow Tie</u>

Step 1: Select a credible incident, such as a ground fire inside of diked area.

Step 2: Define the Hazard: storage tank containing a flammable liquid.

Step 3: Define the Top Event (credible scenario): here, it is a large loss of containment from Threats:

- Pump failure
- Piping failure
- Tank overfill

Step 4: Select an acceptable consequence for the Threats.

An acceptable consequence could be the loss of the pump, a single tank, or the entire tank farm with minimal off-site impact.

Step 5: Identify and evaluate the Consequence Mitigation Barriers separating the Top Event from the acceptable consequence.

If the risk analysis team (which should include an emergency response expert) believes the Barriers can reliably mitigate the Top Event and achieve an acceptable consequence, this portion of the analysis is over. *Go to Step 7.*

If, however, an acceptable consequence cannot be realistically obtained using the existing Barriers, then proceed to the next step.

Step 6: Look for opportunities to improve or add a Consequence Mitigation Barrier such that an acceptable consequence is a realistic outcome of the threats.

or

Build out the Prevention Barrier leg of the Bow Tie for each threat and identify opportunities to reduce the probability of the Top Event such that an acceptable risk is achieved.

NOTE: A Layer of Protection Analysis (LOPA) may be needed to evaluate items such as emergency shut down systems. The company risk matrix can be used to determine what is an acceptable risk.

Step 7: Document the Consequence Barriers associated with each Threat. Incorporate this information into the emergency response plan in the form of actionable fire pre-plans for the credible fire incidents the terminal has.

The completed Bow Tie analysis should be managed as Process Safety Information. It will be a very useful resource evaluating future tank farm projects in addition to building the fire pre-plans.

Conclusions

Fire protection regulations and oversight of fuel terminals by local fire protection agencies within the USA is minimal. Therefore, the fire protection safeguards installed for many fuel terminals do not match up with the fire hazards they possess or the emergency response plans they have in place. As such, small fires can quickly grow into large fires and burn for several days before they are extinguished, even if there are strong local firefighting organizations. The economic, environmental and company reputational consequences can be very high.

A Bow Tie analysis of the fire hazards at a tank farm can assist terminal operators in understanding the role of each of their prevention and protection safeguards (Barriers). This information can be used to develop better emergency response plans, improve their Prevention and Consequence Mitigation Barriers and assist in future expansion projects.

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