Design Guidelines for Safety in Piping Networks

Karl Kolmetz
KLM Technology Group

Stephen J. Wallace
Wallace Consulting Services

Dr. Wai Kiong Ng
Institute of Chemical and Engineering Sciences

Jim Gorski
Seal Tech

Jonathan A. Kolmetz
KLM Technology Group

Jeff N Gray
KLM Technology Group

Mee Shee Tiong
KLM Technology Group

Design Guidelines for Safety in Piping Networks

Introduction

When compared to other equipment in a hydrocarbon processing plant, the piping network is designed to the most stringent standards. Mechanical Engineering codes require a 400% safety factor in the design of these systems. The piping system is normally considered the safest part of the plant. However, even with this level of safety, reviews of catastrophic accidents show that piping system failures represent that largest percentage of equipment failures (1).

Since these systems are responsible for many catastrophic accidents, operations, design, and maintenance personnel should understand the potential safety concerns. The best tool that we have to prevent future accidents is to review past incidents and incorporate lessons learned into future design and operation of piping systems.

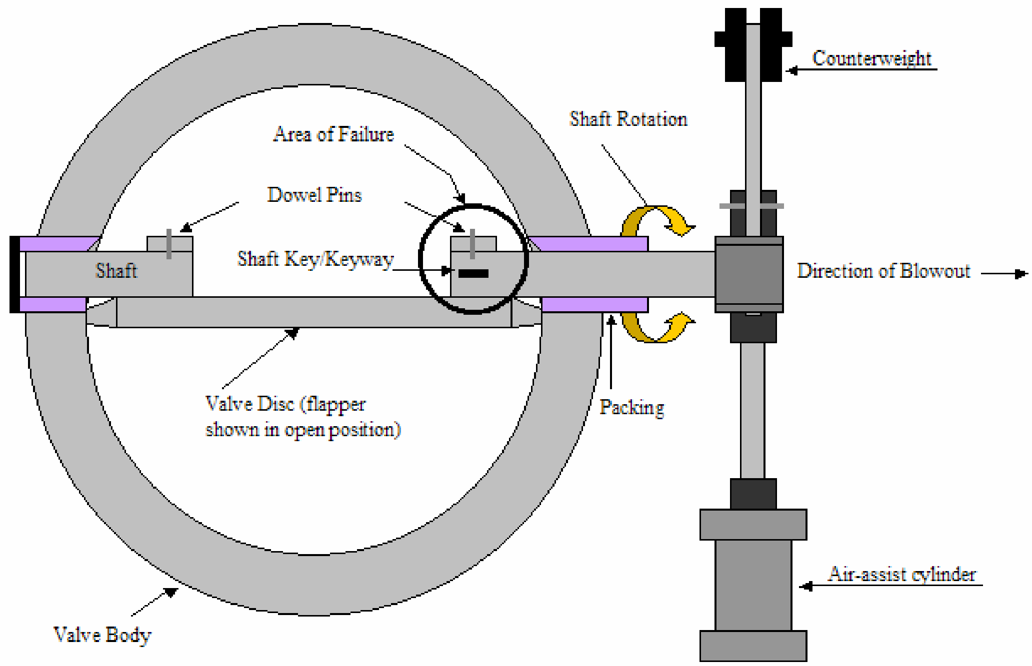
This paper will discuss various case studies that will help to illustrate the consequences of inappropriate design, operation, and maintenance of piping systems. The case studies include 1) Check valve failures; 2) Small bore piping in compressor discharge piping, 3) Low temperature embitterment, and 4) Hot tapping safety issues and hot tap shavings concerns.

Check Valve Failures

Check valves are important safety devices in piping. Check valves have been utilized in the process industry for many years to keep material from flowing the wrong way and causing operational or safety concerns. One common mistake is installing the check valve backwards and blocking the process flow. There is normally an arrow on the check valve designating the proper flow direction, indicating the proper installation position. There have been cases where the manufacturer showed the arrow incorrectly, which greatly hindered troubleshooting.

Case 1 - In December 1991, a chemical plant in Saudi Arabia (2) experienced a release of propane gas due to a check valve shaft blowout. The incident followed a process upset in the facility's ethylene plant, where the inadvertent shutdown of a cracked gas compressor resulted in downstream flow instabilities and initiated a 13 hour period of surging in the unit's propane refrigeration compressor.

Simplified cross-sectional view of check valve (flow direction is into page)



During this period, the check valves installed in the propane refrigeration compression system slammed closed repeatedly. The shaft of the compressor's third stage discharge valve eventually separated from its disk and was partially ejected from the valve. The shaft was not fully ejected because its path was blocked by an adjacent steam line inches away from the valve, keeping about 70 mm of the shaft's length within the valve body.

Propane gas began to leak out of the valve around the gap between the shaft and its stuffing box until operators discovered the leak and shut down the compressor. Operators also discovered that the valve's drive shaft counterweights had broken off of the drive shaft and had been propelled approximately 16 meters (45 feet) from the valve.

The facility was fortunate that an adjacent steam line kept the shaft from being fully ejected from the valve, thus limiting the leak rate and preventing an accident of potentially greater severity. It was also fortunate that no one was struck by the counterweights when they were propelled from the valve.

A subsequent investigation and analysis of the check valve's internal components revealed that the dowel pin, which secured the drive shaft to the valve flapper, had sheared, and the shaft key had fallen out of its key-way. The investigation report also revealed that facility maintenance records indicated a long history of problems with the check valves installed there. The valves were installed in 1982, and due to continuing valve malfunctions, underwent repair or modification in 1984, 1986, 1987, 1989, and 1990. These repairs and modifications included replacement of damaged counterweight arms, replacement of seals and gaskets, replacement of dowel pins and internal keys, and installation of external shaft "keepers".

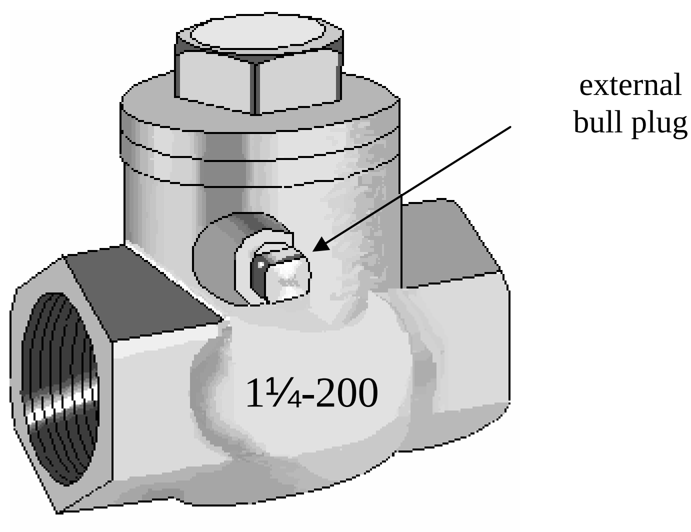
Case 2 – An incident with a similar failure mechanism occurred in an Ethylene Plant in Texas in June 1997 (2). The check valve was on the process gas compressor discharge line, which had high flow, high pressure and high temperature, along with compressor vibration; however, the investigation team found no evidence that these temperature and pressure limits were exceeded at any time prior to or during the accident. The check valve was installed on the fifth stage of the compressor and had an internal diameter of 36 inches and weighed 3.2 tons. The valve had a design limit pressure of 480 psig, and a design limit temperature of 115 degrees F.

The drive shaft penetrates the pressure boundary through a stuffing box. The exterior portion of the drive shaft is connected to the pneumatic piston and counterweight, and the interior portion of the shaft is coupled directly to the valve disk using a cylindrical hardened steel dowel pin and a steel rectangular bar key. This arrangement provides a counter weight to partially balance the weight of the valve disk, and provides the pneumatic power assist to maintain the valve closed as described above.

This check valve was the same design as the previous check valve and had the same failure mechanism. The pneumatic assist assembly became unattached from the check valve, leading to loss of hydrocarbon containment and a major unit fire. The unit was down for several weeks for repair.

This fire resulted in minor process operator injuries, public road closures, and property damage both within the olefin unit and to off site business. The EPA and OSHA undertook an investigation of this accident because of its severity, its effects on the public, and "the desire to identify those root causes and contributing factors of the event that may have broad applicability to industry, and the potential to develop recommendations and lessons learned to prevent future accidents of this type".

Case 3 - An Ethylene Plant in Louisiana had a near miss from a check valve failure in 1999. The check valve had an external bull plug, which allowed the check valve swing pin to be installed. The bull plug slowly rotated out over time leading to loss of hydrocarbon containment on a medium pressure ethane feed line. The line was isolated, copious amounts of water were applied to the leak, and fortunately the vapor did not find a source of ignition.

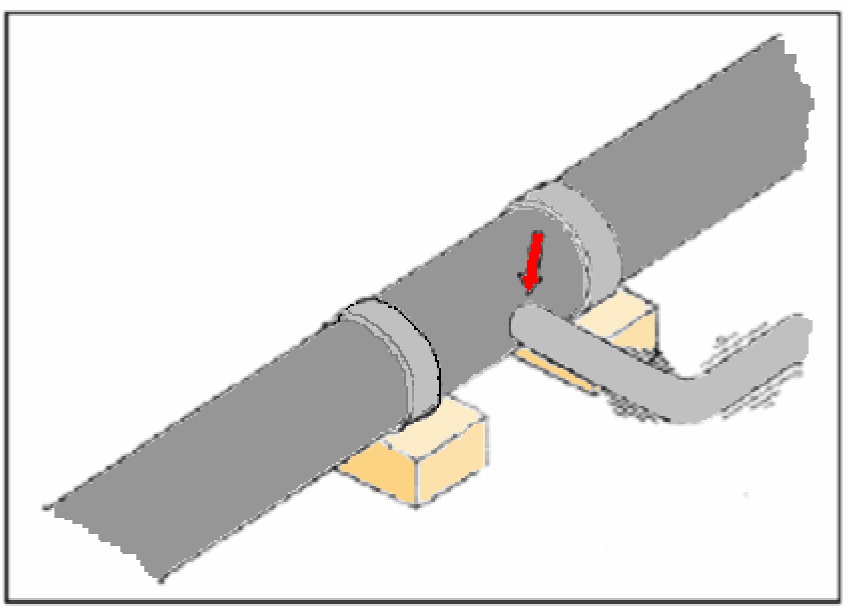


This check valve was far away from a source of vibration such as a compressor. The root cause of the incident is was not totally identified but one theory is that normal piping vibration caused the bull plug to rotate. The Ethylene plant reviewed all check valves in hydrocarbon service and installed a anti rotation locking device to prevent the bull plugs from rotating and causing a loss of hydrocarbon containment.

Small Bore Piping in Compressor Discharge Piping

Since 1997, sixteen incidents attributed to vibration fatigue failure of piping within compressor stations and pump stations were reported to the Canadian National Energy Board (3). The fractures associated with these incidents typically initiated near welded junctions where small diameter pipe (NPS 2 or smaller) was tied into a larger pipe. The typical location where this occurred is on the discharge piping immediately downstream of a compressor/pump unit. The consequences of these failures include facilities shutdown, worker injuries, loss of product and site contamination.

Although vibration fatigue has been deemed to be the immediate cause of all these failures, poor design and lack of effective piping support is considered the basic cause of the incidents. Designs included poor support for the smaller pipe components, sizing (length, diameter and thickness) of the piping itself, and lack of consideration for additional stresses on the pipe-to-pipe junction in situations where a valve or regulator was installed at the remote end of the small diameter pipe. This resulted in bending stresses at the junction being increased to the point of failure.



Vibration levels imparted to the piping adjacent to compressor/pump units should be monitored and managed. Piping configurations potentially at risk such as the one described above should be investigated and modified to manage any vibration, which may impact the pipe and associated junctions.

Case 4 - An Ethylene Plant in Malaysia had a major near miss from small bore piping on the discharge of a propylene refrigeration compressor in 2002. The compressor discharge piping had very high vibrations from unit commissioning. The original diagnosis of the high vibrations was the piping network, and several solutions were implemented on the piping network without success. The root cause of the high vibrations was eventually found to be the compressor rotor.

One guideline is to restrict the small-bore piping to a safe distance from the discharge of the compressor to limit piping fatigue failure. A three quarter inch stub and valve on the fourth stage of the propylene compressor at 15 bar gauge (160 psig) discharge pressure experienced the high vibration from the compressor and failed, leaving a open ¾ inch line. The resulting massive loss of containment went unnoticed because the propylene vapor was at a high temperature 70 C (155 degrees F) and did not cause a vapor cloud.

The compressor was shut down and even with the massive loss of containment, greater than 10 tons of propylene in the battery limits of a functioning ethylene plant, the vapor cloud did not find a source of ignition.

Piping Low Temperature Embrittlement

Piping low temperature embrittlement is the loss of ductility, toughness, and impact strength that occurs in some metals at low temperatures. Normal carbon steel piping is rated for -20 F (–29 degrees C) at atmospheric pressure. This is also about the vaporization temperature of liquid Propane and Propylene (-49 F). In units with propane and lighter components, there is the possibility to exceed the low temperature limit of normal carbon steel.

Carbon steel piping is typically used in services with temperatures above -10 to –20 degrees F. At temperatures below -10 to -20 degrees F. normal carbon steel loses ductility and strength and the metal becomes brittle and can be susceptible to brittle fracture. Impact testing can certify the use of carbon steel piping in services as cold as -49 degrees F, and is named “killed” carbon steel.

John A. Reid (4) put together list of ethylene plant hydrocarbon incidents. He noted four incidents where low temperature embrittlement cause line failures. Cases he noted included;

1. 1965 Explosion and Fire Due to Cold Brittle Flare Line Fracture at PCI Olefin Unit in Lake Charles, La.

2. 1966 Flare System Explosion - Monsanto's Chocolate Bayou Olefin Unit

3. 1975 DePropanizer - Explosion in a Naphtha Cracking Unit – Dutch State Mines – 14 fatalities

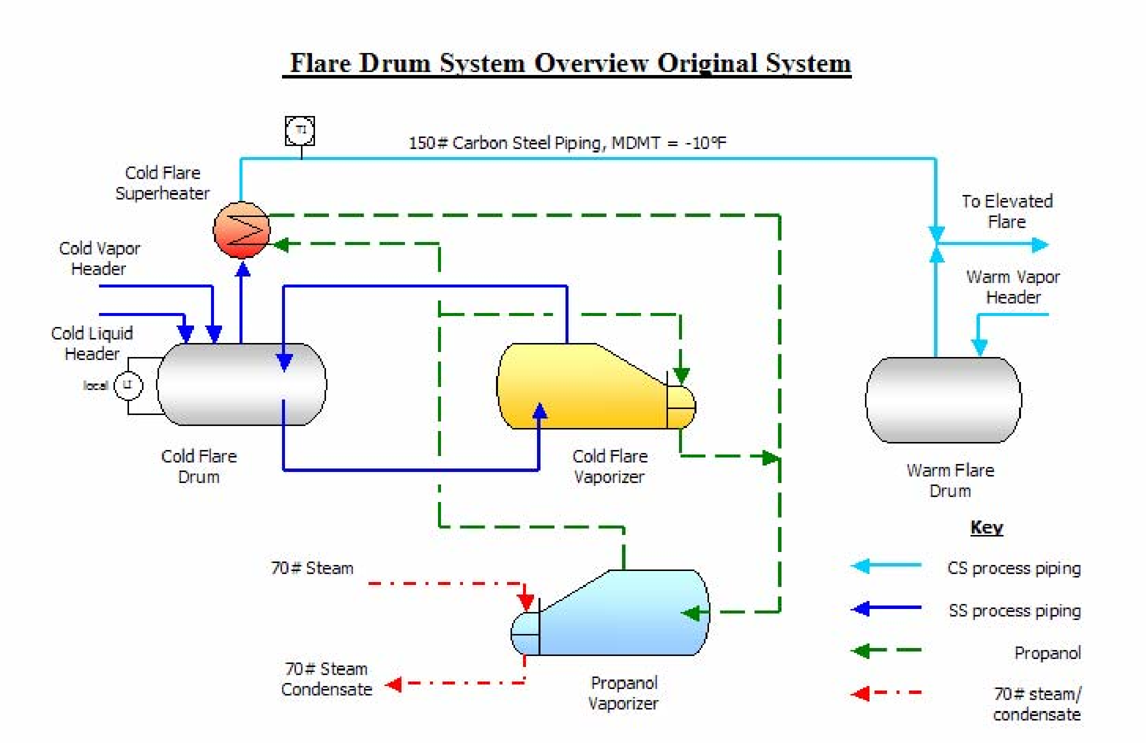
4. 1989 Cold Brittle Line Fracture Results in Gas Leak, Explosion and Fire at Quantum's Morris Illinois Ethane/Propane Cracker – two fatalities

Case 5 - An incident occurred in January 2002 at an Ethylene plant in Louisiana. The Ethylene Plant published the incident in the AIChE Ethylene Producers Conference in

2004 (5) and in a conference in Asia in 2002 (6) to increase safety awareness in the process industry.

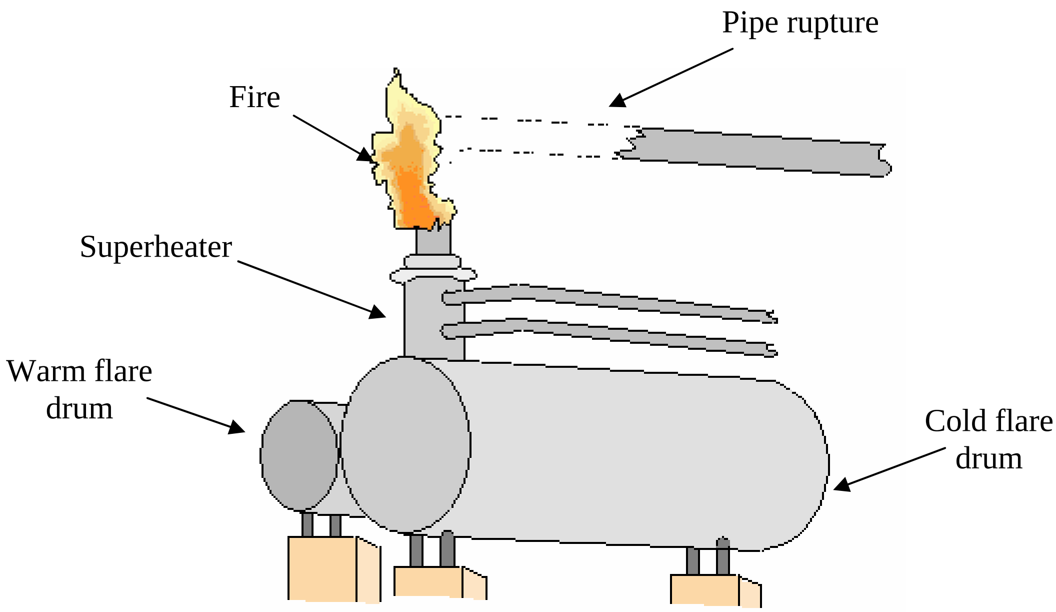
The plant was Olefins Ethane Cracker with a flow scheme of the DeMethanizer first and a back end acetylene converter. An off-spec event on 1/4/02 at the acetylene converter led to flaring of ethylene product via the unit cold flare drum. Through a sequence of events, the cold flare drum overhead line fell to below its minimum design metallurgy temperature. On 1/5/02, the cold temperatures led to brittle fracture of the cold flare drum overhead line, loss of hydrocarbon containment, and ultimately an explosion and fire.

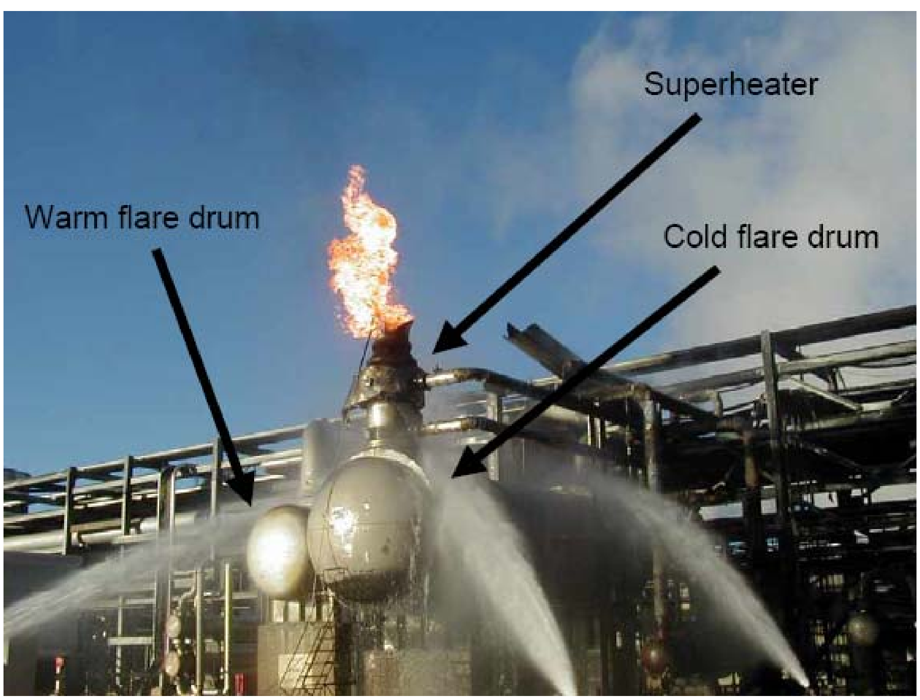
The cold flare drum contents are vaporized and superheated with a closed loop propanol system. Heat is supplied to the propanol system with 70-pound steam, which is about 270 F. The vaporizer and super heater heats the cold flare drum material from cryogenic temperatures to above the minimum design metal temperature of the cold flare drum carbon steel overhead piping.



The event sequence was the ethylene product went off specification on acetylene and initiating flaring of liquid ethylene product began. The acetylene converter outlet analyzer was in error, which allowed the ethylene splitter inventory to be contaminated with acetylene prior to corrective action being taken. A portion of the off spec liquid ethylene product was consumed by internal customers, with the balance being flared via the cold flare drum. Malfunction of the cold flare drum vaporizer and super heater allowed the cold flare drum overhead line temperature to fall sharply.

A low temperature alarm sounded as the overhead flare line temperature fell to 0 F, and the thermocouple went bad at a value of -13 F. With the cold flare drum overhead line running below its minimum design temperature of -10 F, the pipe ruptured, resulting in loss of hydrocarbon containment. The hydrocarbon released found an ignition source, resulting in an explosion and fire.

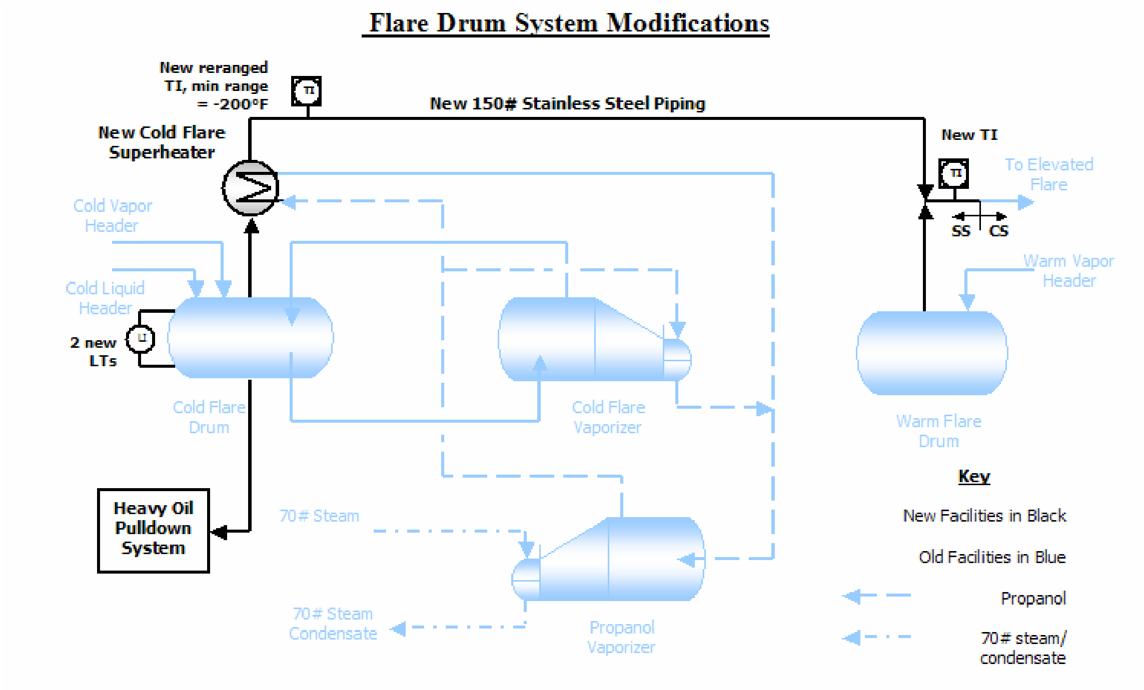




The root causes of the incident included the vaporizer and super heater exchanger fouling, which had reduced heat transfer capacity of the cold flare system. Once flaring began, the cold flare drum overhead line experienced low temperature resulting in the brittle fracture of cold flare drum overhead piping due to operation below the minimum design temperature of the carbon steel line.

The final stress that ultimately caused the brittle fracture of the piping has not been identified, but could have been any number of internal or external stresses. 1) External stress - Hard rain that came at the time of event, 2) Internal stress - Contraction of the cold flare line due to temperature gradient.

The incident causes an explosion and damage to equipment, but no first aid or recordable incidents to personnel. As a result of the incident the ethylene plant upgraded many carbon steel systems to stainless steel, which has a lower temperature limit.



Hot Tapping Safely and Process Concerns

Hot Tapping is used in plant maintenance activities to obtain access to a pressurized line or vessel. Hot tapping involves welding on a piece of equipment, typically a spool piece to which a valve is then connected. The types of equipment include pipelines, vessels or tanks that contain steam, natural gas or flammable liquids under pressure, in order to install additional connections to reroute or to block the flow in a line. It is commonly used to replace or add sections of pipeline without the interruption of service for air, gas, water, steam and petrochemical distribution systems. The hot tap process is utilized to install a new working valve or to control the de-pressuring of the equipment.

During the hot tap process a drill bit assembly is connected to the new spool piece and a new working valve. The new valve is attached to the line and the drill assembly is installed and the hole drilled. The bit is retracted past the valve, which can then be closed. A flow or line can then be fitted into the valve. The American Petroleum Institute has guidelines for precautions to take during hot taps.

One of the main concerns of hot tapping is the metal shavings, which are produced by either drilling or cutting. Some of the metal shavings will enter into the process and could be carried downstream and cause problems by entering pumps or strainers. Therefore, careful planning must be made to determine if the metal shavings will cause a problem down stream.

During the initial planning of the hot tap one aspect to look at would be to tap from the bottom, which would give you the best chance of retaining most of the metal shavings. However, there is also a concern about shavings entering the seat of the valve. The rule of thumb would be never tap at 5 o’clock or 7 o’clock as shavings could get into the seat and keep the valve from closing.

Case 6 - An olefins producer in Louisiana had two ethylene plants that shared a single flare area. The two steam lines to the flares were at one point only 100 feet apart. Whenever a unit upset occurs, steam is utilized in the flare tip to mix the hydrocarbons with air for complete combustion. This mixing reduces the flare smoking and environmental damage from carbon monoxide.

At times during unit upsets there can be a shortage of steam. This shortage can lead to additional flaring at the very time you need steam to reduce the smoking flare. Therefore, to address this scenario, the ethylene producer decided to connect the two flare steam lines together. When one unit was having operational problems, the adjacent unit could provide steam to the flare and potentially have the first unit recover faster while reducing overall flaring, with the additional economic benefit of being able to produce on specification product faster. The two adjacent steam lines were hot tapped and a line installed to connect the two new hot tap valves.

At the next unit upset the line was utilized to reduce the overall flaring and optimize unit production. Unfortunately, some metal shavings were left in the steam lines. These metal shavings were carried to the flare steam ring and blocked a portion of the steam ring above the steam line connection to the steam ring.

The steam ring no longer had uniform steam distribution as a portion of the ring was blocked by the hot tap metal shavings. This was not fully known until the next major unit outage when the flare tip was upgraded to reduce the smoking. Due to the mal-distribution of the steam the flare now smoked constantly, even at low flaring scenarios. The producer was then fined for the continuously smoking flare.

Guidelines

These six case studies provide many incites into piping safety concerns. Petroleum plant personnel should review these case studies and consider implementing the guidelines where applicable for increased safety.

1. Check Valve Installations

   Review large and small check valve installations for potential release scenarios. For large high-pressure check valves review the internals and the sited case study failure mechanism. Install anti rotation devices on external bull plugs.

2. Small Bore Piping on Compressor Discharge Piping

   Review and reduce small-bore piping on compressor discharge piping. One guideline is to restrict the small-bore piping to a safe distance from the discharge of the compressor to limit piping fatigue failure.

   Vibration levels imparted to the piping adjacent to compressor / pump units should be monitored and managed. Piping configurations potentially at risk should be investigated and modified to manage any vibration, which may impact the pipe and associated junctions.

3. Low Temperature Embrittlement Concerns

   Understand piping low temperature embrittlement concerns and potential release scenarios. There have been multiple piping failures and hydrocarbon releases from piping low temperature embrittlement. Review the process temperatures and the piping metallurgies where the temperatures are below –49 F, which is approximately liquid propane / propylene.

4. Safety Perform Hot Taps

   When making a hot tap, certain steps should be followed prior to starting the actual tap. The following steps consist of basic procedures used in completing the hot top installation;

   A) Perform a site visit, to determine if the job safety analysis information meets the proper criteria for that particular hot tapping operation.

   B) Recognize and identify the hazards of the equipment, then outline steps to mitigate those hazards into a job safety sheet.

   C) Review the job and file a basic safety plan.

   D) The proposed hot tap area should be marked on the piping network.

E) Minimize the piping network pressure to the practical operations limit.

F) A plan for isolating the piping network should be prepared for an emergency.

Conclusions

Piping network safety is a concern for all hydrocarbon producers even though piping may be the considered the safest part of the plant. The authors goals and hopes are that these case studies and guidelines provide additional safety incite into piping design, operation and prevention of future incidents.

References

1. Chemical Processing Safety: Fundamentals with Applications; Crowl and Louvar; Prentice-Hall; 1990

2. EPA/OSHA Joint Chemical Accident Investigation Report of the Shell Chemical Company's Deer Park, Texas Olefin Complex Fire of June 22, 1997. EPA Document 550-R-98-005

3. Canadian National Energy Board Safety Advisory, File 3750-A000-8 3 December 2003

4. Ethylene Plant Safety Incidents, John A Reid, unpublished

5. Kuo A., Pitt R, “Flare Line Failure Case, What Have We Learned”, 16th Annual Ethylene Producers. Conference Session T8001, Ethylene Plant Safety, New Orleans, LA, April 25-29, 2004

6. Tarkiz Ruslan, Tham Chee Mun, Karl Kolmetz, “Flare Safety Overview”, 7th Regional Olefin Committee Technical Conference, Kerteh, Malaysia 16-18 September 2002