Liquefied Natural Gas Safety

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1. Learning Objectives

This is the second in a series of progressively more in-depth courses on Liquefied Natural Gas. Although this learning focuses on LNG facilities, many of the concepts presented also apply to any petrochemical plant.

This course introduces the learner to the safety topics related to the production, storage, transportation, and vaporization of Liquefied Natural Gas (LNG). In-depth books can be written on LNG safety; this course is not all-inclusive. This course should be considered a high-level starting point introduction to select topics related to LNG safety.

LNG is widely used around the world. It is a very compact form of natural gas in liquid form. It is used on frigid days to supplement gas from the interstate pipelines and supply gas load centers like New York, Boston, and other major gas load areas.

Natural gas, the same as vaporized LNG, is the cleanest burning fossil fuel, as it contains the least amount of carbon of all the fossil fuels. Thus, many electric power plants now use natural gas or are converting from dirtier fossil fuels to natural gas or vaporized LNG. Upon completion of this course, the learner should, at a high level, be able to:

- Understand the profound importance of putting safety first when dealing with petrochemicals, particularly LNG
- Explain the characteristics and properties of LNG
- Understand the hazards associated with LNG and natural gas
- Understand the safety measures used in the design and operation of LNG facilities
- Understand the methods of hazard detection
- Understand the methods of preventing hazards from escalating to accidents
- Understand some of the safety measures and devices needed to manage an LNG facility
- Understand the significant need to train human resources and develop a culture of safety and reliability

2. Introduction

Liquefied Natural Gas (LNG) is essentially natural gas in liquid form. To get natural gas to become a liquid, components that may freeze to a solid need to be lessened in concentration, and the remaining gas must be chilled down to ~ -260 F.

Natural gas is mostly methane (typically 90+%); thus, LNG is also typically 90+% methane. Therefore, for the rest of this study, we will treat vaporized LNG as natural or methane gas.

Natural gas is measured in standard cubic feet. A.G.A. defines a standard cubic foot as a cubic foot volume of gas at 60 F and 14.73 psia. Natural gas is also measured in decatherms. A Therm is, by definition, 100,000 Btu of energy, and a Decatherm is, thus, 1,000,000 Btu of energy. A Btu of energy is the amount of heat to raise 1 pound mass of water (Lbm) 1 degree F.

Many people think of Btu as an accurate way to measure energy. Still, it needs to be better defined because different countries or industries use different water temperatures to measure the heat required to raise the water by 1 F. Since the specific heat of water changes with temperature, the amount of heat measured in Btu output may differ (by a very small amount) across different countries or industries.

Btu measures are presented in the introduction to give the learner a sense of the amount of energy stored in an LNG tank. LNG tanks range in size. The typical tank size is 1 Bscf (billion standard cubic feet), but tanks can be as large as 4.2 Bscf. A 1 Bscf LNG storage tank inventory contains enough energy to run a typical single-house heating system (125,000 Btu/hr.) 24 hours per day, seven days a week, for ~ 1,000 years.

Engineers designing and operating LNG plants are responsible for a massive amount of energy.

Like all hydrocarbons, natural gas liberates a large amount of heat energy when it burns with oxygen. Regardless of the amount of heat released during combustion, burning can be a hazard if uncontrolled. In a house heater or a stove, it is controlled combustion. However, uncontrolled combustion due to a leak of natural gas or a spill of LNG, which converts to vaporized LNG, is hazardous.

Unintentional combustion of LNG vapors is an obvious hazard related to LNG. This hazard, as well as many other hazards unique to LNG, will be presented. Further, methods to lessen these hazards and how to react to other threats of LNG will be explained.

Many hazard mitigation measures can be designed into the plant operating hardware and software. Passive and active steps can be built into the design and procedures. However, operator error is one of the more significant hazards that is more difficult to design against occurring in a plant.

An airplane can have many safety features built into its automatic operating systems, which can compensate for, but cannot eliminate a pilot's error in judgment. Often, such errors are due to a lack of the operator's knowledge or experience.

The purpose of this training is to present the basics of LNG safety. This training can be a springboard for further training to help engineers understand the hardware, software, and human interface needs for safe LNG systems. Further, this training can assist engineers who train LNG operators to understand the technologies they oversee. Although this training is not all-inclusive, it is intended to stimulate the learners to think not only of the expected hazards that could accelerate a crisis but also of what is unexpected.

Understanding, what is technically happening is a necessary part of understanding how to recognize abnormal operations.

In this training, we will present:

- Combustion hazards
- Cryogenic hazards
- Thermal hazards
- Asphyxiation hazards
- Myths about LNG operations
- How the essential safety asset is you – the design and training engineer
- Human resource development
    - Integrity
    - Trust
    - Open communication
    - Leadership
    - Teamwork
    - Creativity
    - Continuous improvement
    - **Developing a culture of safety and reliability (highlighted intentionally)**
- Who is ultimately responsible for safety – Everyone involved in the plant
- If you see an unsafe act or condition, the responsibility is yours to remedy it
- Preventive actions
    - Wearing Personal Protective Equipment (PPE)
    - Following "all" procedures
    - Following "Management of Change" (MOC) requirements
    - Knowing and implementing emergency procedures
    - Initiating a partial or complete plant shutdown, if necessary
    - Having procedures updated if they are found to be inadequate
- If you identify a needed repair or dysfunctional equipment – get it fixed
- The technician's life and that of his co-worker is everyone's responsibility
- You must understand the hazards
    - Basics of combustion
    - Effects of extreme cold
    - Consequence of low oxygen levels

This learning document is meant to be at an introductory technical level. The most crucial intention of this document is to give you the basic technical knowledge, at an elementary level, that you need to start your study on how to continue to make the Liquid Natural Gas Industry "Safe and Reliable."

The image to the right is placed here as a reminder that everyone has someone who loves and needs them to come home at the end of their shift.

Reliability is also related to safety because if the LNG plant cannot make send out when needed, the consuming public may be out of gas during the worst of cold weather times. This would put the public at a severe health risk.

As engineers, we must ensure that our design, planning, operation, and maintenance of LNG facilities help assure safety and reliability.

This will help assure that everyone comes home at the end of their shift and that gas is supplied when the end-use customers need it.

Culture

Plant Safety

Figure 1: Beautiful Granddaughter
Source: Self-made photo

3. Terms And Units of Measure for Natural Gas and LNG

The following abbreviations, terms, and units will be used in this document for natural gas and LNG:

U.S.	United States
Peak Shaver	An LNG facility used to supplement natural gas supply during times of high gas demand.
Satellite	An LNG facility used to supply gas to a localized area
Send out	Natural gas or vaporized LNG sent out, by a gas utility, via pipelines to customers
Boil-off gas	The gas that boils off from an LNG tank as heat is leaked into the tank from the environment (sometimes just called boil-off)
BOG	Boil-off gas
Pad gas	Pipeline gas injected into an LNG tank or large vessel to prevent the tank or vessel from experiencing a negative pressure.
F	Degree Fahrenheit (a measure of temperature)
Psia	Pounds force per square inch absolute (above absolute zero)
Psig	Pounds force per square inch above atmospheric pressure
Lbm	Pound mass
Lbf	Pound force (the force exerted due to 1 lbm accelerated at 32.2 ft./sec^2)
Cu.ft.	A cubic foot of volume 1 foot x 1 foot x 1 foot (1’ x 1’ x 1’)

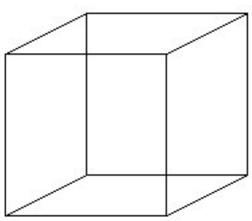

Figure 2: Cubic Foot is a volume 1’ x 1’ x 1’
Source: Self-made

SCF	A standard cubic foot is a 1’ x 1’ x 1’ volume of gas at a standard temperature and pressure. The American Gas Association (A.G.A.) defines standard pressure and temperature as 14.73 psia and 60 F (this is used for this document)
Btu	Btu is the amount of energy needed to raise 1 lbm of water 1 deg F. This is not a precise measure of energy because different industries and countries use different standard temperatures of the water being heated. The heat capacity of water differs with temperature.
HHV	Higher heating value is the heat released from burning a SCF of natural gas at 60 F with air at 60 F and bringing the combustion products down to 60 F.
Therm	By definition, a Therm is 100,000 Btu.
Decatherm	Deca means 10, so a Decatherm is 1,000,000 Btu.

MSCF	In the U.S. Gas Industry, "M" means 1,000. Thus, MSCF is 1,000 SCF.
MMSCF	In the U.S. Gas Industry, "M" means 1,000. Thus, MMSCF is 1,000,000 SCF (one million standard cubic feet)
BSCF	In the U.S. Gas Industry, "B" means billion. Thus, BSCF is 1,000,000,000 SCF (one billion standard cubic feet)
Gallon	Is an imperial unit measure of volume.
m	A meter is a measure of length in the International System of Units
m^3	A volume measurement 1 meter x 1 meter x 1 meter

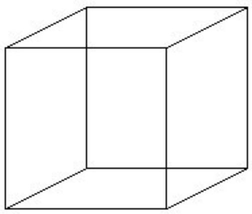

Figure 3: Cubic meter is a volume 1m x 1m x 1m
Source: Self-made

Nm^3	Normal cubic meter is a cubic meter volume of gas at a defined "Normal" temperature and pressure. Different countries and different industries use different values for "Normal" properties.
Barrel	There are two different barrel terms, one for the Alcohol Industry and the Petrochemical Industry. For this training, the Petrochemical Industry Barrel will be used, thus, 1 barrel = 42 gallons

Approximations used in this training:

1 m^3 ~ 35.3 ft^3

One cu. ft. of LNG ~ 600 SCF of vapor

One cu. ft. ~ 7.48 gallons

1 gallon of LNG ~ 80 SCF of vapor

4. Facilities In the United States and Codes That Govern Them

The Federal Energy Regulatory Commission (FERC) governs most permanent LNG facilities in the U.S. via the federal code of regulations (code 49 CFR193). This code requires the controlled facilities to abide by the consensus code, National Fire Prevention Association (NFPA) 59A. Many countries around the world also conform to NFPA 59A.

The U.S. Pipeline and Hazardous Material Association (PHMSA) collects data on LNG facilities annually. According to PHMSA, the inventory of LNG facilities as of 10/1/2022 for the 2021 annual reporting year is as follows:

https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids

- 71 Peak Shaver (PS) LNG Facilities (48 with liquefiers)
- 23 Satellite (Sat) LNG Facilities (1 with liquefier – that is how it is reported)
- 26 Base Load LNG (liquefiers - not counted)
- 40 Mobile or temporary LNG facilities
- 8 Other LNG facilities
- Of the 94 Peak Shaver and Satellite LNG facilities, 44 (47%) facilities in the Northeast
- Of the 94 Peak Shaver and Satellite LNG facilities, 72(77%) 1960's – 1970's vintage
- Of the 48 PS and Sat in the Northeast U.S., 40 (83%) 1965 – 1975 vintage
- Of the 48 PS and Sat in the Northeast U.S, 12 (25%) have liquefiers

The Northeast is emphasized because it is the country's area where local distribution companies (LDCs) depend heavily on LNG. Many of these facilities receive LNG via tanker truck from the Everett LNG import terminal (just north of Boston).

5. An Accident That Changed the Course of My Career

The year was 1973; it was a Sunday. My direct supervisor (and close friend) was overseeing a significant job. I had asked him to check on a pressure test I had in progress a few city blocks away from his work site.

I called his home late in the afternoon, expecting to find him home (this was in the days of no cell phones). Instead of him answering the phone, his wife answered the phone, and she was frantic. She had heard on the radio about an explosion in the same area where her husband was working. She called the gas dispatcher's office repeatedly and only got a busy signal. I told her not to be concerned and that I would drive to the job and have her husband call her.

While driving to the jobsite, my boss's name was announced over the radio as deceased. I got to the hospital, and they would not give me any information as I was not next of kin.

What had happened? There was no explosion, but there was an accident. Six of my co-workers were asphyxiated by nitrogen and natural gas. Most of the six had climbed down the ladders into the 10-foot-deep street opening to save their co-workers who had fallen unconscious. One by one, each of the six fell unconscious. One was not revived; that one was my boss, my friend. He and his direct report had driven many city blocks to the street opening and climbed into it to save their fellow co-workers, but they also fell unconscious. My boss fell with his head very close to where the nitrogen and gas were blowing into the street opening. There he died.

What had happened? The job was to remove a small section of the 48" diameter gas main and to cap the main at that point. Many city blocks away, gas stoppers had been installed to stop gas flow, and the section between the stoppers and the street opening work location was purged with nitrogen. The accident happened when the section of the main was cut and being removed from the street opening. As the pipe section was being raised, suddenly the gas stoppers were over-pressurized and blew out, then the gas started flowing down the open-ended 48" gas main. As employees fell due to a lack of oxygen, other workers jumped in to pull the fallen workers out, but they collapsed. My boss and his direct report drove from the stopper location to the street opening location and also climbed into the opening to help the others out of the opening. He was never revived.

Why were the gas stoppers over-pressurized? The 48" gas main was connected to the plant facility. The plant facility included two gas holders, a city gate station (where interstate pipeline gas is dropped in pressure) and an LNG facility.

There is a safety procedure in use in petrochemical facilities, including LNG facilities in the U.S., but I was not in place at that plant then. The procedure is called the Lock-out Tag-out procedure (LOTO). The LOTO procedure requires plant operators to place a physical lock and a tag stating not to unlock unless authorized. LOTO should have been used for a job like this one, but it was not.

At the time of this accident, a gas plant employee was leaving the compressor building when he noticed that a valve typically opened was closed. He opened the valve and then continued with on his regular duties. The valve he opened over-pressurized the gas main that was being worked on. The opening of that valve caused the stoppers to fail and resulted in the nitrogen and natural gas flowing into the street opening where the men were working.

The employees who were revived did experience loss of oxygen to the brain, but after a recovery period, they were well enough to return to work. When I spoke to them, some told me they pulled their shirt over their mouth before entering the street opening to save their co-workers. This clearly showed me the need for education on confined space entry, as cloth over the mouth does not protect one from a lack of oxygen.

That incident gave me a first-hand understanding of the need for safety education in our industry and changed my career.

Over the past 50 years of Gas Industry experience, I have first-hand investigated many accidents. Almost all of these were preventable if only preemptive thought had been given to the hazards and if only proper procedures had been implemented.

6. LNG Plant Safety

Throughout this training, brain-teasing scenarios will be presented. These brain-teasing scenarios are apparent anomalies that could happen at an LNG facility. The purpose of delivering these is to stimulate the learner to think of actions to mitigate the hazards of such events. After each scenario, some potential causes for the anomaly will be presented.

In the same way that all petrochemical plants have hazards associated with the specific hydrocarbons being managed, LNG plants also have hazards specific to LNG plants. In addition, all plants have generic risks, and the plant operator must have personnel trained to avoid generic and site-specific plant hazards from turning into accidents.

Generic hazards are those that pertain to any plant-type facility. These include fall and vehicle accident prevention. Even though these are generic, many of the injuries incurred at plants involve the generic type of injuries, which often can be prevented by training on standard safety practices like proper lifting and having a backup person alongside the vehicle guiding the driver while backing up.

As simple as these preventive measures might seem, the LNG technicians need to realize whether the injury is from a generic or site-specific accident an injured employee (Figure 4) results in an injured family. Broken bones, heat burns, cold burns, asphyxiation, and other injuries can come in an instant and take months to heal. During that healing process, the cost to the company is high, but the emotional and physical cost to the injured employee and their family is even higher.

Figure 4: An injury is not only to that person but also to the entire family
Source: Self-made

In any petrochemical plant, the danger of fires, explosions, and subsequent burns are always hazards. For a fire or explosion to occur, three parameters are needed (see Figure 5). The fuel, oxidant (typically oxygen), and heat must be present. Eliminate any of these three components, and the fire does not occur or, once started, will not propagate.

An LNG fire can give off a substantial heat rate because of its very high vaporization rate. Because the LNG is so cold and the ground or water it spills on is so relatively high, the LNG rapidly converts to a flammable vapor. Once a fire is started, the fire above the LNG makes the fire even more extensive as the radiant heat from the fire above the pool of LNG enters the LNG resulting in an even higher rate of vaporization of the LNG to flammable vapors.

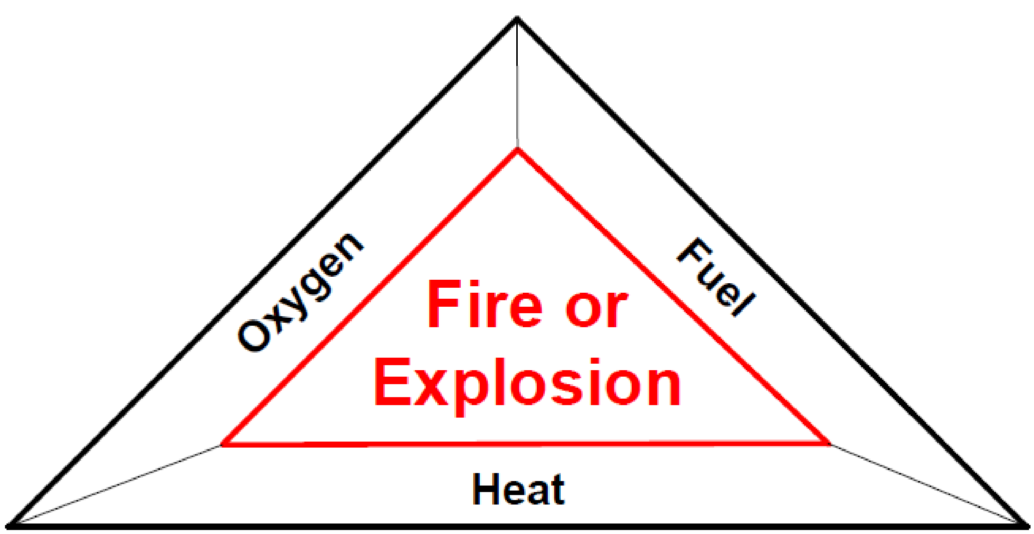

Figure 5: For a fire to occur, fuel, oxygen, and heat must be present.
Source: Self-made

6.1. Some myths about LNG

Myth #1: LNG vapor is nothing more than natural gas, which is lighter than air and will harmlessly dissipate by rising into the air.

Fact: LNG vapor is heavier than air until it warms up to about –150 deg F.

Myth #2: John was a hero; he was able to stop “that” LNG leak.

Fact: Often if John had followed proper procedures, the LNG leak might not have occurred!

Myth #3: If I stay out of the immediate combustion area, I will not get burned.

Fact: Burns can come from radiation energy, which extends well beyond the area of combustion.

Myth #4: We can smell gas, so we will sense it if there is enough gas for a fire.

Fact: LNG vapor is odorless, so you may not smell anything while in a gas leak from LNG vapors.

Myth #5: I will see it if it is on fire.

Fact: A natural gas fire is usually visible, but small well mixed gas fires may be nearly invisible on a sunny day under certain conditions. Hydrogen fires are very often invisible.

Myth #6: If I put a rag over my mouth, I can go into a place that does not have sufficient oxygen

Fact: Insufficient oxygen will cause you to collapse almost immediately.

Myth #7: A heat burn is more damaging than a cold burn.

Fact: Both burns can be severe. Both heat and cold burns can be flesh-damaging and life-threatening.

Myth #8: It didn’t happen (catch fire or explode) the last time we did this hazardous act; it won’t happen now.

Fact: Today is the first day of the rest of your life. Live it safely.

6.2. Scenario 1

- It is 2 am, and the outside temperature is 0 deg F.
- Send out in progress and is needed to avoid a natural gas supply shortage.
- LNG storage tank pressure is steadily rising.
  - 1.2 psig @ 2am
  - 1.5 psig @ 2:10 am (you maximize boil-off compression)
  - 1.7 psig @ 2:20 am (LNG tank pressure is still rising)

6.2.1. Scenario 1 – what might be happening?

- The barometer may be dropping rapidly; however, dropping that rapidly would not be likely
- Pad gas, also called cover gas, might be entering the LNG storage tank.
- A relief valve somewhere in the LNG plant may be releasing warm LNG or vapor back to the LNG storage tank.
- Pad gas may be flowing to the re-condenser at the same time the re-condenser is venting gas to the boil-off gas header.
- LNG pumps may be recycled back to the LNG storage tanks, causing work energy to enter the stored LNG.
- An LNG rollover may be in progress
- An internal tank leak may have occurred, causing excess boil-off gas to be generated as the leaking LNG contacts the warm bottom of the outer tank foundation.
- The boil-off gas compressors may be on re-cycle (thus not removing boil-off but adding heat to the BOG system)
- Many other circumstances could cause this over-pressure condition

6.3. Hazard facts about LNG

There are hazards associated with LNG. Some of these are as follows:

6.3.1. It is cold

6.3.1.1. Bodily exposure to LNG can cause injury or death

Being a cold liquid, it can cause freeze burns if it is splashed on your skin. Extreme exposure, as in a burst vessel, can cause death (see Figure 6).

Being cold, it is constantly absorbing heat from the environment. Thus, one must be sure that LNG is never trapped between 2 closed valves. Wherever the possibility exists for LNG to be locked between two valves, a thermal expansion relief device is installed in that section of the pipe. If LNG is trapped between 2 closed valves without any pressure relief, the pressure will increase until the pipe or valve fails.

Also, because LNG is so cold, special materials need to be used to contain the LNG.

Figure 6: Freeze burns can be painful and cause injury and death.
Source: Self-made

Touching a cold surface can freeze the flesh to the surface and cause tear-away damage to flush. Breathing in the cold vapor can damage the lungs.

Hypothermia is a life-threatening drop in body temperature resulting from prolonged exposure to cold temperatures. As body temperature falls, the ability to perform tasks (physical and mental) decreases. The resulting cardiac and other body disturbances can cause death.

Exposure to freezing weather, falling into the bay (where an LNG tanker is docking) when the water is cold, and exposure to very cold vapors for an extended period may result in hypothermia.

6.3.2. Its vapors are flammable

LNG itself will not burn, but its boil-off vapor is nearly the same as natural gas and will burn when mixed with air. The flammable range for LNG vapor is ~ 5% to 15% gas in an air mixture at atmospheric pressure and temperature. If the mixture is less than ~ 5% gas in the air, the mixture is too lean to burn and if the mixture is greater than ~ 15% gas in air, the mixture is too rich to burn.

6.3.2.1. LNG spill on ground behavior

LNG leaks from a highly pressurized pipe will flash into a mixture of cold vapor and cold liquid. At atmospheric pressure, the temperature will be at the LNG saturation temperature (~ -258 F). Leakage from a high-pressure pipe can impinge on non-cryogenic materials causing them to fail. Sprayed LNG and its associated flash vapor can burn a person’s skin and cause respiratory or eye damage. In large amounts, such impingement can cause severe injury and can be fatal.

LNG spills from a lower-pressure vessel or piping will typically just pool without the impinging damage of a high-velocity jet of liquid and vapor. An LNG spill will tend to pool as the LNG liquid finds a low point on the ground. Often in areas with a potential for LNG to leak, there are channels to bring the spilled LNG to an impoundment area. An impoundment area is typically a sump where LNG can collect. The sump location generally is in a place where the hazard is minimized because it is remote from people or equipment.

The liquid is very cold and may crack any non-cryogenic materials. Special precautions are taken to avoid structural damage to critical plant components when there is the potential for such spills (around flanges, etc.). Since the environment is so much warmer than the LNG, it will boil-off rapidly to a cold vapor.

LNG vapor will deflagrate in an open-air environment and not detonate if ignited. However, a detonation may occur if the flammable mixture is in a confined space or a space congested with much piping.

When LNG pools on the ground or in an impoundment basin, large amounts of vapor are produced because of the warm surface area of the land or the impoundment surface. This vapor is clear but because it condenses the water vapor in the air, it appears white. If there were no water vapor in the air, one would not be able to see the vapor cloud.

LNG vapor at ambient temperature is lighter than air with a specific gravity of ~ 0.6. However, since boiled off gas from LNG is very cold, it is heavier than air, and even as it mixes with air, it cools the air, making the mixture denser than the ambient air surrounding it. Thus, the vapor coming off an LNG spill will be heavier than air and hug the ground. It will follow the path of the terrain to a lower location, or if there is wind, it will hug the ground and be blown to where the wind takes it.

A method used to disperse LNG vapor is by warming it up. It is a common practice to have water sprays strategically placed around the plant to warm up LNG vapor clouds. Once warmed up, the vapor cloud becomes buoyant.

It is critically important not to allow the water spray to enter the LNG pool as that would greatly accelerate the rate of boil-off and could cause a mechanical explosion called a Rapid Phase Transformation (RPT) (to be explained later in this study).

6.3.2.2. LNG in contact with water behavior.

If LNG spills on water, it will vaporize very rapidly as the water is a significant source of heat entering the LNG. It is typical for ice to form on the water where the LNG has spilled. In the case of a large amount of water and LNG coming in contact, an RPT often occurs.

If LNG is spilled on water or if water is hose sprayed into a pool of LNG, it can cause a **Rapid Phase Transformation** (RPT). A rapid phase transformation is a mechanical explosion (not a combustion explosion). The RPT is a mechanical explosion caused by the heat transfer from the water to the LNG, expanding so rapidly that is produces a shock wave. This phenomenon does not happen every time water and LNG come in contact, but it has been shown to happen often as the two fluids are put in contact with each other in large quantities.

It is typical for ice to form when LNG is spilled on water. The water itself does not get contaminated as in a petrochemical spill. After the LNG vaporizes, there is no remaining residue in the water.

6.3.2.3. Ignition and burning of LNG vapors.

LNG vapor is odorless. In 1979 at the Cove Point LNG import terminal, odorless LNG vapor leaked past an electrical seal, entered a building, and ignited. One employee was injured and one employee was killed in this incident.

Gas industry employees familiar with outside pipeline gas work must be extra cautious because they may need to be aware that LNG vapor is odorless.

Figure 7 below shows conceptually, on a molecular level, what happens during the combustion of methane and oxygen. This reaction will only occur if the methane and oxygen molecules are: 1. Near each other and 2. Are brought up to the activation energy (temperature) needed to initiate the reaction.

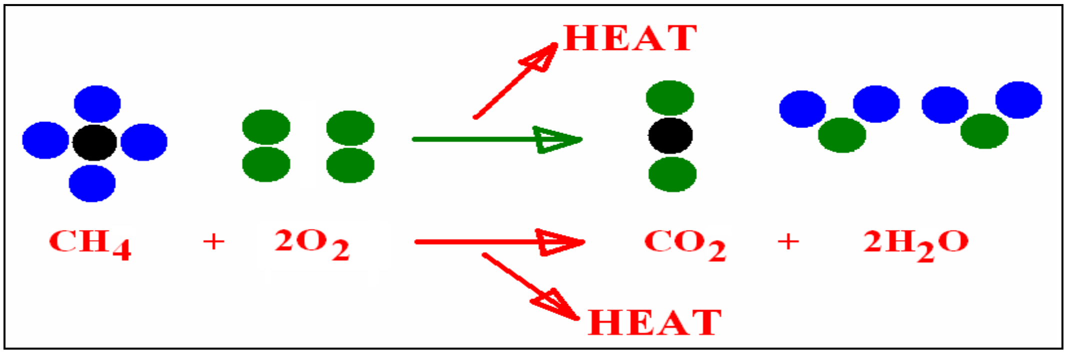

Figure 7: Simplified conceptual graphic showing one methane molecule (CH_4) reacting with two oxygen molecules ($2O_2$) to produce 1 CO_2 molecule and 2 H_2O molecules plus heat.
Source: Self-made

Each time such a reaction occurs, it gives off heat. If there is another set of methane and oxygen molecules nearby, and if the heat released reaches this other set of molecules with enough energy to have it get its activation energy, then this set of molecules will also react. If this continues to chain react from groups of molecules to other groups of molecules, a fire will prorogate.

However, if there is too much insulation between the molecules that have reacted and the nearby set of methane and oxygen molecules, the group of molecules receiving the heat from the first reaction will not reach its activation energy, and fire won’t propagate.

What is the insulation being referred to in the above paragraph? It is too much fuel, too much air, or an inert gas, such as nitrogen. If the mixture of methane in the air is too rich (above ~ 15% gas in air (upper explosive limit (UEL)), the excess fuel molecules will insulate the locations, where fuel and oxygen exist so that they never reach their activation temperature. Thus, the flame will not propagate.

The same holds if there is too much air in the mixture. If the mixture of methane in the air is too lean (below ~ 5% gas in air (lower explosive limit (LEL)), the excess air will insulate the locations where fuel and oxygen exist so that they never reach their activation temperature. Thus, the flame will not propagate.

Figure 8 below conceptually shows the explosive window for methane in the air. Methane is used for this discussion because LNG vapors are a mix of many different gases in varied compositions. Still, it always has methane as the highest quantity component (typically above 90% methane).

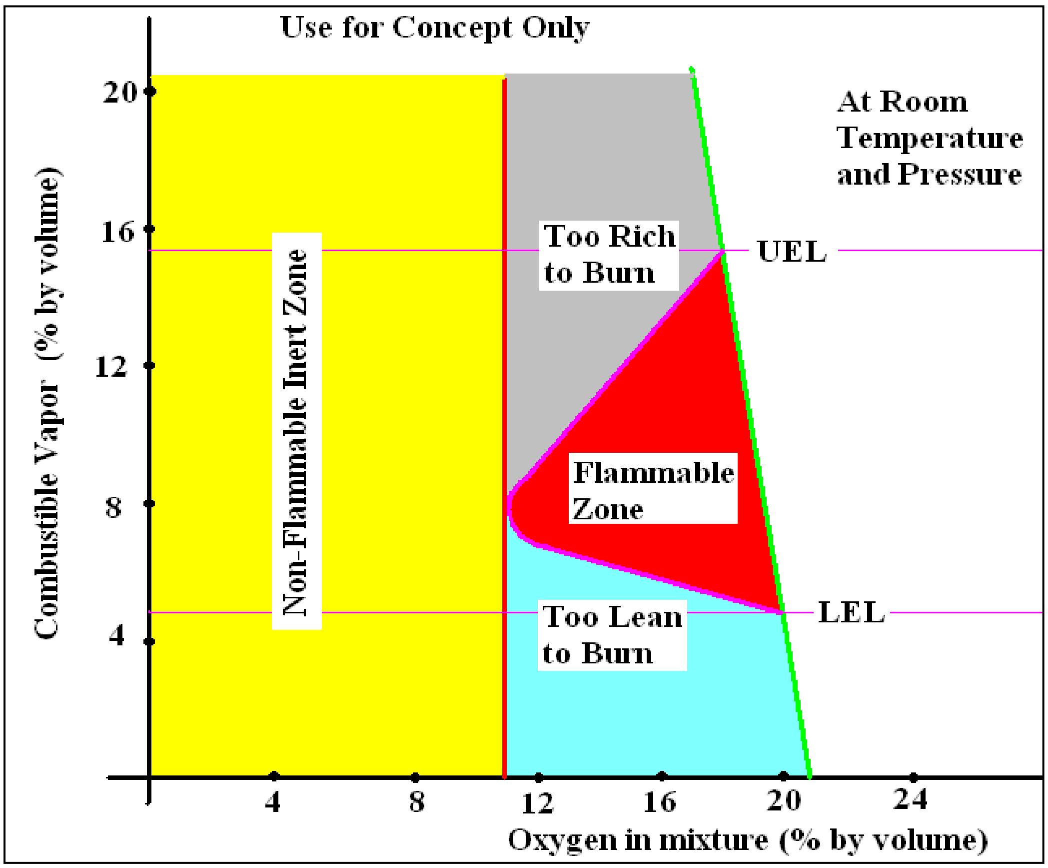

Figure 8: Conceptual graphic to show the flammable zone of methane at various oxygen/methane concentrations at atmospheric conditions.
Source: Self-made

In Figure 8, the percent of the fuel is shown on the Y axis, and the percent of oxygen is shown on the X axis. Note also that at zero percent methane, the air contains 21% oxygen; as fuel is added, the mixture reduces in oxygen (follow the green line).

These flammable zone graphics assume that the mixture is at atmospheric temperature and pressure.

In Figures 9 and 10, it is shown that if the space considered started with less than 21% oxygen, the explosive window gets smaller. This would be the case if a vessel were partially purged out with nitrogen. If enough nitrogen is added to the space, as gas is brought into the space, the oxygen concentration lessens further, and the mixture never passes through the flammable zone. In Figure 9, this is shown as a green arrow.

In the gas industry, it is common practice to drive the oxygen level down to near zero in piping and small vessels before bringing a flammable vapor into the piping or vessels. For large vessels, bringing the oxygen level down to near zero is very difficult, and higher oxygen concentrations are acceptable for such vessels. Note: For such applications, it is typical to use the A.G.A. Purging Guidelines to determine the safe oxygen level for gassing in large vessels and tanks (like LNG storage tanks).

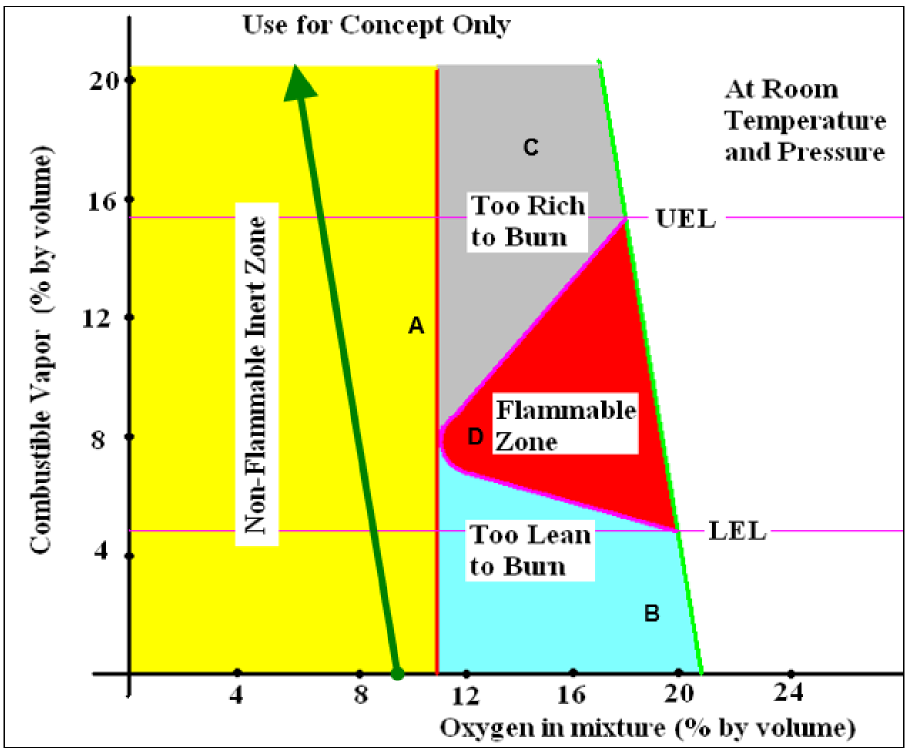

Figure 9: Conceptual graphic to show the flammable methane zone, at various oxygen concentrations at atmospheric conditions. When the space is brought down to ~9% oxygen, by purging with nitrogen before injecting methane vapor, the concentration line (shown in dark green) does not pass through the flammable zone.
Source: Self-made

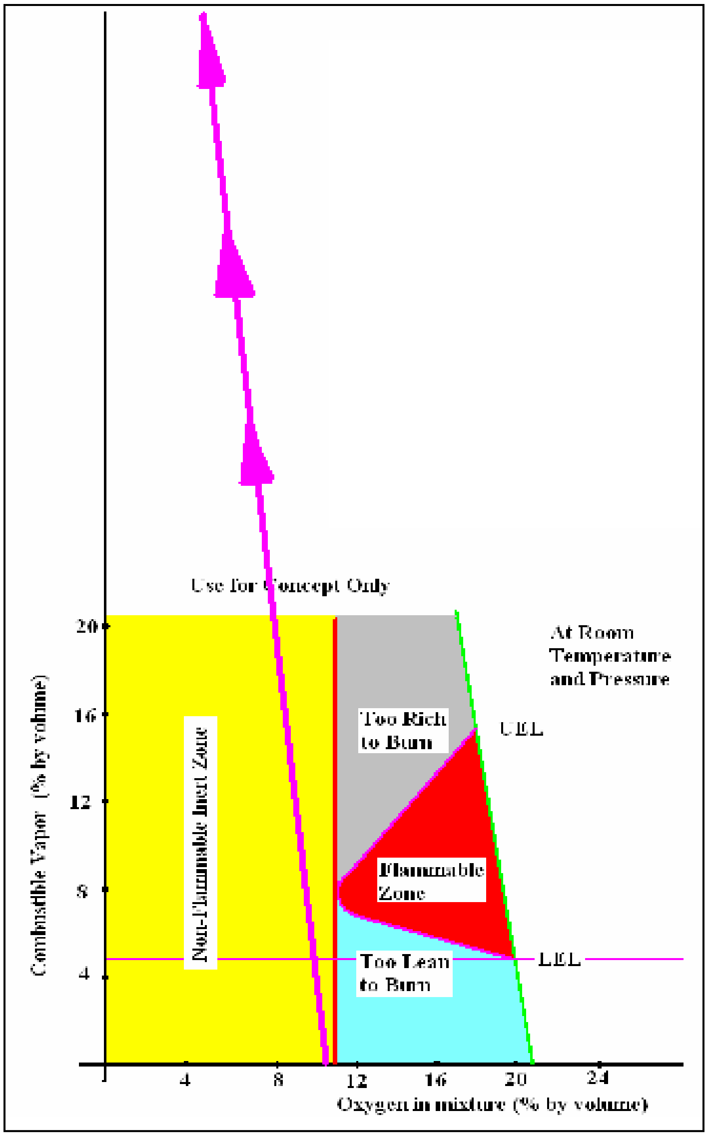

Figure 10: Conceptual graphic to show the flammable methane zone, at various oxygen concentrations at atmospheric conditions. When the space is brought down to ~9% oxygen, by purging with nitrogen before injecting methane vapor, the concentration line (shown in dark green) does not pass through the flammable zone.
Source: Self-made

The products of combustion are very hot and can cause injury or death even if one is not within the actual flame. Heat is transferred by conduction, convection, and radiation. Therefore, even if not directly engulfed in the flame of a combustion accident, severe injury or death can result. Inhaling hot vapors can burn lungs, and skin burns can become extensive if protective clothing is not worn. As shown in Figure 11, heat transfer from radiation decreases the further one is from the fire. Thus, impoundment areas where LNG may collect in the event of a spill are strategically placed to best protect personnel and equipment.

Table 1 below is used as a learning aid to reinforce learner's understanding of flammable and non-flammable concentrations. Use Figure 8 to determine if the concentrations shown in the below table, are flammable.

	Combustible Gas	Oxygen	Flammable
A	14%	12%	No
B	2%	21%	No
C	18%	17%	No
D	10%	9%	No
E	9%	15%	Yes

Table 1: Various combustible gas and oxygen compositions and determination of their flammability based on Figure 8.
Source: Self-made

It is important to note that different fuels have different upper explosive limits (UEL) and lower explosive limits (LEL). Some LEL and UEL levels are shown for other fuels in Table 2 below.

Gas	LEL	UEL
Hydrogen	4%	75%
Carbon Monoxide	12.5%	74%
Methane	5.3%	15%
Ethane	3%	12.5%
Propane	2.2%	9.5%
Butane	1.9%	8.5%
Pentane	1.5%	7.8%
Acetylene	2.5%	81%

Gasoline	1.4%	7.5%

Table 2: Table showing lower explosive limits and higher explosive limits for various fuels
Source: Self-made

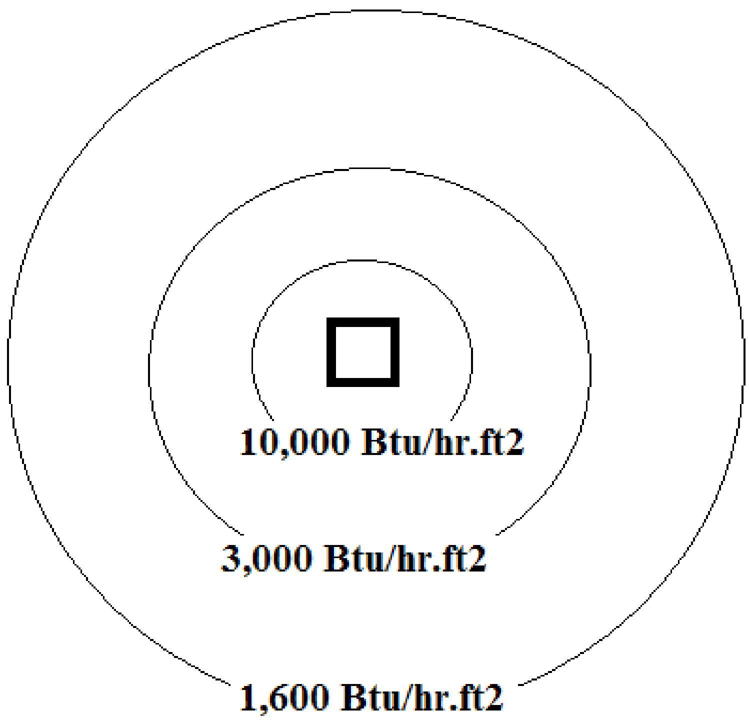

Figure 11: Conceptual graphic showing how distance from flame source reduces radiation heat transfer exposure. Note: it is not linear. Also, realize that this assumes no wind. Wind may place the flame right over your head even if you are away from the source of fuel release!
Source: Self-made

Impoundment basins reduce vapor dispersion from an LNG spill and reduce the fire size of an ignited LNG spill.

An LNG spill results in a vapor dispersion. Vapor dispersion is reduced by reducing heat transfer into spilled LNG. This is typically accomplished by:

- Reducing the surface area of the containment that touches the LNG via use of a containment impound basin (see Figure 12 has drainage around the tanks to an impound basin.
- Insulating the containment surface
- Covering the LNG with high-expansion foam

- o High expansion foam acts like an insulating blanket to prevent the environment over the LNG from radiating heat into the LNG
- o High expansion foam acts like an insulating blanket to prevent a fire over the LNG from radiating heat into the LNG

Figure 12: Graphic of two single containment LNG tanks within their outer dikes. Note: there are impoundment areas that are intended to contain spilled LNG. These impoundment areas (far left and far right of image) are away from the LNG storage tanks.
Source: Google Earth - Random Image

Even with plenty of distance between you and a spill, the wind may whip the vapor cloud or the fire directly over your location. Keeping in mind that there are 3 components needed for combustion, fuel and air and heat up to the activation energy, plants are designed to the extent possible to avoid having these components occur. The activation energy for methane is ~ 1000 F. The activation energy can be caused by something as small as a static electricity spark. Thus, even in areas where there is only explosion-proof equipment, present blowing gas can result in a spark, particularly if solids are blown along with the gas or if plastic or rubber pipe is involved. It is not uncommon for hoses used for fill pearlite into vessels via elastic hoses to develop very large static charges which can arc several inches. Also, flying debris from a rapid venting of gas can also result in a static or impact spark.

It is also important to realize that although LNG vapor flammability is a major emphasis at an LNG plant, from first-hand experience, experience shows that many other fire hazards are just as likely to pose a threat. These fire hazards include the handling of process refrigerants (e.g., ethane, propane, isopentane, etc.), paints and solvents, gasoline and oils, and plant construction and operating debris. Another significant fire hazard at many plants is that of electrical fires. Often, high resistance connections and overheated transformers and switchgear can result in a fire. When a transformer fire results in an oil spill, not only might the smoke from the fire be toxic, but the oil itself may be a hazardous material.

Heat is transferred from a fire by conduction, convection, and radiation. The theory of these modes of heat transfer are not here-in discussed, but it needs to be realized that any of these modes of heat transfer can result in cause severe injury or death.

A high-level overview of the flammability concerns for an LNG plant is as follows:

- Even in a mixture that could propagate a flame, if there is no ignition source, the chain reaction will not occur. For natural gas, a temperature of approximately **~1000 F is needed for ignition**.
- The Lower flammability limit for natural gas (predominantly methane) is approximately 5% gas in air.
- The higher flammability limit for natural gas (predominantly methane) is approximately 15% gas in air.
- Combustion of fuels other than natural gas or other materials (paints, oils, hydrogen, acetylene, refrigerants, debris) is also a severe concern for any plant.
- 1ft^3 of LNG produces ~600ft^3 of LNG vapor
    - 600ft^3 of vapor, if uniformly mixed at 10% gas in air, produces 6,000 ft^3 of the flammable vapor mixture
- You can significantly reduce the risk of heat burns by wearing protective clothing.
- Inhaling hot vapors, even for a short time, can damage the lungs and cause death
- Thermal radiation is measured in Btu/hr.ft^2 or W/m^2
- 10,000 Btu/hr.ft^2 is equal to ~30,000 W/m^2 (this was not mentioned in the above text but is stated as a reference piece of conversion data)
- The energy radiated reduces quickly with distance (See Figure 11 above)

6.3.3. LNG vapor can be an asphyxiant

Although the vapors from LNG are non-toxic, they displace air, and replacing air reduces the oxygen content needed for life. Thus, in the same way, breathing in nearly pure nitrogen will not sustain life; breathing almost pure LNG vapor will not sustain life. Also, because LNG vapors are odorless, the possibility of asphyxiation can come without warning (see Figure 13 below).

- Nitrogen, like LNG vapor, is odorless, thus, any oxygen deficient environment is a concern
- Employees from many different industries, including the LNG industry, may be overcome, and killed by asphyxiation.
- The lack of oxygen kills brain cells and thus, being revived may not result in being without permanent injury.
- Multiple deaths have occurred as fellow employees attempt to rescue fallen colleagues.

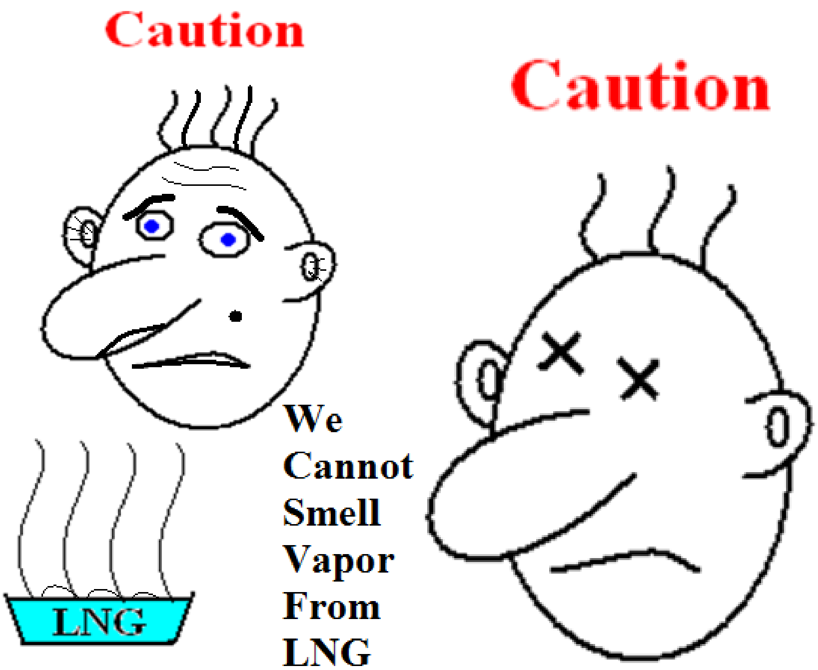

Figure 13: Although LNG vapors are non-toxic, they can displace air which contains oxygen necessary for life.
Source: Self-made

6.4. The Oxygen Balance – Amazing! 23% – 21% – 19% – 16% – 6%

It is essential to realize how sensitive our environment is to oxygen content. If we lived in an oxygen environment of 23% oxygen, everything would be so flammable that containing fires would be extremely difficult. If your plant is equipped with Air Separation Units (ASUs), you must take extreme care. ASUs are used in some LNG plants to produce nearly pure nitrogen. However, the exhaust waste gas of an ASU, used to make nitrogen, is oxygen at a very high percent concentration. This exhaust gas may be ~ 70% oxygen. A 70% oxygen gas will make even normally non-flammable materials explode. Even maintenance on such ASU plants requires extreme attention to detail. For example, handling the inside of the waste gas piping can cause a fire if the oil from a technician's hands is not cleaned off the piping interior. Further, any flammable gas sucked into the intake of an ASU could cause an explosion if it were to mix with the exhaust's high oxygen-content waste gas. For this reason, it is common to have multiple gas detectors monitoring the ASU's inlet air. Any combustible gas reading would trigger an ASU shutdown.

If we were in an environment of 19% oxygen content, we would be below the oxygen content allowed by OSHA. If we were in an atmosphere of 16% oxygen in the air, we would not be able to perform our duties as engineers and LNG technicians, as our judgment, mental and physical ability would be significantly impaired. In addition, our actions would be unpredictable, with impairment characteristics being different from person to person and from time to time.

With that in perspective, the world is incredibly in a sensitive balance, with ~21% oxygen content in the environment. Anymore, and fires would be uncontrollable. Any less concentration and normal human activities would be difficult.

A confined space that is safe now may not be safe later.

Unfortunately, some still believe that placing a rag over their mouth in a low-oxygen environment will allow them to enter and not be overcome. That is terribly

Source: Self-made

6.5. Scenario 2

- 3 am, 0 deg F
- Send out in progress and is needed
- Tank pressures have been unusually high all-day
- Outside operator reports a cold spot and an ice formation at the base of LNG storage tank #1

6.5.1. Scenario 2 – what might be happening?

Many things could be happening here; however, the operator reporting a cold spot is particularly concerning.

- Of immediate concern is that LNG may have gotten out of the inner tank and is near contacting the outer tank. It is highly probable that if LNG makes contact with the outer tank, it would have cracked it.
  - The LNG inner tank may have been overfilled.
  - The LNG inner tank may have a leak.
  - There may have been a disturbance in the inner tank that caused a wave of LNG to splash over the top of the tank, and that LNG may have run down the outside of the inner tank.
  - There may be a void in the insulation at a location causing the ice spot to form
- High tank pressures can be caused by a host of reasons, including but not limited to the following:
  - A dropping barometer
  - A constant recycling of the LNG pumps putting energy into the LNG
  - A failure to operate the boil-off compressors when needed
  - Pad gas passing into the LNG tank
  - A relieving of LNG or BOG from plant piping and/or vessels to the boil-off gas header or LNG relief header, which are connected to the LNG tank.
  - A rollover may be in progress
  - A failure of the insulation may have occurred
  - LNG may be leaking into the annular space

6.6. Brain Teaser

A crack has occurred in the bottom of the LNG tank, and cold vapor is escaping. How can you tell if that vapor is due to boil-off from the top of the tank or from an inner tank LNG leak?

6.6.1. Possible answer

One indicator would be the composition of the vapor. If the vapor contains a significant amount of ethane, it is a good indicator that it is from LNG that has leaked out of the inner tank or overflowed. This is because boil-off gas is nearly pure methane (with nitrogen if nitrogen is in the composition of the LNG). Ethane in the boil-off gas is only in tiny amounts. I.e., the LNG may contain 6% ethane; thus, LNG spilled into the annular space and vaporized would also have 6% ethane. Boil-off, on the other hand would have only a tiny fraction of a percent (~0.015%) of ethane.

6.7. BLEVE

BLEVE stands for Boiling Liquid Expanding Vapor Explosion. A vessel half filled with water and exposed to a fire can BLEVE. Such a vessel may experience the top of the vessel overheating and weakening and then rupturing. This would be because the top of the vessel is not cooled by the water as there is steam in the top of the vessel. This is depicted in Figure 14 below.

This would be a mechanical explosion resulting in shrapnel, super-hot water flashing to saturated water, and saturated steam vapor. Parts of the vessel may be projected far distances from the explosion area. It would release a large amount of energy via the mechanical explosion.

When a BLEVE occurs, much of the liquid in the vessel rapidly atomizes and mixes with the air. If the fluid in the container is combustible, the BLEVE is significantly worsened as the large, atomized combustible mixture can result in a very rapid secondary explosion. This secondary explosion, which may occur immediately after the BLEVE, can be much more damaging than the BLEVE itself.

Consider a BLEVE with the fluid in the vessel being water. The explosion can cause significant damage. Then consider that same BLEVE but with the liquid in the container being propane. The secondary “detonation” of the atomized propane would cause significantly more damage.

Typically, a BLEVE occurs in a vessel exposed to a fire, whereby the top of the vessel weakens and fails.

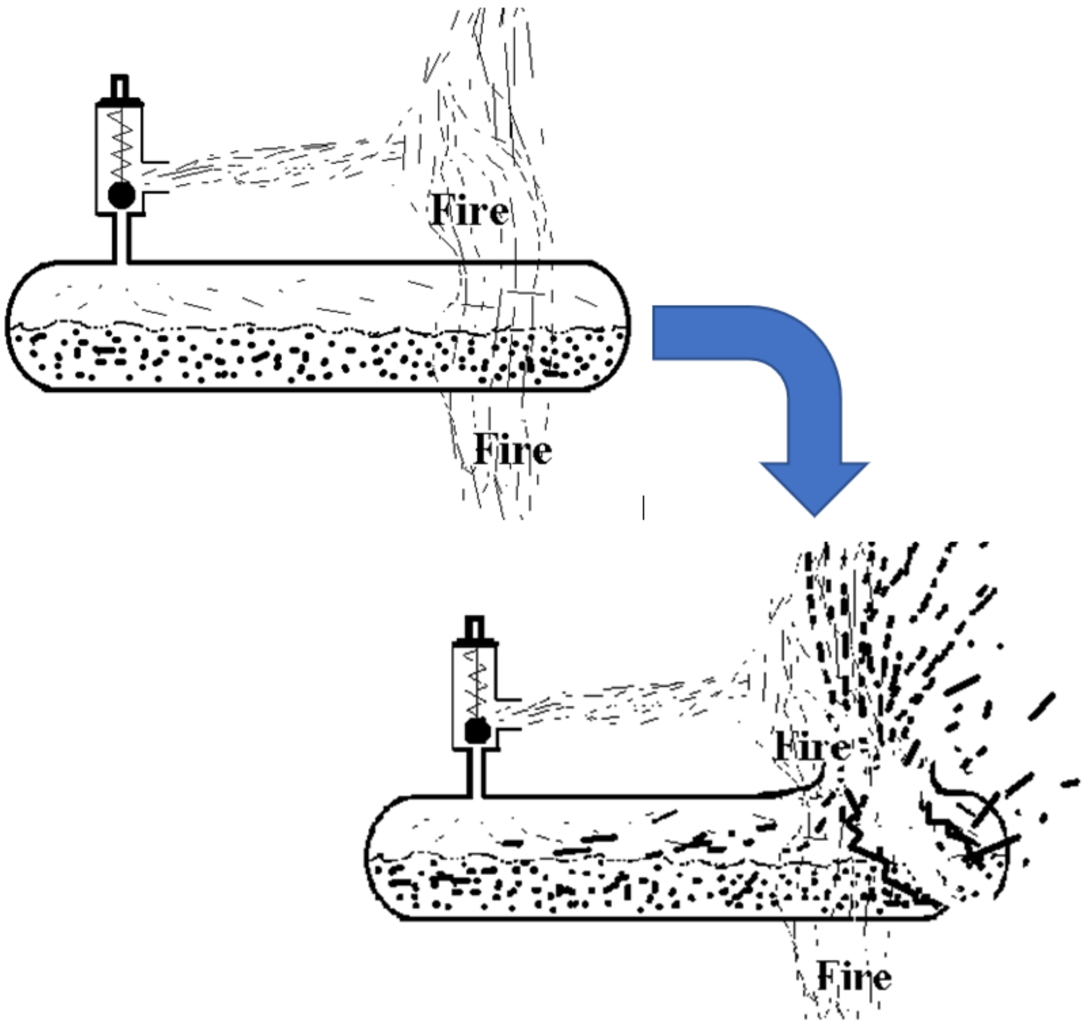

Figure 14: A BLEVE is a mechanical explosion, not a combustion explosion. It involves a liquid at high pressure at its boiling point. Often it is accompanied by a fire that weakens the vessel's upper portion. A secondary explosion will likely occur if the fluid inside the container contains a flammable boiling liquid.
Source: Self-made

However, a BLEVE may also occur without any external fire. Consider the following conditions that can cause a BLEVE without being exposed to fire:

- A reboiler containing propane was blocked in without any relief valve protection. Heat was added to the reboiler by steam entering the reboiler heating tubes, resulting in a BLEVE. This did occur as described by the Chemical Safety Board review of the Williams Geismar Olefins Plant accident of 2016.
- A section of LNG piping blocked in without any means of relief experiences high pressures resulting can result in a BLEVE.

6.7.1. BLEVE of LNG tank is very unlikely

A BLEVE of an LNG storage tank is very unlikely because:

- Most LNG tanks have double wall construction and have substantial insulation between the inner and outer tanks. Thus, if involved in a fire, under the most plausible conditions, the inner tank would be protected from the heat of the fire by the outer tank and the insulation.
- Our large LNG tanks are maintained at near atmospheric pressure. Thus, a tank failure would not result in liquid flashing into a large atomized vapor.
- All LNG storage tanks are equipped with pressure relief valves, and procedures are in place to prevent the trapping of LNG between two valves without a means of pressure relief.
    - Although equipment and procedures are in place to help ensure that a BLEVE of an LNG vessel or pipe should not happen, operator error or failure to follow procedures or a mechanical failure of a relief device coincident with heat gain to a vessel or piping containing LNG could result in a BLEVE. Although this is unlikely it is possible.

6.8. Purging of vessels.

Care must be taken when purging vessels to ensure that pockets of oxygen or flammable gas concentrations are indeed reduced to appropriate levels throughout the entire vessel. Diffusion and displacement purges are shown below (see Figure 15 below).

Measures need to be taken to prevent channeling during a purge, as a channeled purge will give a false sense of safety, as there could still be high concentrations of flammable gas or oxygen in the parts of the tank, where the channeling has not occurred (see Figure 16 below). Keep in mind that the operator is measuring the outlet gas concentration to determine if the purge is complete.

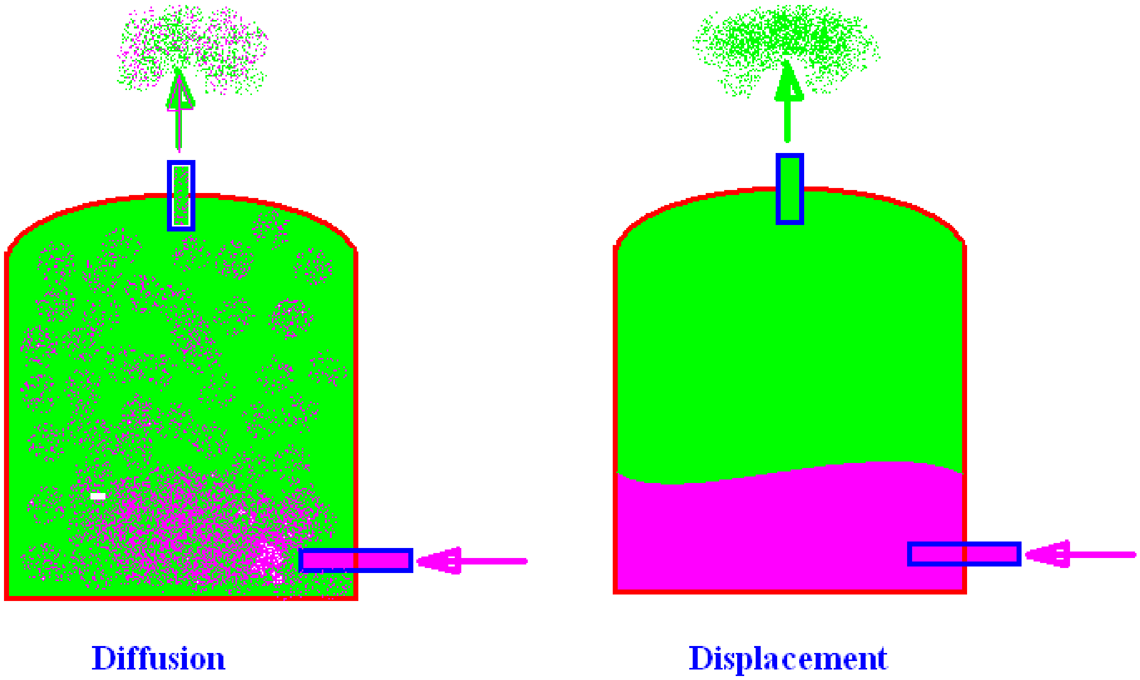

Figure 15: Conceptual view of two different types of purges. To get a displacement purge, it is necessary to have the purge gas be of a significantly different density than the gas being purged out of the tank.

6.8.1. Source: Self-made

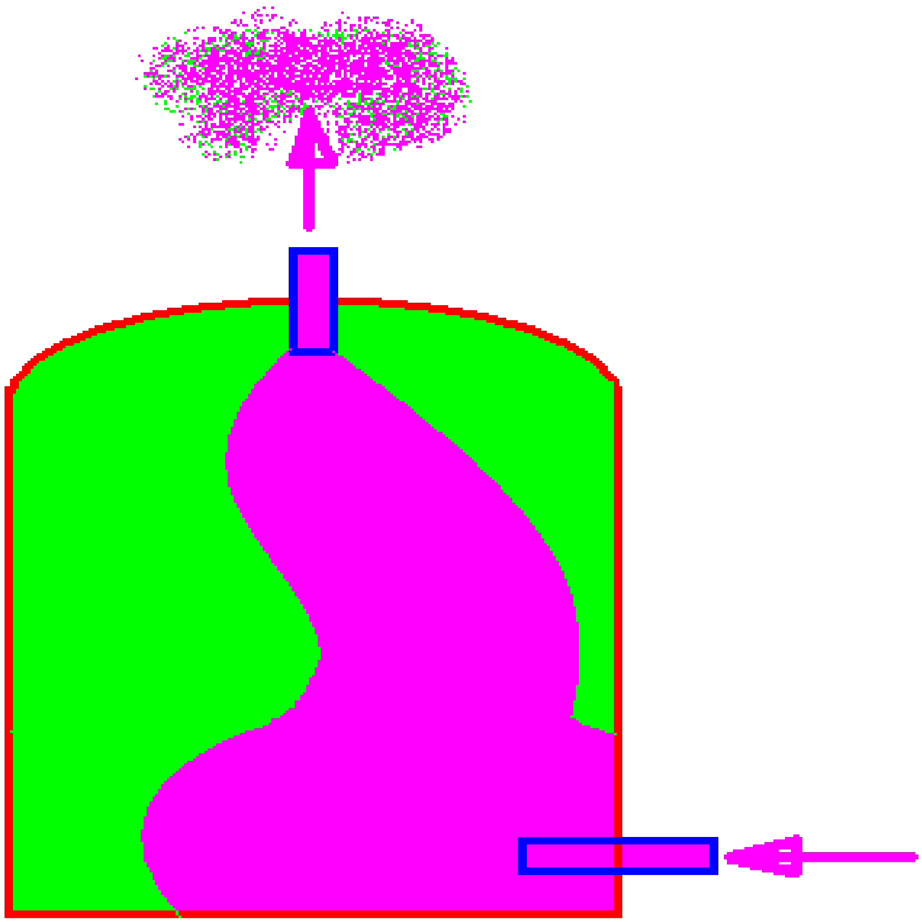

Figure 16: Conceptual drawing of a purged vessel where channeling is occurring. The areas in green show spaces which may not have been adequately purged.
Source: Self-made

It is more difficult to purge a vessel that contains a solid adsorbent, a reactant, or any powered or granular material. This is because the solid tends to adsorb the flammable gas, and moving the purge gas uniformly through a packed vessel is difficult.

Typically, adsorption occurs at high pressure and low temperatures, and desorption occurs at high temperature and low pressure. Note that capturing gas molecules on a solid surface is an adsorption process, not an a**b**sorption process.

Adsorption occurs when molecules are captured in crevices on the surface of a solid, and absorption occurs when molecules go into a solution with a liquid. The graphic in Figure 17 below conceptually shows how a solid can adsorb gas molecules on its surface and between the granules and trap molecules between small powder-like particles. Although perlite is not designed to be an adsorbent, it does have a huge surface area with crevasses that can trap gas. In an LNG storage tank that has been purged and opened, such crevices can out-gas further as the barometric pressure drops.

Thus, thoroughly purging out the annular space of an LNG tank is difficult, first because the purge gas would tend to channel through the fiberglass layer (the annular space has a layer of fiberglass around the inner tank and purge gas more easily passes through the fiber glass than through the pearlite), and secondly, because it would be difficult to remove all of the gas, from between or from the surface of the perlite particles.

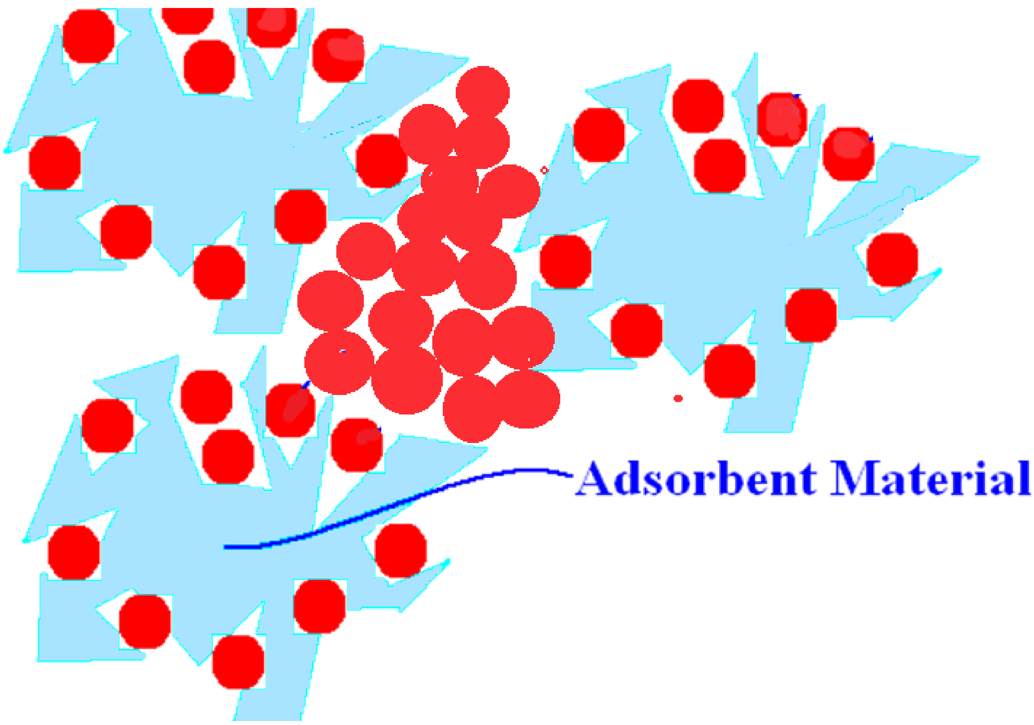

Figure 17: Vessels filled with powdered or granular materials are challenging to purge because of channeling and adsorption of the gas molecules on the surface of the materials. Source: Self-made.

6.9. Operational Hazards.

One of the more difficult hazards to avoid is human error. Although training programs are in place, and automatic safety devices are built into the plant's design, operators need to always to be aware of what is technically occurring while operating the plant. People may react differently to the very same events on different days based on a number of factors including, other concerns that may be distracting them or due to how coworkers perceive the event.

Plant operators need to assure that their actions, even those intended to improve safety do not create hazards that can lead to accidents.

For example, when pressure relief valves are serviced, the technician needs to ensure that the valves are operating correctly, before putting the system back into service. All procedures, such as lock-out-tag-out, confined-space work permits, hot-work permits, car-seal procedures and all safety protocols, must be carefully followed whenever doing maintenance.

Also, the operating technicians must be aware of the “not-so-obvious phenomena” that can occur. LNG tank stratification and water hammer occurrences, to name two, can result in significant hazardous conditions. Water hammers and inventory rollovers are only two of the many phenomena that occur with LNG. These two are explained below.

6.9.1. Water hammer effect (fluid need not be water)

A condensation water hammer happens when an LNG piping system with a warm leg is operated at high pressure, then depressurizes and repressurizes (see Figure 18 below). When a pump shutdown or another event causes the pressure to drop, the LNG in the warm leg vaporizes. Then, if the pressure is restored rapidly, the pressurized LNG rushes to the end of the warm leg pipe. When the LNG gets to the end of the pipeline with significant momentum, it causes a high-pressure spike known as a condensation water hammer. Note, it is called a water hammer, even though it does not involve water!

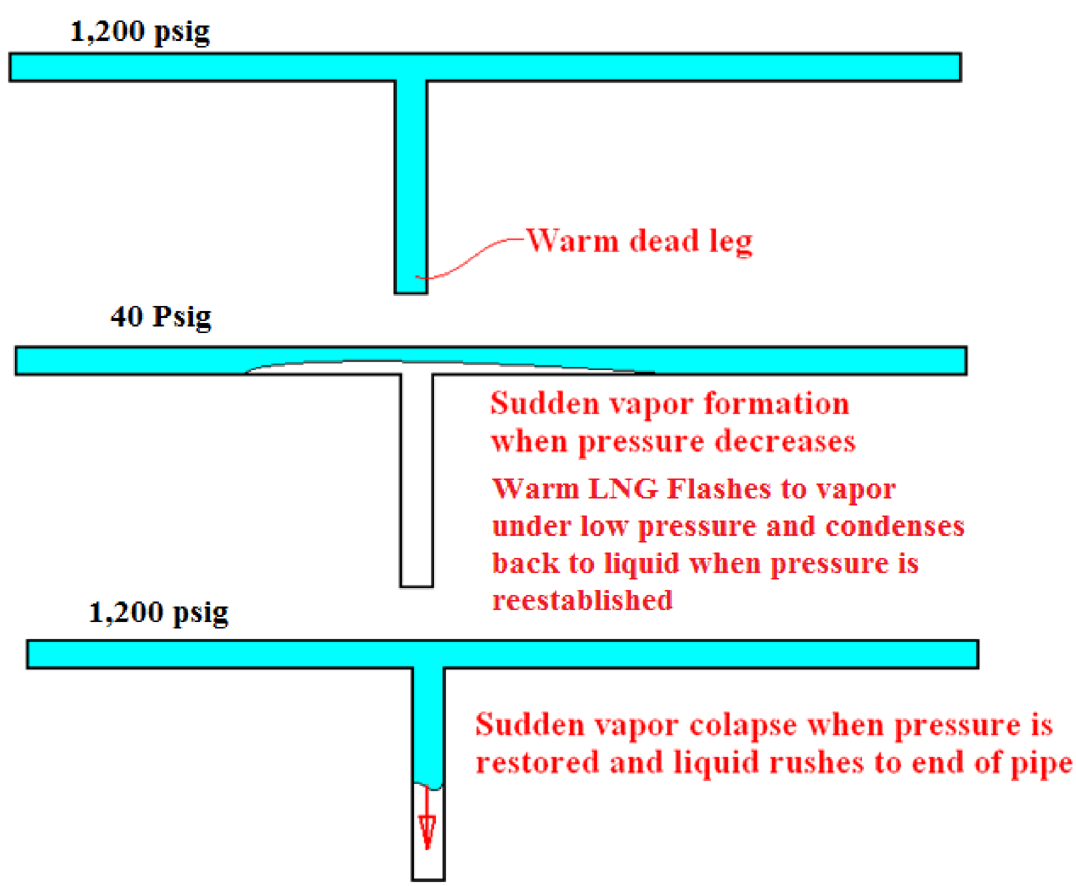

Figure 18: Conceptual graphic of a condensation water hammer

Source: Self-made

6.9.2. Joukowsky equation hydraulic hammer (often called water hammer, but fluid does not need to be water)[1]

A water hammer occurs if fluid flows and a valve downstream is suddenly closed. A "water hammer' as it is called, need not involve water. It consists of any fluid that, when suddenly stopped, has a momentum associated with it that causes a pressure spike at the end of the pipe. That pressure spike sends a pressure pipe back up the line to the source of the flow, and that wave is again reflected down the pipeline. This pressure wave bounces back and forth several times as a function of the pipeline configuration and fluid properties.

LNG facilities often have some prolonged closure time associated with liquid flow valves to avoid a serious water hammer. As an example, it could be 1 second per diameter inch of the pipe. The actual time required is a calculated value, based on the pipe properties, configuration, and fluid properties.

One set of valves needing particular analysis is the powered emergency release coupling (PERC or ERC) on ship loading/unloading arms. These valves are designed to close rapidly if a ship moves away from the loading berth. It is critical to analyze if this rapid closing of the PERC does not cause a water hammer in the loading/unloading piping connecting the plant to the loading/unloading arms.

A generic Joukowsky formulation of a straight pipe can be analyzed using the following:

Pressure spike = ϱCVel

Where:

P is the pressure spike compared to the pressure initially in the pipe

ϱ is the density of the flowing fluid

Vel is the original velocity in the pipe which becomes zero upon the valve closure.

C is the pressure wave speed velocity of the fluid in the pipe. The pressure wave speed velocity is a function of the fluid's compressibility, the pipe geometry and the pipe material's elasticity (or rigidity).

Thus:

$C = (1/ (\varrho\ [(1/K) + (D/Et)]))^{0.5}$

Where:

K is the bulk modulus of the fluid

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[1] http://www.fluidmechanics.co.uk/hydraulic-calculations/water-hammer-2/

E is Young's modulus of the pipe material

t is the wall thickness of the pipe

The phenomena of a water hammer can result in highly damaging pressure spikes near the pipe valve reflecting well upstream of the valve.

Also, the flow downstream of the valve can result in a water hammer due to a vapor bubble formation and a subsequent flow reversal. Once the valve is closed, the significantly lower pressure downstream of the valve (can even be down to a vacuum), depending on the initial flow velocity, can, due to the downstream flow momentum, cause a fluid vapor bubble to form and a subsequent flow reversal. As the vapor bubble collapses, the reversed flow crashes into the back side of the valve.

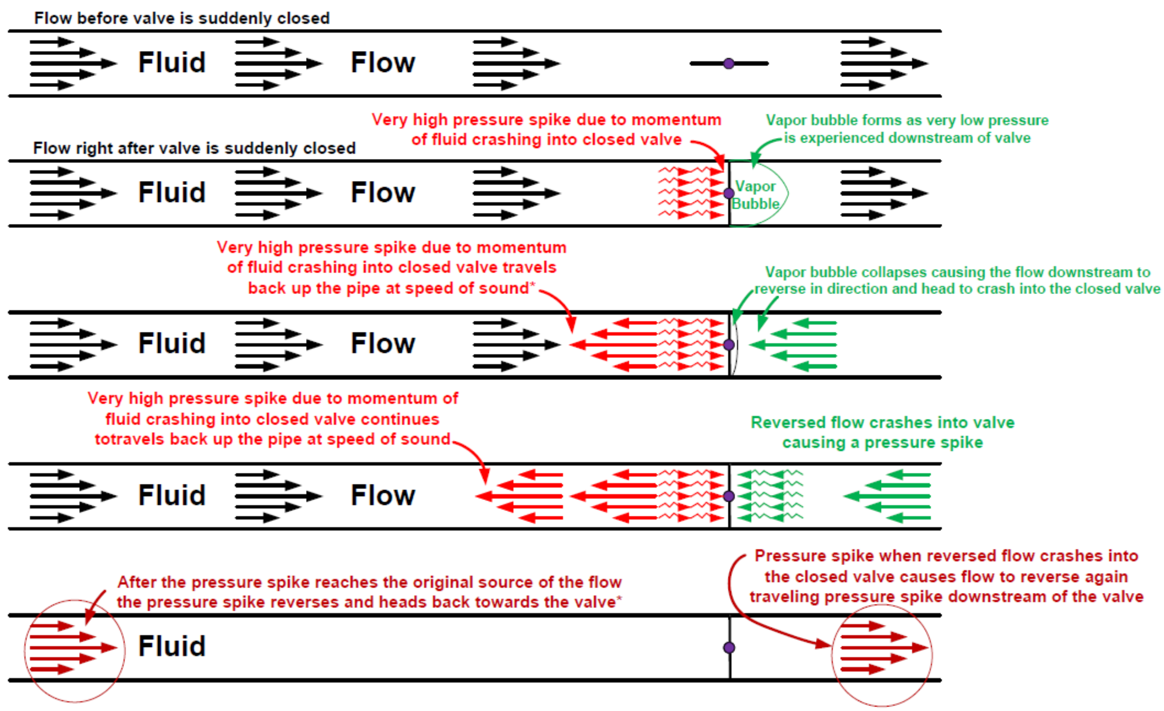
An easy way to visualize why this pressure spike is happening is to imagine a 5-mile-long freight train hitting a solid wall of a mountain. Think of each car of the train as a cube of fluid. If the vehicles are elastic, like springs, after the initial crushing of the first cars, those cars will spring back pushing back on the cars behind them. With a fluid, in an infinitely rigid pipe, this pushing back on the liquid cubes happens at the speed of sound which is a function of the density of the fluid and the compressibility of the fluid.

In real world pipes, the rigid pipe speed of sound is modified by the expandability of the pipe. Keep in mind that the speed of sound is nothing more than the speed of a pressure wave, as sound is made up of pressure waves.

In addition to the concerns about the pressure spikes, water hammers result in significant dynamic forces on the piping, which can damage pipe rack supports and result in pipes moving off their pipe racks.

A conceptual graphic of the water hammer pressure spike occurrence is shown in Figure 19 below.

Conceptual Graphic of Joukowsky Effect



* The actual velocity of the pressure wave, the frequency of the pressure spike reversals and the closure time needed to prevent a water hammer depends on many parameters including the expansion of the pipe due to the pressure spike, the configuration of the piping and the parameters of the fluid. Each individual piping system would need to be analyzed to determine the actual risk and valve closure time needed to prevent excessive pressure spikes that oscillate back and forth after valve closure.

Figure 19: Conceptual graphic of a water hammer of a ridged pipe with an immediate closure of a pipeline valve showing pressure peaks at the valve closure propagating back upstream and reversing again back to the valve. This pressure spike can cause pipelines, vessels, and valves to over-pressurize.
Source: Self-made

6.9.3. LNG stratification and subsequent rollover

LNG stratification is another avoidable phenomenon that can be prevented by proper operator awareness and actions. LNG inventory stratification can be either fill-induced or nitrogen induced. Other reasons for a stratification may exist, but are not presently discussed here-in (e.g., it is unknown if the liquefaction of LNG containing hydrogen (HENG) might cause stratification – HENG is a not presently being liquefied for commercial LNG facilities).

Stratification can lead to an LNG rollover which is hazardous. Stratification is the layering of the LNG storage tank inventory, whereby the layers do not mix. Typically, this occurs if a low-density LNG layer exists above a denser layer of LNG. The layers do not mix but instead circulate within their own stratum. This stratification is typically caused by an improper placement of LNG added to the tank, but in some cases can be caused by nitrogen as will be explained later in this section.

In a stratified LNG storage tank inventory, the upper layer remains cold as it continuously evaporates at the surface (where the LNG is at its saturated temperature (boiling point temperature)) and the lower layer warms as heat is added from the environment. There is no way to get rid of that heat entering the lower layer, so the temperature of that lower layer warms up. As the lower layer warms, it expands and becomes less dense. Eventually, the lower layer density approaches the same density as the upper layer, and the two layers rapidly mix. This rapid mixing allows the warmed lower layer to rise to the surface, where the lower head pressure causes it to boil-off rapidly. This rapid mixing and associated boil-off is called a “rollover.”

The above discusses two layers of different density LNG strata. However, there can be more than two layers.

A rollover can cause the LNG tank pressure relief valves to release vapor into the atmosphere. In extreme cases, the pressure excursion can exceed the relief valve’s capacity, potentially causing tank damage.

A conceptual rollover is shown in Figures 20 and 21 below. In Figure 20 a layer of liquid methane is placed over a mixture layer of 97% methane and 3% ethane. The methane/ethane layer initially stays in the bottom stratum but as it warms, its density decreases. Eventually, it becomes close to the density of the upper layer, which is when the rapid mixing occurs.

6: methane/ethane: Specified state points (0.97/0.03)

	Temperature (°F)	Pressure (psia)	Density (lbm/ft³)	Enthalpy (Btu/lbm)	Entropy (Btu/lbm-°R)
1	-257.50	24.630	26.862	0.44395	0.0018596
2	-255.00	24.630	26.736	2.4833	0.011885
3	-252.00	24.630	26.584	4.9381	0.023792
4	-250.00	24.630	26.481	6.5795	0.031658
5	-247.00	24.630	26.326	9.0490	0.043353
6	-246.60	24.630	26.306	9.3790	0.044903

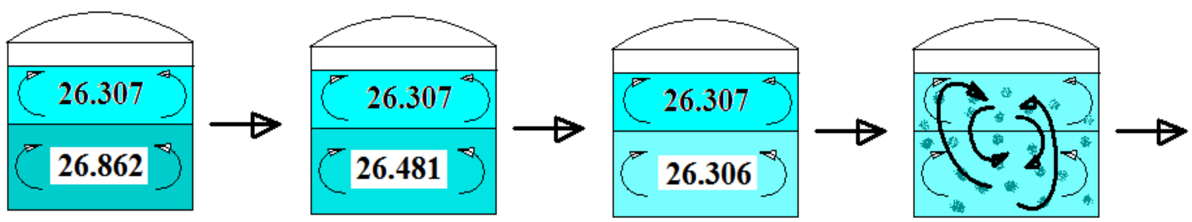


Figure 20: Conceptual data and drawing of a stratification resulting in an LNG inventory rollover
Source: Self-made

6.9.3.1. Fill induced Stratification

A conceptual graphic of a rollover is shown in Figure 21 below. The LNG Industry literature is not definitive about, if the layers flip as shown below, or rapidly mix as shown above. However, it is known, that the resulting breakdown of the layering does result in a high boil-off rate, potentially at rates over the relief valve ratings.

In Figure 21, the term weathered LNG is shown. As the bottom layer heats up and becomes less dense, the upper layer becomes denser as it is preferentially boiling-off the more volatile component, methane. Since methane is the component with the lowest molecular weight, as the LNG of the top layer lessens in methane content, its density increases. This weathering, resulting in increased density, presumes that the initial upper layer of LNG did not contain any nitrogen.

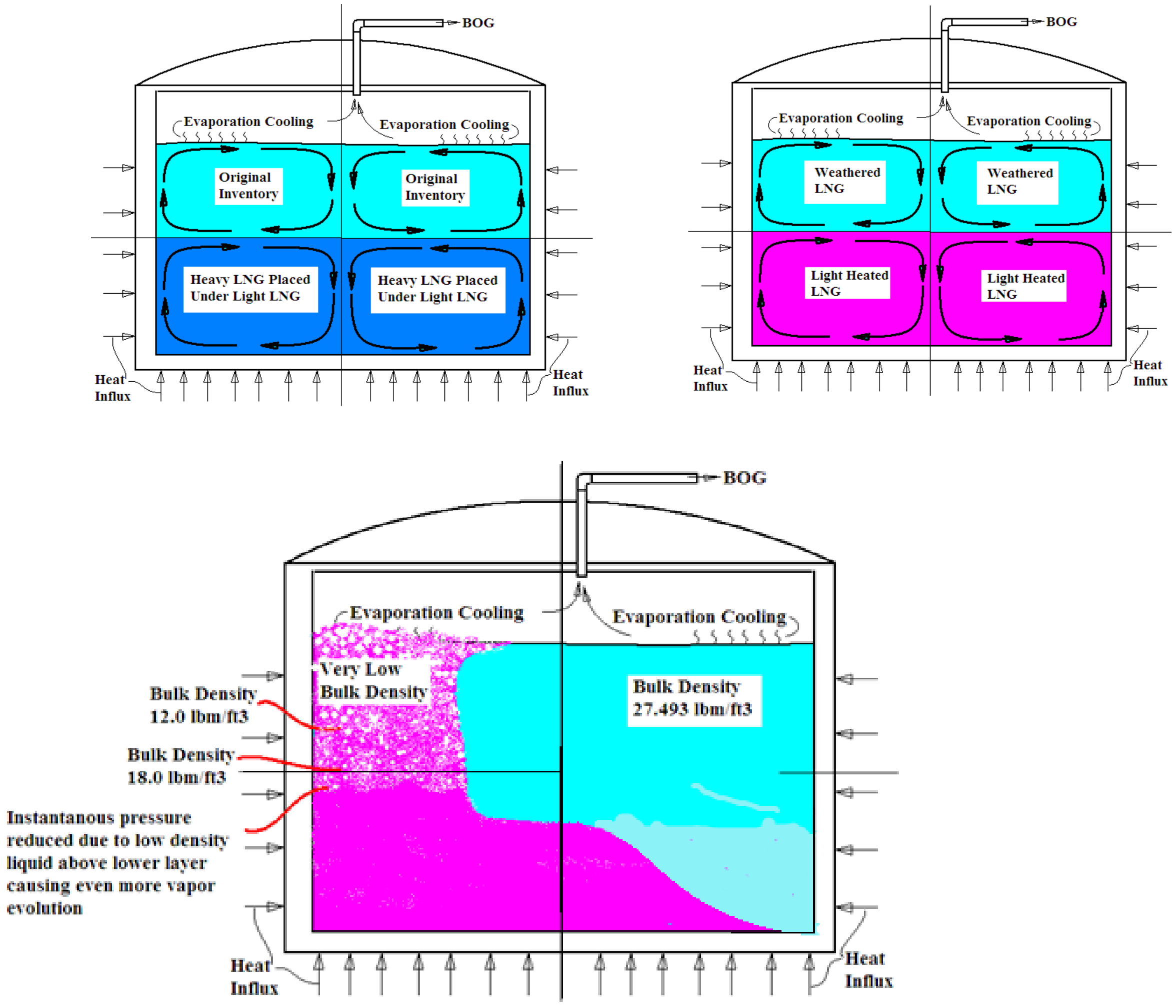


Figure 21: Conceptual graphic of an LNG stratified tank leading to an inventory rollover
Source Self-made

6.9.3.2. Nitrogen induced stratification via nitrogen evaporation

Typically, a well-mixed LNG tank will only self-stratify if the LNG has a high nitrogen content. Typically, 1% or greater nitrogen content is a precursor to self-stratification.

To avoid these hazards, personnel handling LNG are highly trained in the management of LNG, and many passive and active hazard mitigation design measures are incorporated in LNG facilities.

There are two common ways nitrogen in LNG can cause stratification, resulting in an eventual rollover.

Below is a hypothetical evaporation and density profile of a 95% methane and 5% ethane mixture of LNG. As can be seen, as the LNG is warmed by 1 F, at the wall it becomes buoyant (see the density as compared to the bulk density in the tank. This caused it to rise to the surface.

As preferential evaporation of methane occurs, the LNG becomes dense and then travels to the middle of the tank, where it drops to the bottom of the tank. The LNG then warms again as heat is added at the bottom and side of the tank. The cycle continues as the LNG in the tank weathers (becomes richer in ethane and leaner in methane). Note that the molecular weight (MW) (proportional to density) of methane is ~ 16 and the molecular weight of ethane is ~ 30, so that as ethane concentration is increased and methane concentration is decreased, the density of the fluid (for a relatively constant temperature) becomes denser. This occurs because, many more methane molecules with an MW of ~ 16 are evaporated, leaving more of the molecules with a MW of ~ 30 in the LNG (it becomes denser).

Also, as the LNG at the surface evaporates, it cools to the saturation temperature corresponding to the surface pressure. This lower evaporation temperature causes the density to be greater than that of the LNG rising up the side of the tank, resulting in the LNG circulating as shown in Figure 22 below.

This pattern of LNG rising up the side of the tank and dropping down the center of the tank results in the normal LNG storage tank having a continuous convective circulation. This continuous circulation, as will be described later in this work, is critically important to maintaining the net positive suction head NPSH for the pumping of the LNG.

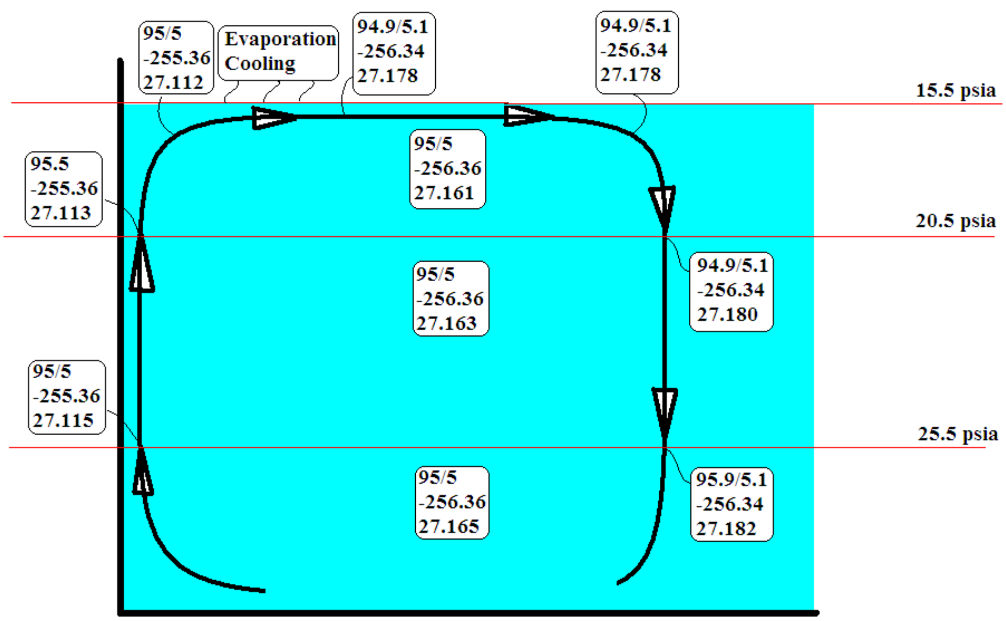


Figure 22: Conceptual graphic of an LNG storage tank undergoing normal convection circulation. The LNG at the bottom of the tank is almost the same temperature as at the surface of the LNG. Thus, the LNG at the bottom of the tank is subcooled as it is under a higher head pressure.
Source: Self-made

Now let's do the same hypothetical analysis using an initial mixture of 94% methane, 5% ethane, and 1% nitrogen.

With this new mixture now preferentially, at the surface as evaporation occurs, more of the nitrogen will evaporate, leaving most of the methane and ethane. The molecular weight (MW) of nitrogen is ~28 and the MW of methane is ~16. Thus, as evaporation occurs, instead of the LNG becoming denser, it becomes less dense. That is because the denser component nitrogen (with a MW of ~ 28) is leaving the LNG and leaving behind the lighter methane (with a MW of ~ 16). Thus, when the LNG that has just evaporated some of its nitrogen reaches the middle of the tank, it is less dense than the bulk density of the storage inventory and it starts to recirculate in a stratum at the top of the tank. See Figure 23 below.

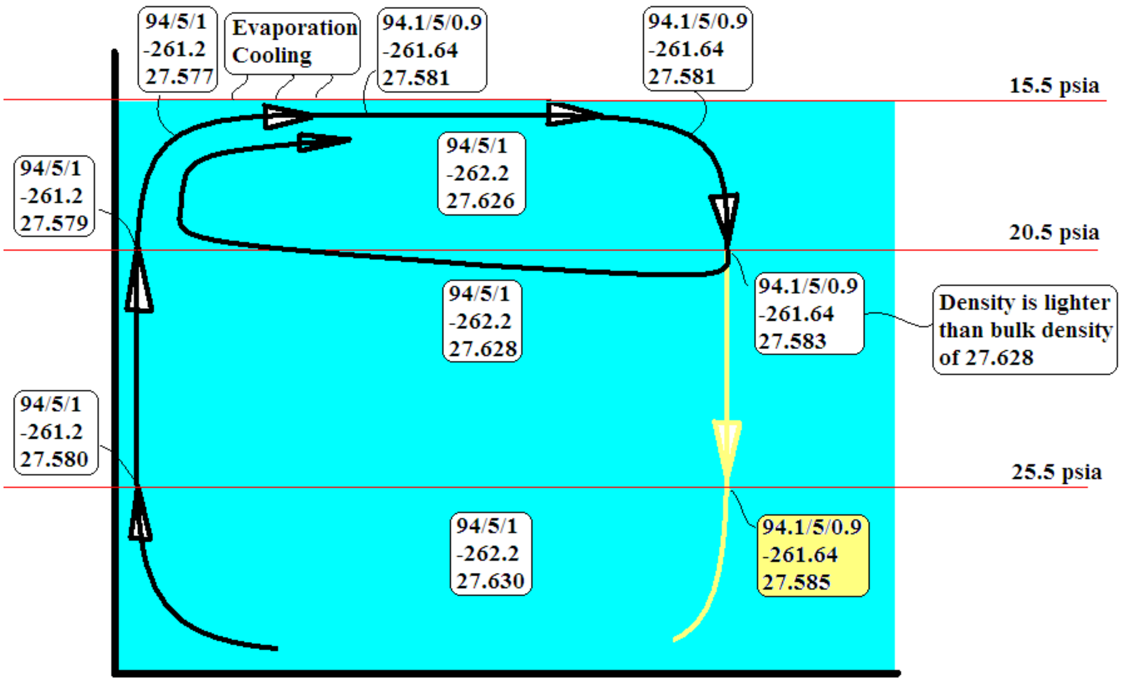


Figure 23: Conceptual graphic of an LNG storage tank with a 1% nitrogen content undergoing evaporation at the LNG inventory surface and a subsequent increase in the LNG density. As a result of the increase in density, two strata start to form.
Source: Self-made

Eventually two distinct strata are formed in the tank. The more the top evaporates the lighter the top stratum becomes and the bottom stratum is left gaining heat without any means of losing that heat gain. As a result, the bottom stratum becomes warmer and as it becomes warmer it expands resulting in it becoming not only warm but less dense. See Figure 24 below.

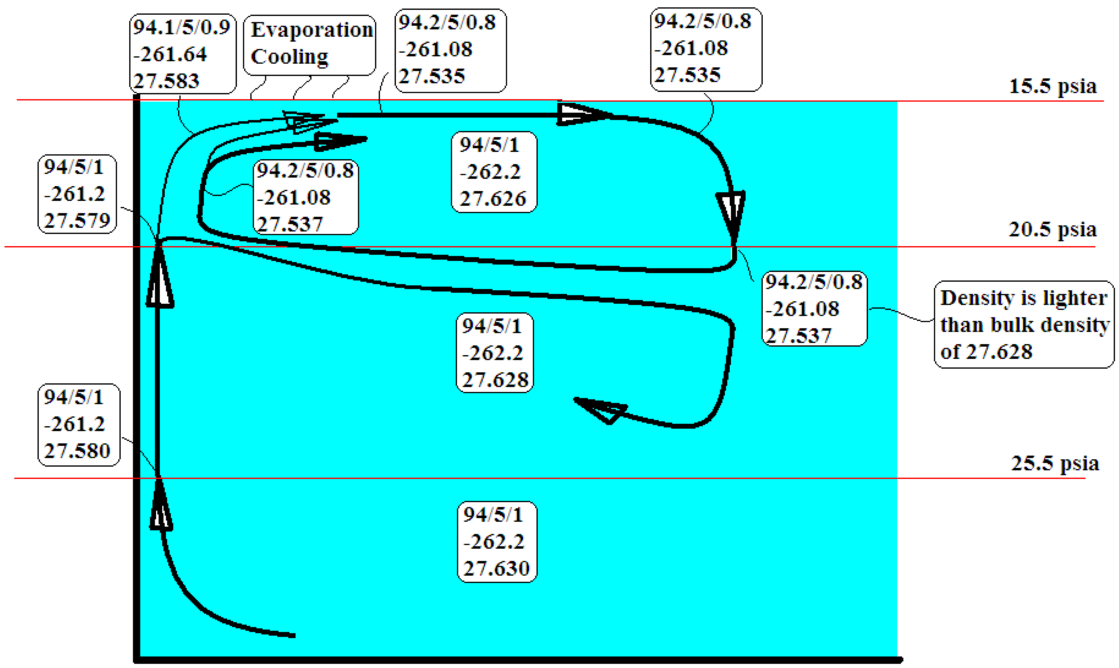


Figure 24: Conceptual graphic of an LNG storage tank with a 1% nitrogen content undergoing evaporation at the LNG inventory surface contacting the vapor space and a subsequent decrease in the LNG density. As a result of the decrease in density, two strata become fully formed as shown in Figure 25.
Source: Self-made

Eventually, after the bottom stratum warms, the bottom stratum becomes close to the same density of the top stratum and the two strata mix causing a rollover as shown by the red arrows in Figure 25.

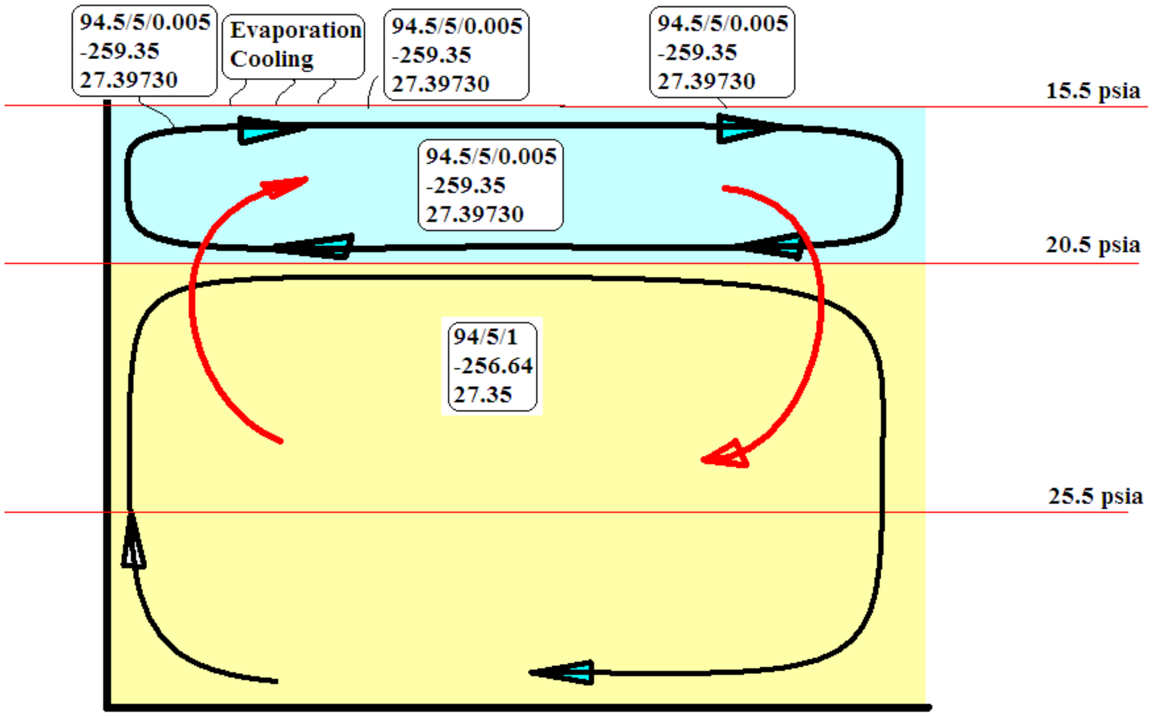


Figure 25: Conceptual graphic of an LNG storage tank with a 1% nitrogen content undergoing evaporation at the top LNG inventory surface and a subsequent decrease in density. As a result of the decrease in density of the top stratum, two strata are fully formed and, over time, the lower layer warms and decreases in density. Once the lower stratum has a density similar to the density of the upper stratum the rollover occurs (see red arrows)
Source: Self-made

6.9.3.3. Nitrogen induced stratification and subsequent rollover due to lower layer boiling
Another mode of stratification and subsequent rollover due to nitrogen in the LNG is caused by the bottom layer boiling. An example of this rollover was publicized due to the Partington rollover in the UK which occurred in 1993.

There are several ways this stratification can occur. One method of having these strata occur is to bottom fill the tank with a denser nitrogen rich LNG under less dense LNG without nitrogen. Over some time, even as the bottom layer is denser than the upper layer, the bottom layer may reach its bubble point.

Once nitrogen bubbles form in the lower layer, the bulk density of the lower layer containing bubbles quickly lowers. As it lowers, it pushes through the upper layer and the bulk density lowers even further as the head pressure lowers further. This is depicted in Figures 26 and 27 below.

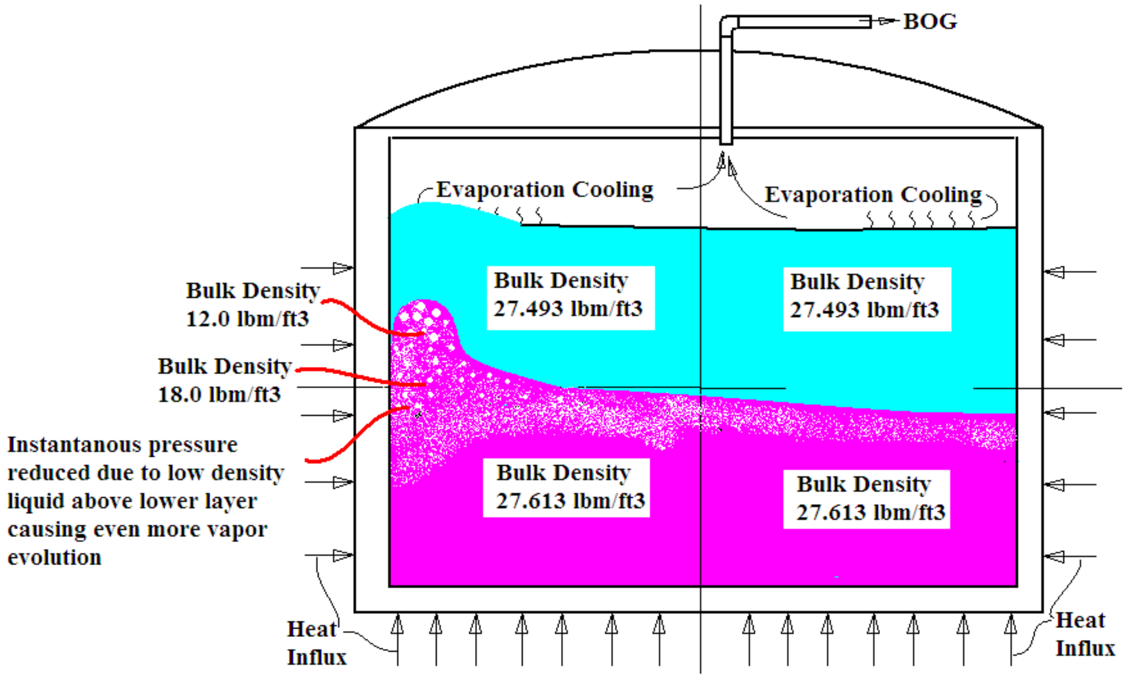


Figure 26: Conceptual graphic of a lower stratified layer starting to boil due to it reaching its bubble point. Even though the lower layer has a higher density liquid, the boiling will cause it to lessen in bulk density and rise through the upper layer.
Source: Self-made

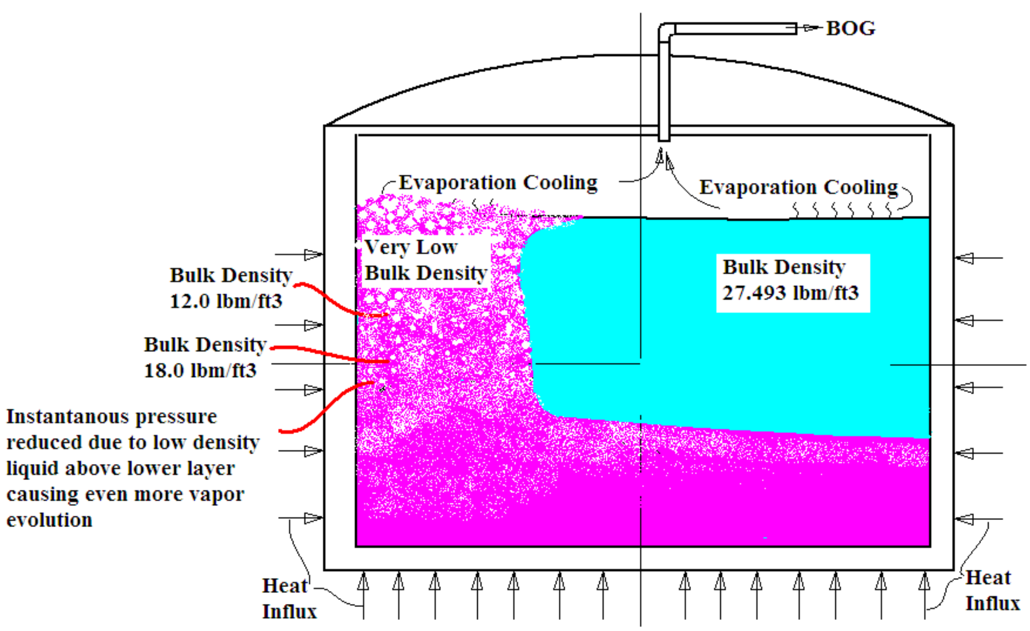


Figure 27: Conceptual graphic showing how a started rollover can continue into a high boil-off condition.
Source: Self-made

6.9.3.4. Rollover prevention

Minor rollovers may occur without much notice. However, a major rollover can not only result in a loss of boil-off gas due to venting the of boil-off gas to the atmosphere, but it may also damage the tank and the potential ignition of the vented gas presents a serious hazard to the plant.

LNG operators must be preemptive in monitor LNG density and temperature from the bottom to the top of the tank. This is possible with many of the newer tanks but is not possible with older tanks that do not have such equipment.

Operators attempt to avoid stratification by top filling heavier LNG onto the surface of light inventory and bottom filling lighter LNG under denser LNG. Doing this is hoped to result in mixing the existing LNG inventory with the LNG being fed to the LNG storage tank. However, such filling can result in the newly filled LNG channeling through the existing LNG inventory and resulting in a lower density LNG stratum under a lighter LNG stratum; resulting in a stratified inventory.

Typically, an indicator of a stratified LNG tank is a lower-than-normal boil-off rate. This occurs because the lower stratum is absorbing heat without any associated boil-off production.

Once a stratification is realized, the LNG operator must remove the lower stratum. This can be accomplished in several ways including any of the following:

- Pumping the lower layer to another tank (top or bottom determined by densities)
- Pumping the lower layer to the top of the same tank. This would be recycling the inventory from the bottom to the top of the same tank.
- Pumping the bottom inventory to the vaporization system of the plant.

In all of the above actions, the goal is to remove the bottom dense layer before it has a chance to warm up, expand and rise to the top of the inventory resulting in a large boil-off event.

In the end, it is much better to prevent a stratification than to mitigate the results of stratification. To do this, an LNG operator needs to follow procedures applied to filling the LNG tanks and allowable LNG nitrogen concentrations. If such procedures do not exist, the plant operators should develop such procedures.

6.9.3.5. LNG storage tank relief capacity

If the barometer were to be constant, the normal boil-off from an LNG tank would be at the designed rate of 0.05% of the storage capacity of the tank per day. This design rate is not a requirement but is the norm for near atmospheric LNG storage tanks.

This boil-off rate may be larger if the barometer were to be dropping and if the tank differential pressure as compared to the barometer were to be kept constant. It may also be much higher if a major rollover were to occur.

In the U.S. the present codes require that storage tank relief valve capacity be designed to manage 3% of the LNG storage capacity boiling off per day. That is 60 times the normal storage daily boil-off. In the U.K. it is common to design tanks to manage up to 100 times the normal storage daily boil-off. Many older tanks in the U.S. were designed to manage only 30 times the normal storage daily boil-off.

The two famed rollover events in the LNG Industry literature (the La Spezia, Italy and the Partington, U.K. rollovers) were in excess of 180 times the normal storage daily boil-off. The actual rate of relief was not defined because it could not be measured beyond 180 times the normal storage daily boil-off.

6.9.4. Geysering

Geysering occurs when a pipe with a horizontal and a vertical leg is filled with stagnant LNG. As heat is added to horizontal pipe section, liquid vaporizes, forcing liquid to be expelled, like a geyser, from the vertical section of pipe. As the vertical section empties, the pressure in the horizontal leg lessens due to the lower head pressure as vapor is pushed into the vertical leg, causing even more vapor to form rapidly in the horizontal leg. The result is that the pipe empties at a very rapid rate. The velocity of the LNG leaving the pipe can be very high and can result in overstressing the pipe connections due to dynamic forces.

Geysering can also result in an oscillating of the pipe as the pipe burps up slugs of LNG. Such oscillations can result in pipe expansion joint cycling and eventually failing. The repairs to such expansion joints may be very difficult if such expansion joints are complicated and connected directly to the LNG storage tank.

Figure 28 below conceptually shows a geysering pipe segment.

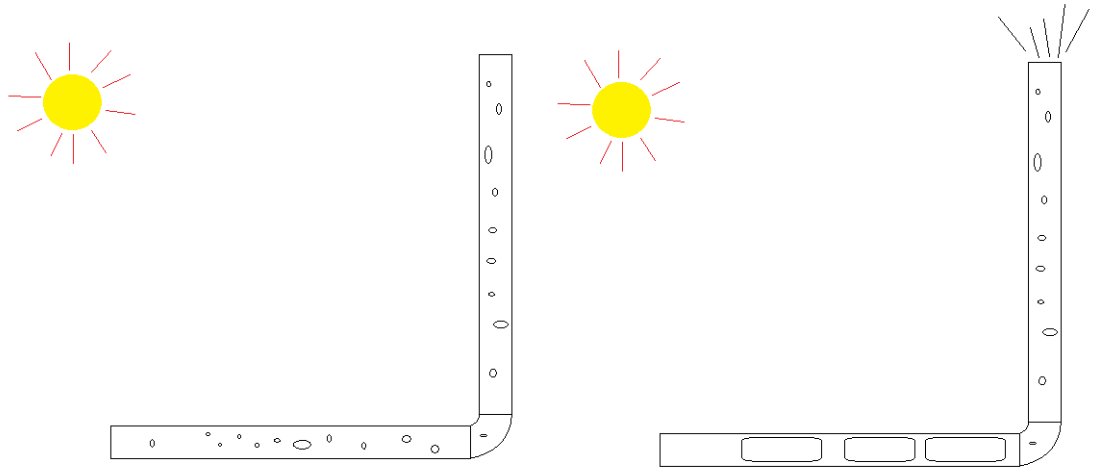


Figure 28: Conceptual graphic of a geysering pipe. Left at the start and right is during the geyering event.
Source: Self-made

6.9.5. Embrittlement

Embrittlement occurs when a material is exposed to temperatures colder than it was designed to withstand. An example of this would be introducing LNG into a carbon steel pipe. Many carbon steels become rapidly brittle as they reach their Nil Ductility temperature. For some carbon steels the Nil Ductility temperature is + 30 F. For some higher quality carbon steels, the Nil Ductility temperature can be lower, typically down to - 40 F.

Embrittlement can be hazardous as it can cause materials to fail in a brittle manner.

Examples of how a brittle failure may occur in an LNG plant include:

- An LNG spray onto the carbon steel outside an LNG storage tank can crack the outer tank.
- A dysfunction of a vaporizer sending LNG out of the vaporizer into the carbon steel sendout pipeline can crack the sendout pipeline.
    - Sprayed LNG can present a hazard if technicians try to use damaged materials
        - Catwalks damaged by LNG exposure
        - Carbon steel gas pipes cracked by LNG etc.
- Boil-off gas injected into an active sendout line is also hazardous (if a boil-off gas heater fails and the outlet gas piping, which is rated for warm gas, sees cold boil-off gas). Also, if the boil-off gas heater fails due to a lack of heating media flow, the heater may rupture as the heating media freezes to a solid.

6.9.6. Rapid cooling of large diameter cryogenic piping via LNG

When allowing LNG into small piping, the LNG cools the top and bottom of the pipe at almost the same rate, and thus, the stresses are small. On larger diameter pipes, this is different. Consider a 30" diameter pipe. As LNG enters the pipe, the bottom of the pipe sees the ~ -260 F LNG as the top of the pipe sees cold vapor. The heat transfer coefficient of the "liquid" LNG is much higher than that of the vapor at the top of the pipe. Thus, the bottom of the pipe will cool down very rapidly while the top of the pipe remains relatively warm.

This uneven cooling can cause extreme tension stresses at the bottom of the pipe as the bottom of the pipe shrinks. Figure 29 below shows a conceptual graphic of a bowed pipe due to the failure to evenly cool down the top and bottom of the pipe at the same rate.

To evenly cool down the top and bottom of the pipe at the same rate, a best practice is to flow cold boil-off gas through the large diameter pipe before allowing LNG to enter it.

Many plants cool down pipes 12" and larger using BOG before allowing LNG to flow into the pipelines. An exception to this is the cooldown of import and export terminal loading/unloading arms. For loading/unloading arms, allowing a small LNG flow to weep into the arms is common. As the LNG weeps into the arms, the boil-off produced moves through the arms, resulting in the pipe downstream of the LNG flow precooling. Many loading arms are 16" in diameter, but some can be larger. This type of cooldown for loading arms is acceptable due to the unique configuration of the arms, that result in the vertical leg producing a large amount of boil-off gas that precedes the LNG filling of the remainder of the loading arm.

Typically, a ship loading or unloading occurs using three liquid loading/unloading arms and one vapor loading/unloading arm. It is also typical for one of the liquid arms to be a hybrid arm (i.e., the liquid arm can be converted to serve as a vapor arm in the event the dedicated vapor arm is out of service).

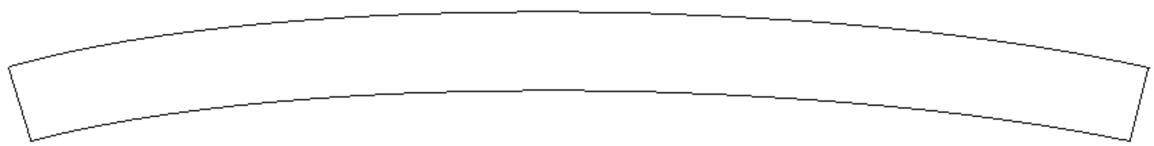


Figure 29: If LNG is introduced into a large-diameter pipe, even if the pipe is made of a material rated for cryogenic service, the bottom of the pipe will cool more quicker than the upper portion. This will cause the bottom of the pipe to shrink while the top does not shrink. This can cause the pipe to bow on the pipe rack and can cause excessive stresses on the bottom of the pipe and on the pipe supports.
Source: Self-made

6.9.7. Ice management

Ice formation concerns include:

- Over-stressed hangers
- Jammed sliding supports
- injury or damage due to falling ice

Since LNG is always colder than freezing water, even in warm climates, ice will form where there is little or no insulation on the piping.

In particular, care needs to be taken to ensure that such ice formations do not result in personnel or equipment damage. Some areas of concern include:

- Ship loading and unloading arms are not insulated, and during the approximately 12 hours of cargo transfer, it is not unusual for large deposits of ice to form. Operating personnel must ensure that falling ice does not injure personnel and that the arms' articulating joints can move freely to account for ship movement or emergency release coupling (ERC) activation. ERC is a device that disconnects the loading arms from the ship if the ship drifts off the berth.
- Connections to the tank are often composed of inner and outer bellows pipe. The purpose of having a bellows is to allow is to allow the pipe to move. These bellows may at times, become fully engulfed by ice. Such ice might impede their ability to flex when needed. Operators must ensure that these flexible bellows retain their ability to move when needed.

- Sliding pipe supports without insulation need to be monitored to ensure that the pipes are free to move as needed.
- Heating elements typically protect in-ground LNG pump cans to avoid having the ground around the pumps freeze and heave. If such heating systems fail, these pump cans can heave up and put excessive stress on the attached piping. In particular, such pumps are typically connected directly to the piping that connects to the bottom of the LNG storage tank penetration. It is important to ensure that the stresses do not transfer to the bottom of the tank penetration.

6.10. Some accident prevention measures

To list the number of accident preventive measures used in an LNG plant would require volumes. Below are just a few of the critical ones.

6.10.1. Over and under pressure relief devices

Pipes and vessels need to be protected from over and under-pressure conditions where such conditions would cause the pipe or vessel to fail. For example, a large vessel such as an LNG storage tank experiencing a vacuum, implodes like an empty soda can would crush when squeezed in your hand. Also, a pipe or vessel would leak or rupture if it were to be over pressurized the same way a bicycle tire would if it were to be pressurized to the point of failure. A conceptual over and under-pressure relief is shown in Figure 30 below.

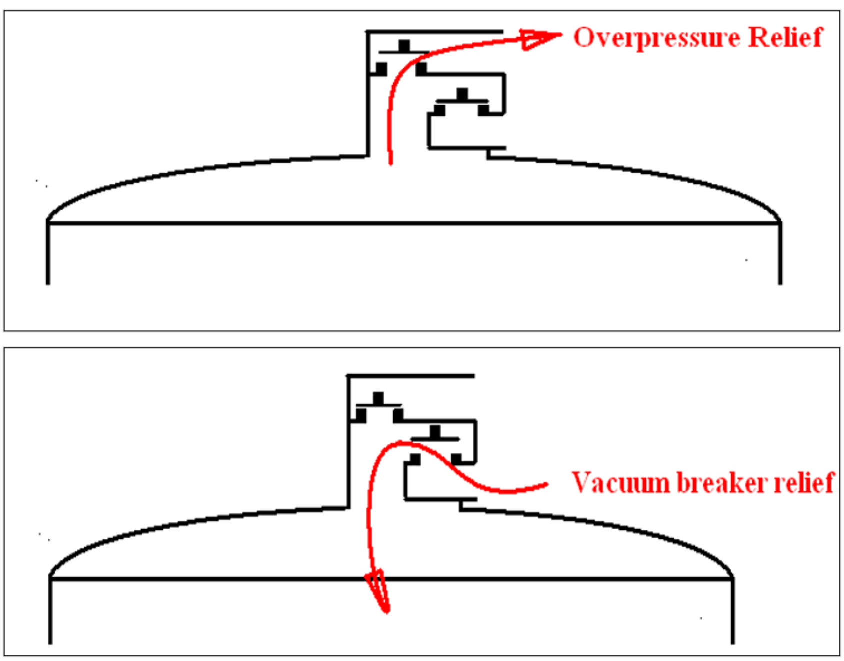


Figure 30: Conceptual graphic of overpressure and under-pressure relief valve.
Source: Self-made

Large vessels (such as a re-condenser) and large tanks, such as an LNG storage tank are also protected by “pad gas,” (also known as cover gas). Pad gas is a supply of gas from the pipeline. If the tank pressure becomes dangerously low, pad gas is flowed into the tank to avoid damage from negative pressure. Although having pad gas enter into an LNG tank is not desirable, due to the pipeline gas containing contaminants, like CO_2 that would freeze, it is an emergency measure to avoid having the tank implode.

Take note that there are many layers of protection to avoid such over and under-pressure conditions. For example, if the LNG storage tank drops to a specified low pressure, a warning alarm is sent to the LNG operator in the control room. If the pressure drops further, an Emergency Shutdown occurs, including shutting the valve that is withdrawing LNG from the tank. If the tank pressure drops even lower, pad gas is deployed and if the pressure drops below atmospheric pressure, then vacuum breaker reliefs activate.

It is essential to have a relief valve in place between any two valves that, if closed at the same time, could trap LNG between them. Such a relief valve is typically called a Thermal Expansion Safety Valve (TESV). TESV valves must be proven to be operationally ready (annual testing of such valves is required by code).

If LNG were trapped between two closed valves without such a relief valve, the pressure would increase until the pipe, or associated valves would fail. If such a failure were to be a rupture, a highly hazardous condition would result. Such a highly hazardous event could be a BLEVE (explained later in this learning).

6.10.1.1. Some types of overpressure devices

Some types of overpressure devices include

- Spring-loaded poppet-type pressure relief valves
- Pilot-operated pressure relief valves
- Rupture disc relief devices (one-time usage – once the rupture disc ruptures, the relieving continues until the rupture disc is replaced).
- Fusible plug which melts out, relieving the cylinder pressure (one-time usage – once the plug melts the relieving continues until the plug is replaced). Of course, the equipment exposed to the high temperature conditions would need to be inspected to determine if it is fit for service before replacing the fusible plug.
- Buckle Pin relief valves. These are typically used for very critical service where a valve is required to nearly instantaneously open to vent out pressure. Buckle pins buckle allowing a latch to release and the valve to spring open and to stay open until manually reset. (Buckle pins are one time usage devices – once the pin buckles the relieving continues until the valve is manually reset and the pin is replaced). It is critically important to ensure the correctly calibrated pin is used to replace a buckle pin. For example, a pin used to buckle at 25 psig may look identical to that used to buckle at 30 psig. The number on the buckle pin must match that which is to be used in that particular valve.

- Weight loaded relief valves. These are the types shown in Figure 30 For such valves the operator needs to ensure that the weight is properly placed on the sealing plate and that the plate is free to move to relieve the pressure when needed. Special care must be taken if such weighted devices are used in underground vaults. If the vault were to flood the buoyancy of the weights and or the weight of water on the plate device will change the relieving pressure of the device.

6.10.2. Lock open (LO) and Lock closed valves (LC)

To avoid requiring a very large quantity of relief valves in an LNG plant, the need for a TESV can be avoided by a procedure that locks a valve open. Such valves require a special procedure to ever close that valve. In the conceptual graphic of Figure 31 below, a relief valve (TESV) is shown between the two line-valves on the right. This same graphic shows no relief valve between the two line-valves on the left of the graphic. The reason no relief valve is required between the two line-valves on the left is because the middle valve is marked as “locked open” (LO). A LO valve, from a design and operational perspective is considered a straight piece of pipe, as the valve is always in the locked open position, unless a special procedure is applied to close that valve with precautions to avoid trapping LNG between two valves. Thus, for this piping configuration, the single relief valve protects the entire pipe between the far left and far right line valves.

Also note that valves may be marked as locked closed (LC) valves. Such a valve is shown in Figure 31 below. LC valves also require a special procedure if they need to be opened.

On the Piping and Instrumentation Drawings (P&IDs), notations as shown below will be included to show which valves are LO and which valves are LC.

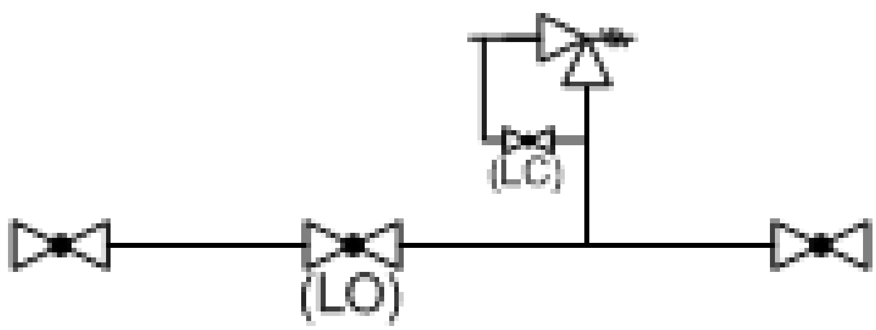


Figure 31: Graphic of a section of pipe (left) not needing a TESV due to the valve in the center of the graphic having a lock open (LO) designation.
Source: Self-made

6.11. Scenario 3

- 3 am, 0 deg F
- Sendout in progress and is needed

- Ship is unloading
- Tank pressures drop rapidly
  - 1.7 psig @ 2am
  - 1.4 psig @ 2:05am (you stop compression)
  - 1.1 psig @ 2:10am (Still dropping)

6.11.1. Scenario 3 – what might be happening?

This can be a serious condition as you never want to experience a vacuum in the LNG storage tank. If the pressure drops further, an ESD will occur, stopping LNG removal from the tank. If the pressures drop to a very low point, pad gas will start to enter the tank. If the tank pressure goes slightly negative, the vacuum breaker reliefs will open allowing air to enter the LNG storage tank (this would be undesirable but necessary to not collapse the tank).

Many things may be causing this lowering pressure condition. Some of the reasons might be one or more of the following:

- The LNG storage tank may be nearly empty and the LNG storage tank was not pre-cooled by recirculating LNG to the top fill line to cool down the vapor space and tank walls. If the LNG vapor is warm, then filling the tank "via a top fill" from the ship may result in cooling down the vapor in the vapor space causing the pressure to drop. This is a plausible cause.
- Sendout may be at such a high rate that the tank pressure drops due to the removal of liquid. This is highly unlikely since ship unloading rates are typically at a very high rate compared to vaporization rate. However, ship unloading may have just started and the unloading rate may not have yet been ramped up to the full unloading rate.
- The barometer may be rising rapidly, causing the differential pressure between the tank and the atmosphere to drop. Unlikely during tank filling since tank filling usually adds flash gas to the LNG storage tank. This is also unlikely as the rate of barometer change is typically not that rapid of a rate.
- One or more tank relief valves may be open. This is a plausible cause.
- Boil-off compressors may be on at too high of a vapor removal rate.
- A major LNG leak in the withdrawal line has occurred. This is unlikely because such a leak would have triggered an ESD via LNG spill sensors (gas detectors and cold temperature in the impoundment areas).

6.12. Several general types of hazard protection equipment

The best protection for eliminating hazardous conditions is to avoid hazards from being present. Typically, if procedures are well developed and strictly followed, and if personnel are effectively trained, most risks can be avoided. However, if risks do occur hazard protection equipment is available to be used. Some of the types of hazard protection include the following:

- Self-contained breathing apparatus (SCBA) and portable oxygen sensors

- Water sprays to make warm vapor clouds to make them buoyant
- Water sprays to protect equipment, structures, and personnel. Water is not to be sprayed into an LNG pool (on fire or not) since this would increase the vapor generation and may cause a Rapid Phase Transition (RPT).
- Portable fire extinguishers (dry powder is the only approved fire extinguisher material for an LNG fire)
- Fixed fire extinguishers (dry powder is the only approved fire extinguisher material for an LNG fire)
- Protective clothing
- Safety integrated system is a programmable control system that takes over the control of the plant to place all or parts of the plant into a fail-safe condition.

6.13. Plant normal and emergency procedures

As stated earlier the best protection for eliminating hazardous conditions is to avoid hazards from being present. Typically, if procedures are well developed and strictly followed, and if personnel are effectively trained, most risks can be avoided. The general requirements of procedures include:

6.13.1. Operating Procedures

Procedure writing must be performed by knowledgeable and experienced personnel and must be field proven by experienced operating personnel. Typically operating procedures contain at a minimum the following:

- Coverage of normal startup, normal shutdown, emergency shutdown, equipment preparation for maintenance, and return of equipment to service after maintenance.
- Procedures need to include:
    - A narrative of the equipment
    - A sketch of the piping and equipment
    - A list of special tools required
    - A list of other procedures that need to be employed (e.g., Lock-out Tag-out, Car seal, and other procedures).
    - A pre-procedure valve line up checklist
    - A place for the technician to check and initial that the step was performed and the time of the performance
    - Starting each line in the procedure with an action word such as open, close, throttle, verify, etc.
        - Each valve or piece of equipment is to be identified by a number and a narrative in the procedure steps (e.g., open block valve 4276, the LNG inlet block valve to vaporizer 301A).

If you find conflicts in procedures, bring them to the attention of your team leader to initiate a review process. Best practices include:

- Using any spare time to review all procedures. This is in addition to formal training
- Perform drills to exercise procedures

6.13.2. Emergency procedures

Emergency procedures are of particular importance. Since emergencies are not normal operations, personnel will unlikely be familiar with such events. Thus, drills and training on implementing such procedures are of critical importance.

Best practices include:

- All procedures should have the same format so that the users would be familiar with their use.
- Having plant personnel conduct round table discussions to ensure emergency procedures cover all plausible emergency events.
- Assure that all responding personnel have adequate training and access to emergency procedures
- Have a program to ensure that procedures are current, fully proofed, and correct. Only a qualified procedure writer working with an expert operating person should perform such reviews.
- If any deficiencies are identified, these should be corrected as soon as possible, and responding personnel need to be notified that edits are pending.
- Whenever an emergency or accident does occur, a scribe should be assigned to record the actions taken. Then a follow-up investigation needs to be performed to gather lessons learned. Upon review of the lessons learned, if appropriate, the procedures would need to be modified based on lessons learned

It is not unusual to find that an accident was caused by not following procedures or by following procedures that were not up to date. Operator complacency and thinking that then know how to do the task without following the step-by-step checklist is hazardous.

Emergency procedures typically contain criteria to determine when an event is controllable, when outside assistance needs to be called in (local fire department etc.) when the regulatory agency needs to be notified, what levels of the chain of command within the company need to be notified and when an evacuation of the plant is required.

All personnel in the plant, including visiting personnel, need to be trained to know the emergency alarm horns and to know where to muster if an evacuation is required.

The main focus of the emergency procedures is to limit the risk of injury to the public, the plant personnel, the plant equipment, and the environment.

6.14. Management of Change (MOC)

It is common for changes to occur in any petrochemical plant. Such changes may be, what is believed to be, an improvement to the process or to a procedure. However, such changes need to be highly scrutinized to ensure that such changes do not produce unforeseen hazards.

For example, connecting a nitrogen line to the compressed air system may be considered to be a viable way to have a backup supply to the air system for controlling valves. This may be so, but safeguards need to be put in place to make sure venting instruments do not vent within a confined space where people may enter. Also, safeguards need to be in place to ensure that there is no way the air might migrate into the nitrogen system. If the air were to contaminant the nitrogen system, there would be a possibility of purging a vessel with air instead of nitrogen.

The process of a performing a robust technical safety review of such changes to equipment and procedures is called performing a Management of Change process (MOC)

If strict adherence to a MOC process is not enforced, changes to plant equipment and procedures may be forgotten and, the resulting hazard may result in an accident that occurs years in the future.

6.15. Distributed control system (DCS) or similar alarm and control systems are key to safety

In larger plants, a DCS is used. In smaller plants, programmable logic controllers (PLCs) are used to communicate data and for the LNG operator and send controls to adjustable plant components (such as to open and close valves and start and stop equipment). Some parts of these systems may include:

- Human Machine Interface (HMI) – computer screen keyboard and mouse
- Tank gauging systems
- Electrical system monitoring and control
- Automatic process and control systems
- Alarm monitoring, handling control, and inhibits
    - Inhibits are logic programed into the systems to prevent hazardous events. E.g., an LNG inlet valve to a vaporizer is inhibited from opening unless the hot heat transfer fluid is flowing to the vaporizer.
- Alarm Priorities
    - A Alert
    - L Low
    - H High
    - E Emergency

Alarm level determination is plant specific. An example of a hypothetical alarm level determination based on risk is shown below in Table 3.

	Consequence	Low	Medium	High
	Urgency	Alert	Alert	Alert
1	Not urgent	Alert	Alert	Low alarm
2	Needs attention	Alert	Low alarm	High alarm
3	Requires correction	Low alarm	High alarm	Emergency
4	Immediate	High alarm	Emergency	Emergency

Table 3: Conceptual table of alarm severity based on consequence and urgency.
Source: Self-made

The plant operator at the control room is monitoring a large amount of data from the various control systems (DCS or PLCs). This data may include:

- DCS interfaces with Local Control Panels
- Metering Units
- Fuel Gas Unit
- Unloading arms
- SCVs
- BOG Compressors

6.16. Safety Integrated Systems

The Safety Integrated System (SIS) is a programmed control system explicitly designed to take control of the plant in the event of an emergency and shut down the plant as needed to render the plant safe.

6.16.1. Emergency Shutdown (ESD) - Typical Numbering Schemes

The emergency numbering system is plant unique. A possible numbering scheme is shown below.

Emergency

EMERGENCY

- Level 1 ESD: Shuts total plant and utilities
- Level 2 ESD: Shuts total plant but not utilities
- Level 2A ESD might be a liquid system shutdown

- Level 3A ESD might be a vapor system shutdown
- Level 4X ESD: Shuts a portion of the plant
  - 4.1 Might be a shutdown of the equipment on a jetty
  - 4.3 Might be a shutdown of an LNG storage tank
  - 4.5 Might be a sendout general shutdown
    - 4.5.1 Isolation of HP sendout system (recondenser, HP pumps, vaporizers, etc.)
- Level 5X ESD: Might be a shutdown of the equipment on a specific berth
- Process shutdowns might be due to abnormal conditions that shutdown individual pieces of equipment

Shutdowns can be automatic or manually triggered. It is important for operational personnel to realize that they may need to trigger a shutdown as shown in Figure 32 if it is necessary to protect the public, plant personnel, equipment or the environment.

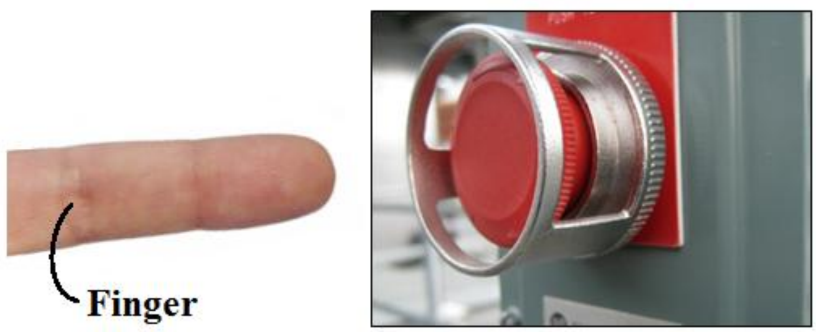


Figure 32: Conceptual graphic showing an operator triggering an emergency shutdown.
Source: Self-made

The control systems of an LNG plant must be carefully designed and programmed. These systems include the interface of the SIS with the DCS and the Fire and Gas system (discussed in the next section). In short, although the SIS overrides the DCS control of the plant, the SIS does send alarm logging messages to the DCS. Although the Fire and Gas (F&G) system is independent of the DCS and the SIS, the fire and gas system sends signals to the SIS which may result in the SIS triggering an ESD. The F&G system sensor activation is also reported to the DCS for data logging. This is conceptually shown in Figures 33 and 34 below.

6.16.2. Fire and Gas System (F&G)
The objectives of F&G system is:

- Protection of the public
- Protection of plant personnel
- Protection of equipment

- Protection of the environment

These objectives are accomplished by:

  - Early detection of flammable gas
  - Early detection of fires
  - Shutting down equipment if needed (via sending signals to the SIS)
  - Triggering automatic hazard mitigation equipment (via sending signals to the SIS)
  - Sounding alarms as needed

- Alerts personnel to potentially dangerous conditions
  - Gas detectors
  - Flame detectors
  - Smoke detectors
  - Temperature detectors

6.16.3. Example of a process being controlled by a DCS when a fire alarm or pressure signal triggers the SIS into action

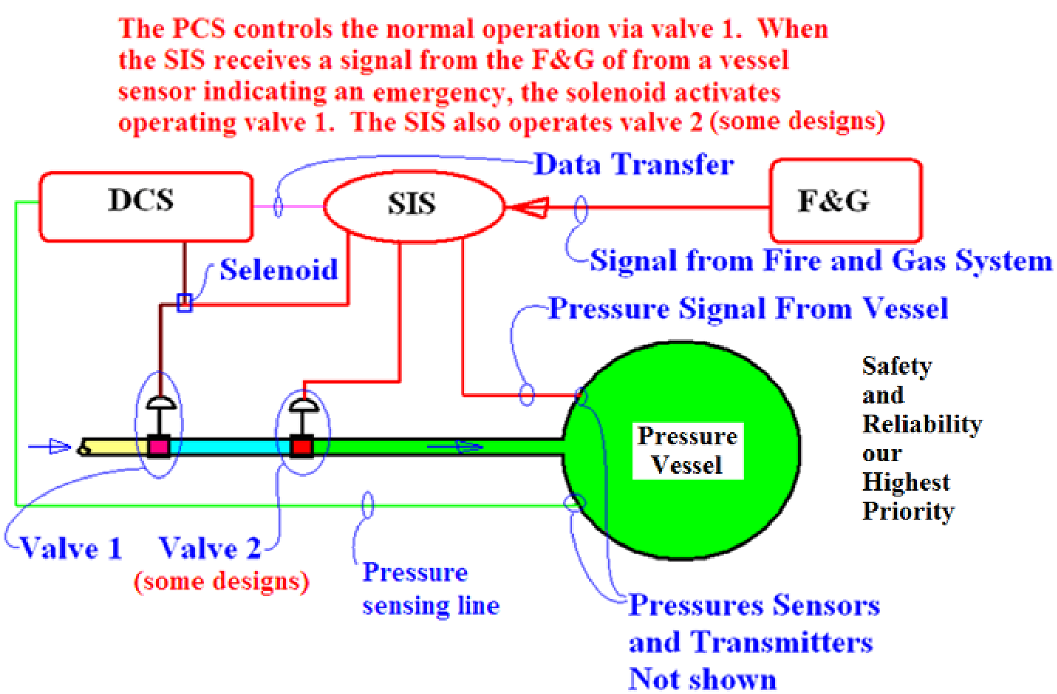


Figure 33: Conceptual graphic showing how under normal conditions, the Distributed Control System (DCS) controls the process. When an emergency occurs (i.e., overpressure of the vessel or a fire) the Safety Integrated System (SIS) takes over control of the plant shutting down valves via solenoids. The DCS can no longer control the ESD valves as the SIS is now in control; however, data logging, alarms and alerts are still reported to the DCS.
Source: Self-made

6.16.4. Example of generic partial ESD flow chart - using a hypothetical numbering scheme

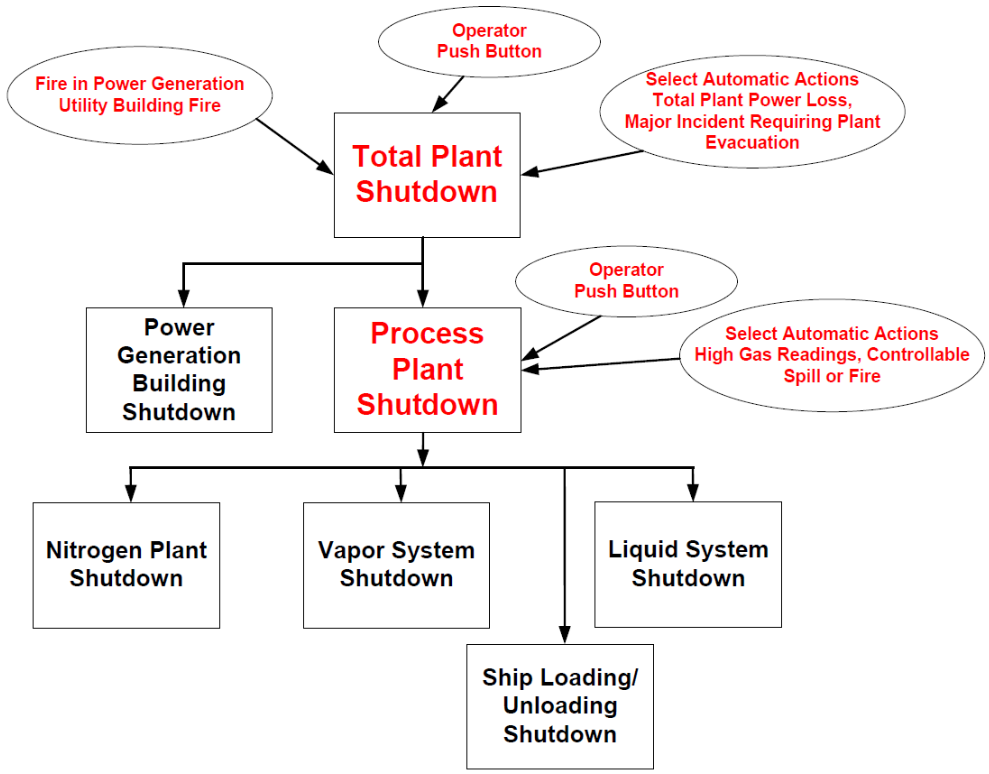


Figure 34: Conceptual configuration of an ESD scheme. Note all actions trigger only in the direction of the arrows. Thus, an ESD 3 Vapor triggers only actions downstream of the ESD 3 Vapor; an ESD 5 Offshore triggers only actions downstream of the ESD 5 Offshore. An ESD 1 shuts down the entire plant except for the power turbines.
Source: Self-made

6.16.5. Types of ESDs

A total plant shutdown of both process and utilities would typically occur only if there is a fire in the utility building or if initiated by a plant operator. It is the most severe type of shutdown because not only does it shut down the LNG plant, but it also shuts down the utility building which incorporates power supplies other than UPS and Emergency power. Also, the utility building may include compressed air and other support facilities required for the LNG plant. However, keep in mind that every plant is unique and the components of the utility building may be different from plant to plant. A total plant shutdown which includes utilities may subsequently require a plant evacuation.

A cause for a complete plant shut, down including the utility building might be an uncontrollable fire in the utility building itself. It should be noted that some plants are isolated from the electric grid and produce their own power. Thus, loss of generation capability renders the plant with only battery powered uninterruptable power supplies and emergency electric power generation. Other facilities powered via the electric power grid are vulnerable to power grid outages outside the plant's control. I worked at one plant where the plant director told me that the plant experienced and earthquake and a subsequent electric outage. When the electric outage occurred, not one of the emergency generators was able to start!

A total process plant shutdown is less severe than a complete plant shutdown since it retains the utility building in operation. With the utility building in operation electric generation, compressed, air and other plant support processes are maintained to allow the plant to be more easily brought back on line after the process shutdown.

A partial ESD is the shutdown of a specific function of the LNG plant. For example, an LNG liquid shutdown would shut down all LNG liquid processes in the plant. This would include the shutdown of LNG pumps, the closure of all LNG transfer valves and the internal tank valves.

A localized ESD shuts down a sub-plant system, such as an air separation unit ESD to shut down the generation of nitrogen or a north berth ESD to shut down the ability to load or unload ships from the north berth.

An equipment ESD would shut down a specific piece of equipment. An example would be the shutdown of a boil-off compressor experiencing low oil pressure.

6.17. Rolling black-out concerns

During times of heavy gas demand, both the gas and the electric utilities compete for available supplies of natural gas. To avoid an escalating total electric grid shutdown, electric companies sometimes initiate rolling blackouts. Rolling blackouts are intentional shutdowns of parts of the electric grid to avoid the total electric grid from being overwhelmed by the power demand. The total electric production capacity might be inadequate for a host of reasons. Thus, the need to assert rolling blackouts may become necessary.

Rolling blackouts during high gas demands periods are extremely difficult for a gas utility to manage. This is because the gas system loses its load diversity during a blackout. Load diversity means that, at any given moment, some thermostats are satisfied even during peak gas demands periods. Thus, when there is an extremely cold day, the gas demand is not equal to every piece of heating equipment being online simultaneously.

However, when an electric outage occurs, every thermostat shuts the gas heat in every building. Thus, when the electric power is restored, every heating system in the entire area calls for heat (there is no load reducing benefit of heating load diversity). This surge need for gas supply can exceed the piping design capacity for that area.

Also, if the local LNG plant is supplied with electricity by the electric grid, the ability to vaporize LNG may be lost during a rolling blackout. When power is restored, the LNG plant may take 15-30 minutes to return to full sendout capacity. During that period, the gas load center may have already experienced such low pressures, that load shedding of that geographic area might be necessary.

Many LNG facilities rely on self-generating electric power to lessen the impact of an electric outage. However, a caution mentioned here is that, if a plant is designed to operate on either grid or self-generation, that plant should test operate at total sendout capacity using grid power and self-generation power. Any equipment to work on a stand-alone basis is only as good as it is proven to be, by testing it under full load conditions.

6.18. ERC release causes offshore ESD - ESD does not cause ERC release

At import and export terminals, LNG tanker ships are loaded or unloaded with LNG at a very high rate. The arms connecting the ship to the shore are articulating arms allowing the ship to move as the loading/unloading occurs. These arms have a limited amount of normal movement. If the ship moves off the berth beyond a specified amount an, alarm is sounded. If the ship continues to move a ship loading or unloading emergency shutdown will occur. This ESD will shut down the loading/unloading process. If the ship continues to exceed its allowable movement, the emergency release coupling (ERC) will disconnect the ship from the loading and unloading arms. The ERC is sometimes called a PERC, where the "P" stands for power.

The ERC or PERC consists of two ball valves and a coupling that opens as soon as the valves close.

An ERC/PERC will always trigger a loading/unloading ESD. However, a loading/unloading ESD will not trigger an ERC/PERC activation (see Figure 35 below).

The only actions that will trigger an ERC/PERC activation are:

- The ship moving off the berth to the extent that will trigger the ERC/PERC
- The on-shore operator manually triggers the ERC/PERC release (typically via a button)
- The on-ship operator manually triggers the ERC/PERC release (typically via a button)

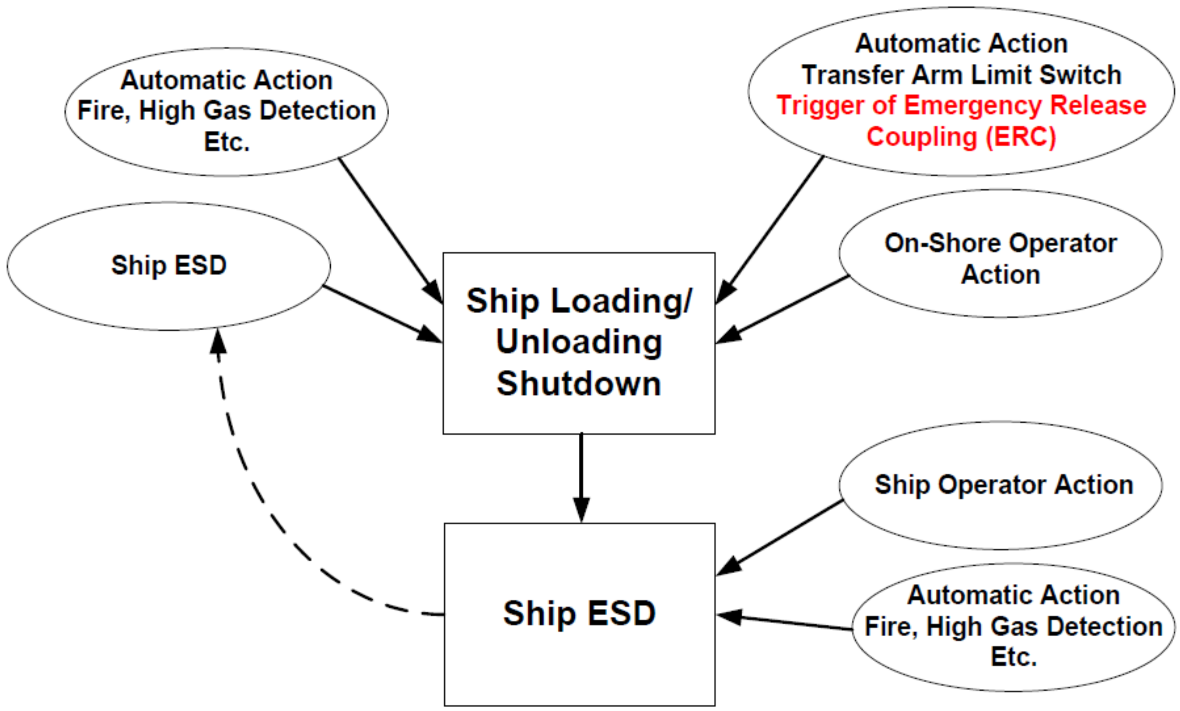


Figure 35: Flow graphic showing that a ship loading/unloading ESD does not cause an ERC activation, but and ERC activation causes a loading/unloading ESD
Source: Self-made

6.19. Berthing line tension monitoring system, mooring release hooks, and berthing velocity safety features

6.19.1. Mooring hooks and rope tension monitoring

The ship mooring ropes are attached to quick-release hooks as a safety feature on import and export terminals. These hooks, when dropped release the mooring ropes from on shore.

When the ship is docking, a capstan (a vertical axis rotating drum) pulls a small rope connected to the large diameter mooring lines. The large diameter mooring lines are placed on the hooks, and a winch on the ship tightens the ropes.

As a safety measure line tension monitoring software is used to monitor the tension on each of the mooring lines. This software displays graphical data to the LNG operator control room. If the tension on a particular line becomes too high, the ship can adjust the tension on that rope or the other mooring ropes. It is typical to have ~ 16 mooring lines to secure the ship.

In an emergency, the quick-release hooks can release the ship from the berth. In one instance, not in the United States, an earthquake occurred, and the plant personnel were alerted that a tsunami was to follow. Because the tsunami was coming, it was decided to release the ship and have its head out to the ocean. Due to the earthquake, the plant's power was unavailable and the emergency generators did not come online. When the operator tried to release the hooks from the control room, they failed to release. An outside operator then went to each hook and released the mooring lines locally at each hook. The ship went to sea to avoid being at the berth when the tsunami arrived. The tsunami was not massive and no further damage to the plant was realized beyond that which the earthquake did.

It should be noted that, other than the free-standing prismatic type B LNG tanker tanks, LNG transport ships are not designed to travel partially loaded. This is because the spherical and membrane type ships are significantly affected by cargo sloshing when partially loaded. The spherical and membrane ships become less stable if partially filled during transport and the membrane ship can experience inner membrane damage. The free-standing prismatic type B LNG tank has inner baffles that mitigate sloshing.

6.19.2. Ship mooring position and velocity sensors

When a ship is mooring, for safety, it is critical to control position and velocity at which the ship approaches the berth. LNG tanker ships have a large sail area (the area which is above water and affected by wind forces). To avoid the ship from approaching the berth at too high of a velocity, an on-shore radar approach device and software is used to give feedback data to the berthing personnel. Tug boats are used to accomplish the mooring adjust the approach velocity.

6.20. Valves are designed with failure modes

Valves are used for control of fluid flows. ESDs result in a valve going to its failure mode position by venting off the air supply to the valve. This venting of supply pressure to the valve is typically via a solenoid valve held into position by an electric power supply. When the power to that solenoid stops, the solenoid vents the supply pressure to the valve. During an ESD most hydrocarbon transfer valves fail closed. If there is an explosion which destroys the air supply to the valve or the electric supply to the solenoid, the valve moves to its failure mode position.

As a safety feature, depending on the use of the valve, the valve can have many different failure mode positions as follow:

- Fail Closed
- Fail Open
- Fail As Is
- Other

Figure 36 below shows an ESD valve with a fail open mode. Note that when air is vented from the valve, the spring in the valve pushes the valve into the up or open position.

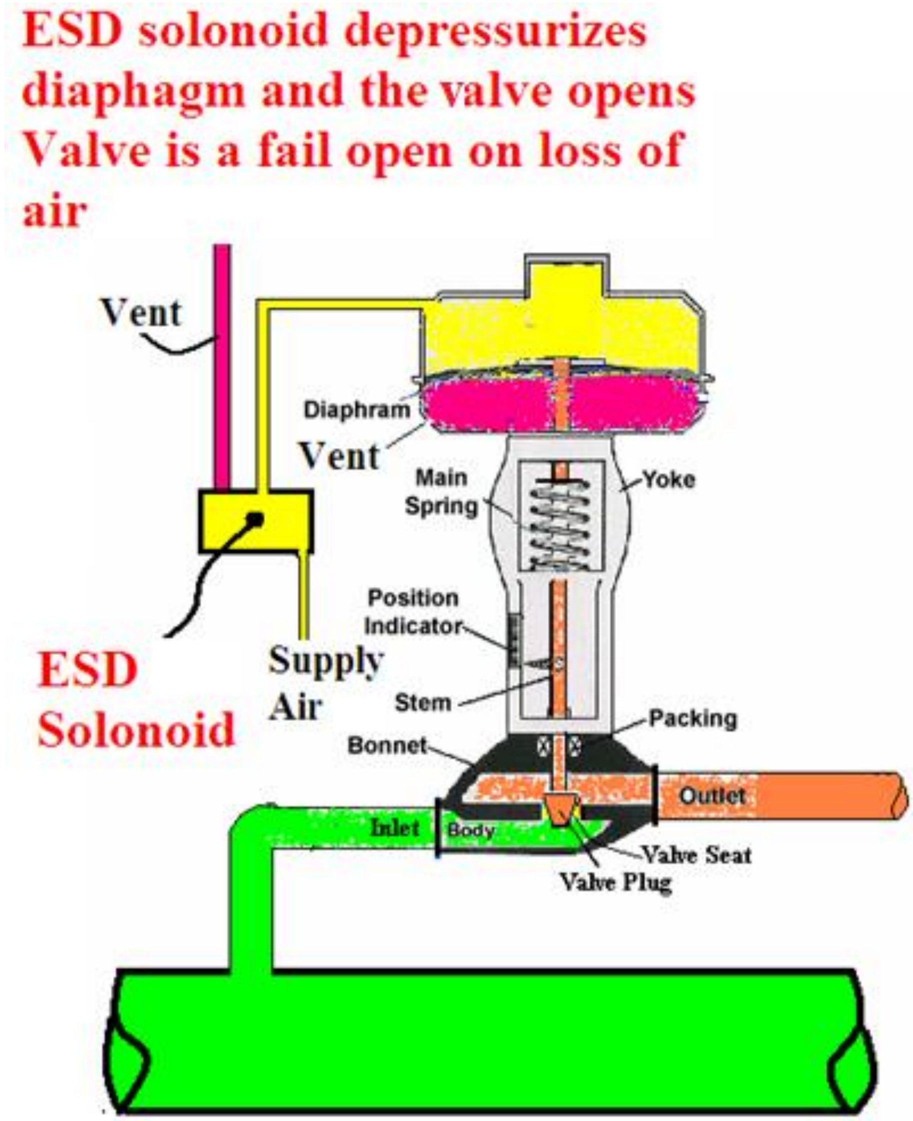


Figure 36: Conceptual image of a "fail open" control valve. Notice that as the air supply to the valve is removed the spring pushes the valve stem upward. As the valve stem rises, the valve opens.
Source: Self-made

6.21. Safety systems that are designed to maintain operability

There are hundreds of hazard sensors in an LNG plant. Since a hazard sensor may malfunction, it is common to use a voting system to trigger an ESD. If there was only one sensor for each hazard detection system and it were to malfunction, nascence shutdowns would occur. A voting system typically uses 3 sensors to determine if the triggering of the sensed parameter is real or not. Using 3 sensors, if 2 out of 3 sensors signal a hazard, the hazard is considered real and an ESD would be triggered.

Using a voting system, a single sensor triggering results in an alarm and a dual sensor triggering above a predetermined level result in an ESD. Below is an example of a voting system that might be used in a fire and gas design.

- Alarm to operator and log data
  - One impoundment cold temp sensing
  - One or two low-level gas sensing
  - One fire signal
  - Single sensor Low recondenser level
- Emergency shutdown and log data
  - One impoundment cold temperature sensing and one gas detector sensing
  - Two high-level gas detectors
  - Two fire detectors sensing

A conceptual voting system is shown below in Table 4.

Generic Safety Cause and Effect Diagram

			ESD 1 CAUSES ESD 2,3,4,5				
	F&G ALARM or OTHER OPERATOR ALARM	**FIRE FIGHTING SYSTEM ACTIVATION**	**ESD 1**	**ESD 2**	**ESD 3**	**ESD 4**	**ESD 5**
CAUSE							
1 UV sensor triggered							
2 UV sensors triggered							
1 cold impoundment sensor							
2 cold impoundment sensor							
1 Point IR Gas detection (low)							
2 Point IR Gas detection (low)							
1 Point IR Gas detection (high)							
2 Point IR Gas detection (high)							
Ship drifts slightly off mooring							
SHIP drifts off mooring to ESD							
PERC Release							

Table 4: Conceptual voting system table – orange means alarm, red means shutdown, and blue means shutdown caused by an ESD 1

6.22. Process controls for safe operation

An LNG plant is a complex operation that requires many automatic controls. These controls need to be correctly set up by knowledgeable and experienced instrument personnel. Proper proportional band, reset, and integral settings are critical for each instrument to ensure that systems work in concert with other instruments across all operating envelopes.

Having instruments work well at total plant capacity does little good for safe and reliable operation if such instruments do not operate properly at a lower plausible plant capacity. In particular, time delays and operating oscillations must be considered when setting up such controls. For example, if a vaporizer heat supply controller uses the outlet LNG vapor temperature to control the heat flow the vaporizer, the design engineer needs to compensate for the time delay so that the controller does not oscillate from very-hot to very-cold LNG vapor leaving the vaporizer.

Also, it is a best practice to make moves in set point changes in small increments to avoid plant instability. Making rapid moves could cause plant instability and resulting hazards.

Some controlled parameters in the plant include:

- Temperature monitoring and control (foundation heating, vaporizer outlet temperature, etc.)
- Recondenser level control to ensure sufficient net positive suction head (NPSH) for proper pump operation
- Tank pressure control
- Tank vacuum control
- High-pressure safeguards
  - Stops loading into tanks, operates reliefs, etc.
- Level and density monitoring (with the redundancy of sensors)
- Low-pressure pump recycles and discharge volume control
- High-pressure pump recycles and discharge volume control
- Vaporizer sendout flow control

6.23. Hazard detection sensors

Fire and gas detectors used to alert personnel of a potentially dangerous condition or to trigger emergency shutdowns and/or fire protection systems automatically include:

- Temperature detectors
  - Caution - some gas detectors require Oxygen to Operate
- Gas detectors
- Smoke detectors
- Flame detectors

6.23.1.1. Open Path Gas Monitor

For the most part, two different types of gas detection are used; open path detectors and point source gas detectors. Open-path gas detectors typically use a transmitter and a receiver with two different frequency infrared (IR) beams sent from the transmitter to the receiver. Gas molecules attenuate one IR frequency and not the other. Thus, if the receiver reads both IR beams as being of the same amplitude, it is concluded that they did not encounter any hydrocarbon molecules. However, if the beam attenuated by hydrocarbon molecules is received at a lower amplitude than the other beam, it is concluded that hydrocarbon gas is present between the transmitter and receiver. In that case, the difference is measurement is correlated to a gas reading by the Fire and Gas (F&G) system and the LNG operator is alerted. The F&G system communicates this information to the SIS and depending on the voting system and the severity of the gas reading, other actions may occur (triggering ESDs, activation of fire protection systems etc.).

It is typical to use a 4 to 20-milliamp (mA) instrumentation link to communicate the signal to the F&G system and the operator. Typically, four mA is calibrated to be a zero-gas reading and 12 mA would be a 50% of-scale gas reading, and 20 mA is calibrated to be 100% of-scale. If a zero-mA reading is transmitted, it is interpreted as a malfunction (it could be a beam blocked by a vehicle or a broken wire, etc.).

Since the beam gets attenuated by gas molecules across the entire length of the sensed field, the sensor cannot distinguish between a high gas concentration over a short distance or a small concentration of gas across a long distance. Thus, the gas reading for an open path gas detector is displayed as either LEL•meter or PPM•meter. PPM means parts per million, and LEL means lower explosive limit. One LEL is 5% gas in air. Thus, 1 LEL•meter is a number of molecules detected equivalent to 5% gas (1 LEL) for a distance of 1 meter. However, 1 LEL•meter could be 2.5% gas across 2 meters or 1% gas across 5 meters or 0.5% gas across 10 meters. The same holds true the reading is given in PPM•meter. For example, a reading of 100 PPM•meter might be 100 ppm across 1 meter or 10 ppm across 10 meters.

The reading scales are typically:

- 0 - 5000 PPM m (0 - 0.5%Gas) m
- 0 - 5 LEL m (0 – 250,000 PPM) m

6.23.1.2. Understanding readings

To better understand the readings, see the Tables 5 and 6 below:

Size of gas cloud	Display	reading
20% LEL x 1 meter	0.2	LEL•meter
10% LEL x 2 meters	0.2	LEL•meter
100% LEL x 2½ meters	2.5	LEL•meter
50% LEL x 5 meters	2.5	LEL•meter
100% LEL x 1 meter	1.0	LEL•meter

50% LEL x 2 meters	1.0	LEL•meter
25% LEL x 4 meters	1.0	LEL•meter
10% LEL x 10 meters	1.0	LEL•meter

Table 5: Conceptual display of an open path gas detector reading in LEL•meter
Source: Self-made

Size of gas cloud	Display	reading
100 PPM x 1 meter	100	PPM•meter
100 PPM x 2 meters	200	PPM•meter
1000 PPM x 2½ meters	2500	PPM•meter
500 PPM x 5 meters	2500	PPM•meter
2000 PPM x 1 meter	2000	PPM•meter
500 PPM x 2 meters	1000	PPM•meter
250 PPM x 4 meters	1000	PPM•meter
100 PPM x 10 meters	1000	PPM•meter

Table 6: Conceptual display of an open path gas detector reading in PPM•meter
Source: Self-made

6.24. Point Source Gas Detector

There are two commonly used types of point source gas detectors.

6.24.1. Pellistor sensor type

This type of detector typically has two different reading scales; 0 – 100% LEL and 0 – 100% gas in air. When the 0 – 100% LEL scale is selected the detector uses a platinum catalyst to burn small concentrations of gas on a heated platinum wire. The platinum is the catalyst that allows the gas to burn at a concentration lower than 5% gas in air. As the gas burns the temperature of the wire changes and the gas concentration from 0 to 100% LEL is reported to the F&G system or to the LNG operator (if it is a portable hand-held detector). Keep in mind 100% LEL is 5% gas in air or 1 LEL.

A downside of this type of gas detector is that oxygen must be present to burn the tested sample on the 0 to 100% LEL. Thus, trying to test using the combustion process for a sample of 100% gas or 5% gas in nitrogen (not air) would not register, as no oxygen would be in the sample. Such a wrong reading would give and operator a false sense of security.

When using this type of detector on the 0 – 100% gas in air scale, the sampled gas passes over a heated wire. Since natural gas has a different specific than air, the cooling of the heated wire is different than if the gas flowing over the wire were to be air. As the wire cools, the resistance of the wire changes and current through the wire is measured to derive the % gas in air.

Caution: A number of chemicals, including halogens, can damage or inhibit the Pellistor gas detector sensor. Thus, you as the "thinking-of-everything" engineer in charge of the LNG plant need to make sure your staff is aware of this. You would not want to be sensing the air in an area where bleach is used or chemicals are stored (chlorine is a halogen). Some other materials that can damage the sensing element include silicone-based products such as lotions, hair products, lubricants, gas additives, lead, and sulfur compounds. It is best to have your chemical gas detector manufacturer provide you a complete list and to audit where your Pellistor gas detectors are sensing to assure that they are not prone to damage.

Caution: As mentioned above a Pellistor gas detector requires oxygen in order to detect gas on the 0 – 100% LEL scale. Thus, it would not register a gas reading in a space that had natural gas mixed with nitrogen (and no oxygen). At one plant it was the procedure for the LNG operator to climb up to the top of each tank every morning to check the tanks annular space. The annular space was blanketed with 100% nitrogen and the gas check was to assure that the inner tank was not leaking. For over 20 years, the operators checked that annular space using a Pellistor type of gas detector. The detector never read any gas reading nor would it have if gas were to have been present. I was the person who questioned the type of detector being used and then I had the chemical lab provide a proper method of testing.

There are many more cautions that could be presented, but this is an overview course and not an all-inclusive study.

6.24.2. IR point source gas detector

A point source gas indicator can also use the same technology as the open path gas detector. The only difference is that the transmitter and receiver are in near each other (perhaps 6" apart). Again, if the signal needs to be transmitted, it is typically transmitted using a 4- 20 mA signal.

Typical displays readings are:

- 0 – 100% LEL (0 – 50,000 PPM) (0 – 5% Gas)
- 0 – 100% Gas (0 – 1,000,000 PPM) (0 – 100% Gas)

Take a look at the fuel-fired combustion equipment within an LNG plant. You should find a point source gas detector at the air inlet by code requirement. The point source gas detector will automatically shut down the gas combustion equipment if flammable gas is detected in the inlet air.

6.25. Flame/smoke detection

There are several different types of fire detectors. Some of the most common are as follows:

- Smoke detector
  - Ionization (see Figure 37)

    – Photoelectric (see Figure 38)
- Heat sensor
    – Mechanical
    – Electronic
- Fusible link
    – Softens and pull apart as heat is applied
- Flame detectors
    – Infrared radiation sensors
    – Ultraviolet radiation sensors

6.25.1. Ionization-type smoke detectors

Ionization fire detectors respond quickly to fires but require the combustion products to enter into the detector sensing element. This type of detector contains a small amount of radioactive material that ionize the air. The products of combustion in contact with the ionized air and affects the air's conductivity. The electronics sense the change in conductivity across the air gap and an alarm is sounded. The performance of the ionization fire detector is adversely affected by humidity and other gases. Figure 37 below conceptually shows how an ionization-type smoke detector operates.

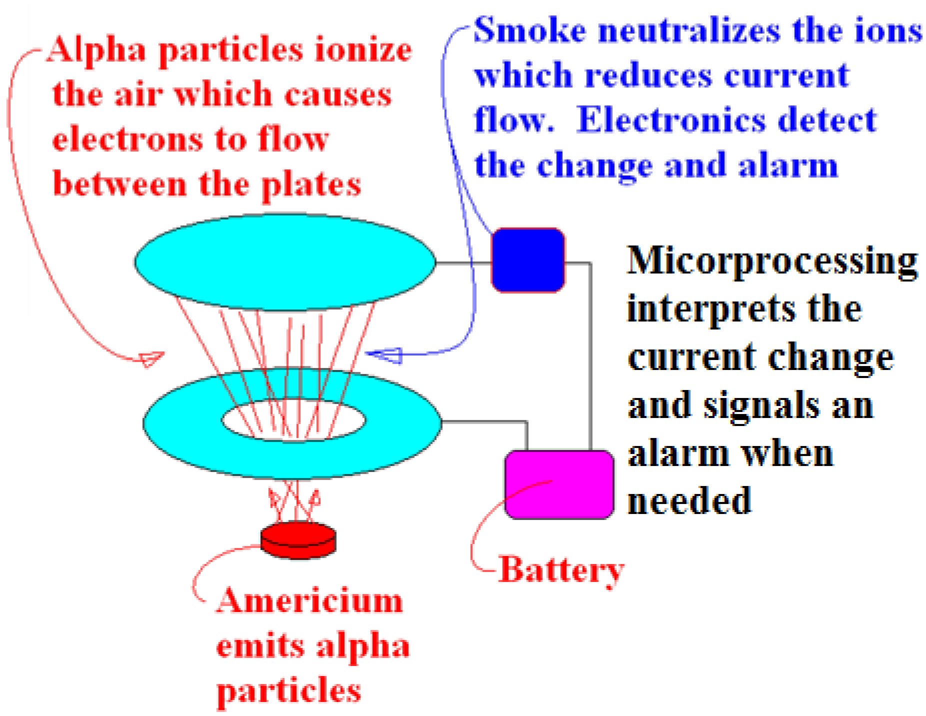


Figure 37: Conceptual graphic of an ionization type of smoke detector
Source: Self-made

6.25.2. Photoelectric detectors

Photoelectric smoke detectors use light scattering technology to sense smoke. A light beam is directed from a transmitter to a receiver, confirming that the light is functioning. A second receiver is positioned outside the normal path of the light and detects light only when smoke is present to scatter the light. This type of detector requires smoke particles to enter the sensing chamber. Dust may also trigger this type of detector.

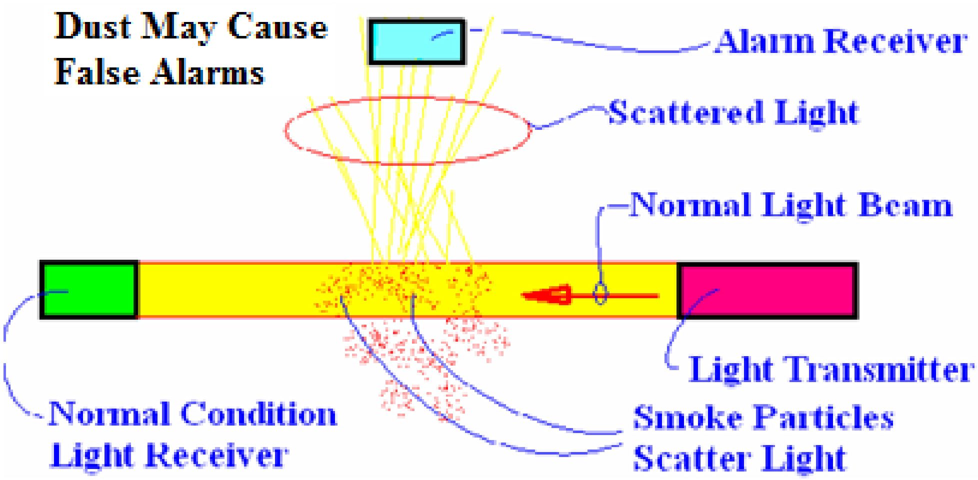


Figure 38: Photoelectric type of smoke detector is dependent on reflective particles of combustion entering the sensed area within the detector
Source: Self-made

6.26. Flame thermal-radiation-type detectors

Some thermal radiation-type flame detector models scan the viewing area for ultraviolet radiation. Others browse the viewing area for infrared radiation. And some models scan the viewing area for both ultraviolet and infrared radiation. Micro processing converts received data to trigger the response in the F&G system. Typically, two sensors positioned at different anglesare used to prove a fire. The reason for using dual sensing is that light sources outside the viewing area can cause false alarms. These light sources could include the rising or setting sun, sun light from a reflective surface, offsite welding, flash camera use, etc.

6.27. Oxygen measurement sensors

The silent killer in many industrial accidents is a lack of oxygen where personnel are present. Oxygen sensors must be used under any condition that may result in an oxygen deficiency where personnel may be present. Notably, whenever personnel enter a confined space, the atmosphere must first be checked using a portable gas detector and an oxygen detector (see Figure 39 below). While personnel are in the space, continuous monitoring should be conducted to ensure the air quality is safe (free of combustibles and with sufficient oxygen content). In addition, personnel should be in continuous contact with personnel outside the confined space.

Figure 39: This is displayed as a confined space. However, many confined spaces are not so well defined. In particular, maintenance of a vessel, a cold box or a not well-ventilated space which requires entry would need oxygen monitoring and a special confined space entry permit
Source: Self taken photo

6.28. Self-contained breathing apparatus (SCBA)

A common, preventable accident, that often results in the loss of life, occurs when a well-meaning rescue attempt is made for someone who has collapsed due to a lack of oxygen or inhalation of a harmful chemical substance. Unless the rescuer is provided with a source of breathing air, the rescuer often becomes an additional victim. A rescue attempt should not be made unless the rescuing person is wearing the proper air supply gear. Typically, this is a self-contained breathing apparatus and a rescue harness.

One type of self-contained breathing apparatus is a face mask with a positive pressure fresh air supply carried by the rescuer. Often the fresh air supply is via a compressed air bottle carried on the back or via a sling around the neck of the person who is to enter the hazardous area.

It is critically important that personnel who use SCUBA equipment be well trained in the use of this equipment. Also, the mask must make a good fit on the face of the user. Many facilities do not allow facial hair on their employees if they may be called upon to use SCUBA.

It is critically important that such personnel be trained and drilled on the use of such equipment as personnel without training could feel claustrophobic and could panic once within the confined space. If such a panic results in the removing of the SCUBA, the would-be rescuer could become another victim.

6.29. Temperature detectors

Temperature detectors have many uses in an LNG facility. They can be used to monitor pipe, tank, and fluid temperatures for safe operations. They can be used to sense fire conditions and they can be used to sense the cold associated with spilled LNG or the venting of cold vapor from relief valves.

Temperature detectors can accurately measure both high and low temperatures and they are a critical component for accurate custody transfer of LNG cargo, since the temperature of the LNG dictates its density. The density along with the chemical composition is used to determine the heating value of an LNG tanker cargo delivered. A typical LNG ship may carry $30,000,000 work of LNG cargo. A measurement error of just ¼ % would be a $75,000 per tanker load of LNG.

As important as custody transfer is, temperature sensors play an even more important role in assuring safety for the plant. Temperature sensors are used within the LNG tank to assure a safe commissioning of the LNG storage tanks and of large diameter LNG piping. Temperature sensors are also used to determine if certain relief valves are venting (e.g., if the top of the tank valves are passing, a temperature sensor is often used to alarm the operator of the venting. Temperature sensors are also used at low points in the plant to determine if LNG leakage is occurring.

The two most common types of temperature sensors are:

- Thermocouples – thermocouples use dissimilar metals that produce a voltage (via the Seebeck Effect). That voltage changes with temperature. Micro processing is used to interpret that voltage and display a corresponding temperature.
- Resistance Temperature Devices (RTDs) are highly accurate temperature devices. They consist of a resistor that changes its resistance as a function of temperature. The resistance is measured and micro processing is used to interpret the that resistance and display a corresponding temperature.

6.30. Fusible links

Fusible links, which melt when a certain temperature is reached, may be used to activate alarms under high temperature or to activate a device, close a door, close a spring-loaded valve etc. If you look up at sprinkler heads, you may see that they may be of the type that is closed off by a plug that is held in place by a metal that will melt and allow the plug to be blown out of the sprinkler head opening. For fire mitigation devices the metal component will melt at a specific temperature (typically 180 F for fire fusible links).

An alternate to a fusible link is a glass capsule with a liquid inside it. When the liquid is heated the pressure in the capsule bursts the glass and the plug it was holding back is released. It is common to see these glass capsules in sprinkler heads.

In some cases when the component melts, a circuit opens causing an alarm. In other cases, a fire door may be held open by a fusible latch that once melted closes the door via gravity or via a spring loading.

Fusible links can also be used on fail closed fuel valves on boilers or other heating equipment. Once the link melts, the supply of fuel is shut down by the valve closure.

Once a fusible link operates, it must be replaced. There is no way to reset the fusible link.

6.31. Fixed Fire Protection systems

The most common fixed fire protection systems are:

- Water sprays
- High-expansion foam
- Dry chemical

Only dry chemical is used for extinguishment; water sprays are used to heat vapor or cool equipment and foam is used to suppress vapor generation or insulate equipment from fire

6.32. Low and high expansion foam systems

When LNG is spilled or when an LNG pool fire is burning, it is common to use high expansion foam over the LNG pool or over the LNG pool fire. In either case the high expansion foam will act as an insulating blanket to hinder the heat transfer to the pool from above the pool. Hindering the heat transfer to the LNG will slow the evaporation of the LNG.

Low expansion foam is used on petroleum spills and petroleum fires for fire reduction and extinguishing if the fire is small enough.

6.33. Water spray systems

Spraying water on an LNG spill **increases** rate of vaporization by adding heat to LNG spill. Thus, water sprays are not used to extinguish an LNG pool fire. Instead, water sprays are used to cool equipment, buildings, and personnel from radiated heat. Thus, do not spray water on LNG spill to lessen fire or rate of vaporization.

Water sprays are also used to warm LNG vapor to make it buoyant and to have it rapidly mix and disperse in the air.

6.34. Water Curtains Are Also Used to Protect the Hull of the LNG Ship

When an LNG ship connects to the loading/unloading arms, quick release couplings are used to allow the ship to disconnect from the berth is certain types of emergencies. High flowrates are used for the transfer of the cargo. There is a very small but plausible potential for LNG to spill or leak during the transfer process.

In order to protect the ship's hull from cracking due to exposure to cryogenic LNG, it is common practice to have a water curtain pouring water over the ship' hull under the loading arms, whenever LNG is being transferred.

6.35. Dry Chemical Systems

Dry chemical fire extinguishers are the only type of fire extinguisher approved for use on LNG. These devices are one time use devices. After use, they need to be refilled to be reused in the future. There are several different types of dry chemical systems. This includes hand-held, wheeled cart and large fixed in place systems.

6.36. Brain Teaser

A ship had been unloaded into tank 100-A this morning. For the past 6 hours, very little boil-off has been produced from that tank and the barometer has been constant all day. What serious concern needs to be evaluated immediately?

6.36.1. Possible answer

It is known that heat has been entering the tank all day and yet boil-off is not being produced at a normal rate and the barometer has been constant all day. This is a clear indicator that stratification may have occurred. When stratification occurs, the lower stratum absorbs heat but does not auto-refrigerate because it is trapped under an upper stratum. If stratification is verified, the lower stratum should be pumped out of the bottom of the LNG tank inventory. The pumped-out LNG could be put back into the top of the same tank or into a different tank. However, care needs to be exercised to avoid transferring a lower stratum into a different tank causing that tank to stratify. To avoid causing the receiving tank to stratify, the densities of the two LNG inventories need to be evaluated. It is typical to place a denser LNG above a less dense LNG or a less dense LNG under a denser LNG.

6.37. Clear communication is essential

LNG employees can be from different countries and cultures. Some cultures are less likely to ask for clarification of directions and other cultures need will ask for clarification. As part of the training, it needs to be emphasized that if there is any ambiguity is the directions given, the operator needs to ask for clarification.

Also, communication between the gas system operator and the LNG plant operator needs to be understood. In one case the gas system operator asked for more pressure and the LNG operator decreased the flow to the vaporizers to build up a higher pressure at the outlet of the LNG pumps. This mis-communication almost resulted in a gas system outage. I was called in to rectify this situation and I instructed the LNG technician on what needed to be done.

When loading or unloading an LNG tanker ship, an umbilical cord is connected between the ship and the shore control centers. This communication link allows data to be communicated

6.38. Technical knowledge is essential

Operators need to be trained to understand the thermodynamics, instrument, mechanical, electrical and safety systems of the entire plant. It is important to give emphasis to the management of LNG, however, it is equally important to also give emphasis to the management of boil-off gas and auxiliary systems. In particular training and drilling of safety and emergency procedures is critical. It is also critical to train technicians to observe their surrounds for everything that may result in a hazard.

Technicians need to avoid complacency. At one plant a steam trap had failed open and was blowing steam to the ground for months. Operators and maintenance personnel walked past that steam trap for months and never gave it any attention. As the steam blew it formed a pool of hot water under the steam trap and a formation of ice around the pool of hot water. One day as a crew and the general foreperson walked past the steam trap, the general foreperson slipped on the ice and slid into the pool of hot water. When he was pulled out, as they took his hot water saturated clothing off, his burnt skin came off along with his clothing. He survived but was severely disfigured by the burns across most of his body. I too had walked past that blowing steam trap many a time and never gave it a thought.

When seasoned employees retire, the training programs in place need to ensure that the institutional knowledge they possess does not leave with them. To do this it is critical to ensure that all their normal duties can be successfully completed by their replacements. Further, their knowledge about what-if events need to be studied. It may be costly to assign the retiring person an understudy before he/she leaves, but that cost is less expensive than an accident due to a lack of knowledge.

As an example, it is important to pre-cool down the vapor space of an LNG tank before top filling that tank from an LNG tanker ship. Every seasoned operator may understand this, but a replacement employee may not understand this subtle need.

6.39. Electrical Safety

Some of the least understood topics related to LNG plant operations are electrical in nature. For instance, a three-phase motor will run backwards if one of the phase wires are crossed. When such a motor is turned on, it could cause an accident and equipment damage. Some basics that need to be understood include

- Less than 0.1 amperes can kill a person
- Amperage that passes through your body is a function of voltage and resistance conditions (wet hands, high contact area, etc.).
- Avoiding injury and death is a best practice (said as humor but it is very true)
- Battery banks are often considered harmless since such batteries are in our cars. However, large banks of batteries, like those in uninterruptible power supplies contain so much energy that a dropped screwdriver causing a short can result in an explosion. One of my direct report forepersons still wears the scars from that dropped screwdriver.

  Further, such batteries give off hydrogen gas and if not managed properly can result in a detonation.
- Novec 1230 Fire Protection fluid (Sapphire) or similar systems are often used in electrical switchgear stations and control rooms (see Figure 40).
  - These are chemicals that inhibit combustion
- CO_2 extinguishers are also used on electrical fires but can displace breathing oxygen.

Figure 40: Often electrical switchgear and computer rooms are protected by fire inhibiting gas systems. Typically alarms sound to allow evacuation before such systems are activated.
Source: Self-made

6.40. Other Safety Topics

Volumes can be written about the design and planning needed for a safe LNG plant. However, just to mention a few of the necessary topics, the below are listed:

- HAZID (hazard identification study)
- HAZOP (hazard and operability study)
- LOPA (layer of protection analysis)
- (MOC) Management of Change
- Training and drills
- Ship unloading water curtain
- UPS (uninterruptible power supply functional testing)
- Stand-by generators and fire water pumps (If they are diesel fuel driven is the fuel of the right grade for the time of year? Is the fuel fresh and uncontaminated by water condensation?).

  In preparation for extremely cold weather, approximately 20 back-up diesel generators and air compressors were rented and sent out to the 14 propane air facilities. On the morning of that very-cold design day, not a single one of the diesel back-up generators or air compressors started. The fuel had gelled in the lines and fuel filters. This is brought up in a course on safety because safety also includes the safety of the end-use customers. The loss of gas supply during a severe cold snap can cause severe injury or death to those without heat.
- Redundancy of equipment helps endure sendout capability. However, if a unit fails, determine why it failed before placing the redundant piece of equipment as that back up equipment may also fail if the cause of failure is not remedied.
- Eyewash and showers, wind socks, portable fire extinguishers and ESD buttons (as you walk through the plant take a mental note where these are located)

6.41. Scenario 4

- 3 am, 0 deg F
- Sendout in progress and is needed
- You are using 4 submerged combustion vaporizers (SCVs)
- Alarm log lights up, and an ESD occurs
  - ESD appears to be due to gas alarms
  - Water has sprayed into much of the vaporizer area
  - Gas readings are decreasing but were significant

6.41.1. Scenario 3 – what might have happened?

The fact that SCVs were in use and that water has blown out of at least one of them is an indicator that an LNG tube may have ruptured within the SCV. If that did happen, the gas detection devices would have shut down the flow of LNG. Look for evidence of the lid having blown off the top of the vaporizer.

6.42. Anatomy of an accident (disaster)

Some of the areas where deficiencies may be found include:

- Procedures
- Maintenance
- Training
- Belief System
- Attitudes
- Equipment

One of the best sources for understanding the "Anatomy of a Disaster" can be found in the Chemical Safety Board 55-minute video of the Texas City Refinery accident. https://www.aiche.org/chenected/2010/03/csb-safety-video-anatomy-disaster-video#:~:text=Anatomy%20of%20a%20Disaster%20tells,of%20dollars%20in%20economic%20losses

6.42.1. Belief system

- If it is on fire, it will be visible (not always)
- A cold burn is not serious (it can be serious)
- John was a hero when he stopped the LNG leak (if John had followed procedures, that leak would not have happened)
- Vapor will harmlessly rise and dissipate (very-cold vapor hugs the ground)
- We will smell it before it can hurt us (nitrogen and boil-off are odorless)
- Out of the combustion zone, will not get burned (radiation burns reach well outside the combustion zone)
- Rag over mouth will help if O_2 level is low (just plain false!)
- It didn't blow up yesterday; it will not blow up today (apathy is a precursor to an accident)

6.42.2. Flight 90 Crash

Accidents in all industries often have things in common. Often accidents are not caused by a single thing going wrong but by a series of events. To show, as an example, below are some of the events that led to flight 90 crashing into the Potomac River are listed below. Take note how many of these precursors are similar in nature to events that could happen at an LNG plant.

- De-icing equipment not functioning correctly
  - Wrong mix of solution (malfunction of mixing valve)
- It is -4 C outside (the operator thinks it is -2 C)

- I will use reverse thrust the engines to help the tug move the plane away from the gate when snow was causing the tug to wheel slip (the pilot said it's fine?) (This action was outside the normal operating procedure)
  - Nonstandard, No MOC, No procedure
- Failure to de-ice again (failed to follow good judgement and procedures)
- Failure to turn on engine de-ice sensor heater
  - Thrust sensor gave wrong data to the pilot
- Failure to abort while they still could (the pilot thought he could get the plane flying disregarding his training)
- End-result - 78 dead

6.42.3. Belief system

Some belief system errors are as follows:

- My instruments are correct (Texas City Accident – 28 dead) (always look for supporting instrument data to confirm primary instrument readings)
- My instruments are wrong (Three Mile Island accident)
- This can't be happening (deer in headlights syndrome – operator does not react as trained) (gas operator did not shut down system resulting in multiple explosions)
- I do not have the authority to react (gas operator did not shut down system resulting in multiple explosions)
- Procedures do not really need to be followed (this is a precursor to an accident)
- Time deadlines are more important than safety (short cuts are precursors to an accident)
- That's what "they" gave me to work with. (If equipment is inadequate, you need to speak up and be a change agent in your plant for safety's sake)
- It's their job, not mine (safety is everyone's job – if you see something – say something)

6.42.3.1. Compressor Explosion at a CNG Station

An explosion occurred at a compressed natural gas station. Below are listed some of the root causes:

- An initial design flaw was not corrected.
- Equipment modification was made by maintenance (removal of vacuum sensor, no MOC).
- Engineering makes another design error (ties in a new compressor without tying in ESD circuit).
- There was a lack of maintenance on the equipment (temperature sensors and insulation fell off of piping over a period of years).
- ESD circuit was used to shut down compressor instead of using normal shutdown procedure.
- End result - Extensive damage, one employee injured, loss of service

6.42.3.2. Attitude

A person's attitude dictates his/her daily performance.

Person one, starts his/her day with some prayer time, and a look in the mirror while grooming for the day. This person one says to himself at the start of the day, "I commit this day to do the very best I can do today and to learn something new today." That person goes out of his/her way to help his fellow coworkers and commits himself/herself to a life of continuous learning, continuous improvement and plant safety and reliability.

Person two, starts his/her day with complaining that he/she has the drudgery of going to another day of work. This person commits himself/herself to finding ways to avoid work and to avoid learning more as that is outside their comfort zone. That person goes out of his/her way to take credit for the work others perform and is not interested in helping others learn or excel.

Person one, becomes a safety and reliability asset to the LNG facility and person two, becomes a liability to the LNG facility.

Attitude can be contagious; thus, it is leadership's responsibility to reward those who strive for to a life of continuous learning, continuous improvement and plant safety and reliability.

Some attitude concerns include:

- **Taking unnecessary risks** (on one job once the jobsite was made safe and the gas supply shutdown was in progress, the employee wanted to manually place a repair sleeve over the blowing gas pipe rather than wait until the source of gas was shut down). Keep in mind, the loss of an hour of production can be made up, the scars of a severe burn injury cannot be erased.
- Complacency
  - That instrument always reads crazy (accepting that as the norm is a precursor to an accident)
  - On one job an operator was unloading an LNG tanker truck into an LNG plant storage tank. Instead of standing by the transfer line valves, the operator sat in the shed reading a newspaper. When I asked him why he was not at the valves, his reply was "I've unloaded trucks hundreds of times and nothing has ever happened." This type of compliancy is a precursor to an accident.
- Ownership
  - It is not my job (I will step on toes)
    - Excavation on LNG site if necessary. I accompanied a chief LNG operator making his rounds. We came across an excavation that was under the supervision of the Engineering Department. The excavation was ~ 10 feet deep with men hand excavating inside it and there was no sheathing. When I asked the operator why he did not shut the job down, he replied "that is Engineering's job and not my responsibility." I shut the job down and told

the chief LNG operator that he owned the responsibility for the plant's safety regardless of who is doing the work. That chief operator had issued the work permit that allowed the work and certainly had the ability and responsibility to pull that permit.

    - Contractor Is responsible to check out repair (no – everyone involved has a responsibility to ensure that equipment is safe to place back into service)

- I never saw this before (abnormal readings, concerning trends, unusual activity)
    - Disbelief may be common, but investigation is necessary (this may be the first time this operator ever encountered stratification)
    - Lack of response (one operator did not take any action when the system was over-pressurizing and explosions were occurring and when interviewed he responded that he did not think he had the authority to shut the system down). Hopefully, such an event never happens in your career, but operators need to realize they have the authority to shut the plant down if the safety of personnel is in jeopardy.

6.42.3.3. Equipment

Every operator needs to fully understand how the equipment and instruments he/she uses works.

- Understand how instruments work. (a pressure differential level gage with a full scale of 6-feet measurement will read 6 feet when the level is 6 feet or 26 feet – understand the technology of the measuring instrument – see the link above for the Texas City Refinery accident)
- Modified equipment – of equipment is modified, it must be thoroughly scrutinized via and MOC process before being put into service.
- Worn equipment (frayed hoses) – operators must be observant and have worn equipment replaced.
- Damaged equipment (corroded pipe) – operators must be observant and have damaged equipment repaired or replaced.
- Broken equipment (cracked screen) – operators must be observant and have damaged equipment repaired or replaced.
- Out-of-service equipment – operators must be observant and have out of service equipment repaired or replaced.
- It-never-really-worked-right equipment – operators must be observant and have It-never-really-worked-right equipment repaired or replaced.
- What was delivered is not correct – then send it back and get the right equipment!
    - Content
    - Tested out
    - Contamination
    - On one occasion, an LNG pump was delivered after OEM repair and it had the wrong impeller installed. Inspection of delivered equipment and a thorough inspection of the repair paper work is essential

6.42.3.4. Turbine explosion on at SYN-Gas plant

At a synthetic natural gas plant, a steam turbine was spun in reverse by the pump which it was intended to operate. When the steam to the turbine was shut down the check valve on the pump failed to close and the pressure downstream of the pump flowed backward through the pump spinning the turbine in reverse at a rotational speed well in excess of its design limits. The turbine blew apart. There were turbine blades protruding from insulated piping and vessels and the 4" diameter turbine shaft was bent like a pretzel and also blew out of the turbine casing. No one was injured as the operators hid for cover when they heard the turbine overspeed. Some of the root causes of the accident were as follows:

- Lack of well-defined procedures
- Use check valves alone without use of block valves before switching turbines/pump units
- Lack of maintenance of the never used reverse break on the turbine
- Contributing factors included - poor procedures, a lack of maintenance, it did not blow up yesterday thought process, etc.

Six Operators were in harm's way but there were no injuries. However, the plant lost use of that turbine for the full winter season

6.43. Accidents

Some notable accidents are as follow:

- Chernobyl nuclear melt: unknown death toll
- Three Mile Island nuclear melt: economic disaster to the Nuclear Industry
- Cleveland LNG leak: over 130 dead
- Mexico City LPG leak: over 500 dead
- Soviet Union LPG leak: over 500 dead
- Bhopal India chemical leak: 2800 dead

6.44. Manuals, Procedures and Drills

- Knowing plant procedures makes you ready to respond when needed
- Knowing plant procedures helps you avoid the need to respond and keeps you prepared if you need to respond
- Running drills sharpens your skills and develops lessons learned

6.45. Prevention is the best protection

- Know plant Operating, Maintenance and Emergency Procedures
- 49CFR Part 19, NFPA 59A and Canadian Standards Association (CSA-Z276-07)
  - Descriptions of all actions
  - Procedure for safe repair of operating equipment
  - Site-specific written maintenance procedures

  - Manner and frequency of inspections and tests
- Avoid complacency

6.46. Lock-out, Tag-out (LOTO)

The LOTO procedure is one of the most critical procedures in the plant. The plant operator is the first person to place his/her lock on the device that locks the component from operation and is the last to take his/her lock off the component when it is restored to service. Each other craft also places their locks on the locking device. As an example, for a given piece of equipment, it may be necessary to have operations, mechanical, instrument and electrical craft persons place their locks on a device before it can be worked on. Figure 41 shows a box of locking devices and tags. As can be seen these locking devices can accommodate up to 6 locks.

It needs to be remembered that:

- Technician **OWNS** plant safety
- Lock-out tag-out (LOTO) is critical to plant safety
- LOTO should never be waived
- The life you save might be your own

Figure 41: Picture of a box containing locking devices for use when implementing the LOTO procedure
Source: Self-made

6.47. Safe clothing choices and personal protective equipment

Some considerations when selecting clothing for plant use are as follows:

- Always adhere to the clothing requirements of you company. Most LNG plants provide or require the wearing of flame-resistant uniforms
- Pants over shoes prevent catching hazards
- No cuffs on pants
- Jewelry can increase hazards
- Always think of what can happen
- Wear other PPE specified by your company (hard hats, eye protection, hearing protection, steel toed shoes etc.)
- Synthetic materials may melt on skin
- Sleeve are recommended be closed to avoid blowing gas from getting under the fire protective clothing
- Loose clothing is typically easier to remove after an injury

6.48. Security in a Post 9/11 environment

Security will not be discussed in detail in this document because security needs to be kept secret to each unique company. However, clearly an LNG plant contains a tremendous amount of energy and can be a terrorist target.

It is brought up in this training to encourage every LNG plant operator and the engineers overseeing these facilities to build into their procedures and training the importance of security.

In general terms the following topics should be considered:

- Each plant should have equipment in place to prevent unauthorized personnel from entering the plant.
- Intrusion systems need to be in place and continually monitored
- Cyber security needs to be enforced.
- Security patrols and coordination with local law enforcement needs to be in place
- Plans for preventing and responding to events need to be continually updated and exercised. Such plans may include:
    - Crisis management plan (what to do if a shooting takes place at the plant etc.)
    - Response plans
    - Table top drills to identify plant vulnerabilities (the findings need to be kept confidential)
    - Hardening of vulnerable parts of the plant.
- In particular access to the tank area needs to be strictly limited.

- Deterrents to sensitive areas need to be heavy-vehicle proof. (a do not enter sign and a bicycle chain across a road is not adequate – barriers that can be driven around or through are not adequate).
- Security breach drills should be conducted.
- Having an outside security petrochemical plant security expert assess the security adequacy of the plant is recommended provided that security expert is well vetted.

6.49. LNG technician expectations

The most important variable associated with plant safety is the performance of the LNG technicians. These people need to be well trained, must understand the technical phenomena that are occurring in the plant, be able to quickly assess and react to abnormal operating conditions and be of ethical character. They must learn from every event, have a spirit of continuous learning and continuous improvement. Extremely important is that they need to respect and fulfill the responsibility they have to follow procedures and not take unnecessary risks. The plant can always be shut down and restarted, if necessary, but a life lost cannot be replaced.

Having been with burned and injured employees and having attended the funeral of a dear co-worker, I can attest to the life long lasting effects of inattention to detail, failure to follow procedures and acceptance of improperly operating equipment.

Below are some of the LNG technician’s duties that are critical to a safe plant operation.

6.49.1. Work permits

Work permits are typically issued by the operating personnel.

- If contractors need to wait, they will need to wait until the jobsite is proven safe for work to commence.
- If in-house forces need to wait, they will wait, they will need to wait until the jobsite is proven safe for work to commence.
- **All** locks on and all sign offs must be in place “before” work begins
- Obtain proper authorization to by-bass any sensors that are allowed to be by-passed for the work.
- Make proper notifications of jobs that are to be performed.
- Cordon off the area (signs and tags as needed)

6.49.2. Hot work permits (where sources of ignition may be present)

- All plant requirements must be met.
- Typically, these include
  - Double block and bleeds where needed
  - Continuous atmospheric monitoring
  - Fire watch assigned by a “qualified person.”

        - Ask the fire watch "what if questions" (good practice)
        - Ask fire watch how the extinguisher works (good practice)
    - Obtain proper authorization to by-bass any sensors that are allowed to be by-passed for the work. For example, if welding is to be performed the automatic ESD function of the flame detectors may need to be placed on alert mode only.
    - Make proper notifications
    - Cordon off the area (signs and tags as needed)

6.49.3. Special entry permits

- Confined Space
- Vessels requiring continuous breathing apparatus
- Just a quick visit back into the vessel to get dropped wallet (not allowed unless entry permit is re-issued)
- Rehearse back up plans and contingencies
- What if someone in the confined space collapses?
    - On one job and employee lied on his job application about being able to work in confined spaces. He had epilepsy and collapsed when stressfully working within a nitrogen filled confined space. The confined space was a vertical vessel that was half filled with a pyrophoric catalyst and thus, the vessel was under a continuous nitrogen purge. Each of the employees inside the vessel had on air supply apparatus. The job was set up with employee extraction equipment (wristlets which are like hand cuffs and a tripod above the top entry/exit flange opening of the vessel). The coworkers of the fallen employee place the wristlets on the fallen employee and he was hoisted up using the rescue tri-pod. When he was revived, I asked the employee what happened. He admitted to having lied on his employment application. I gave him a desk job and he was so appreciative of not losing his job that he became the best clerk in the department.

6.49.4. Especially beware of the unusual job

Special care needs to be applied to any unusual job because the jobs are new and the procedures for performing such jobs are not well proven. Some of these jobs might include:

- Operating without the recondenser in service
- Removing an in-tank pump
- Truck to truck transfer
- Tank to tank transfer
- Loading of high nitrogen LNG
- Taking systems out of service

6.49.5. Miscellaneous

- If you know safety critical equipment is malfunctioning – GET IT FIXED!
- If you do not have enough sensors or data feedback to operate safely – GET THOSE SENSORS!
- If you see something unsafe, do not think it is someone else's job to remedy. Get it remedied even if you need to go to a higher authority to get it remedied.
- Expect the unexpected and always rehearse in your head your actions to events.
- Make sure you have enough equipment (gas and oxygen detectors etc.)
- Make sure in-house personnel and contractors are qualified (random ask for proof of qualification (welders' qualification, government Certifications etc.)
- Make sure your equipment is properly functional and calibrated.
    - In particular check on equipment that is typically never called on (vacuum breakers etc.)
- Provided the necessary escorts when required

6.49.6. No Exceptions

It is common, for high level personnel to visit a jobsite at and LNG plant. These persons need to abide by all the same safety requirements of the plant personnel performing the work. For instance, if they are to visit the site and the workers are required to wear fire retardant clothing and steel toed shoes, they should also be so required. Some types of personnel that might visit and LNG plant jobsite include:

- The engineers who designed project
- The equipment manufacture representative
- The chief LNG operator's boss
- The plant director
- The company vice president
- The company president
- The company CEO
- The Public Service Commission representative
- The FERC top representative

Regardless of their title, they do not have the right to violate the plant's safety rules.

6.49.7. Expect the unexpected

- Although ice formation is a normal occurrence in an LNG plant, the LNG technician always ensures that ice build-ups do not interfere with the normal operation of moving components or become a slipping hazard.
- Although under normal operating conditions one would not expect an Emergency Release Coupling (ERC) to release, the LNG technician must realize that an ERC may trigger at any time.

6.49.7.1. Look for what have might have been overlooked

The diligent LNG technician realizes the importance of equipment maintenance. When he sees equipment that is out of reach, he follows up to ensure that the equipment has been maintained, as required (see Figure 42).

Figure 42: Spring hangers at the very top edge of an LNG tank – difficult to service but important to service

Source: Self-made

6.49.8. The technician takes pride in the appearance of his/her plant

Although it is hard to quantitatively correlate plant appearance with safety and performance, my personal experience observations are that a well-maintained plant is a good indicator of a good work place attitude.

6.49.9. The LNG technician is always prepared

The LNG technician is always prepared to take action. He observes the wind direction and anticipates the actions needed in the event of a spill or vapor release.

The technician is always alert to surroundings

6.49.10. The technician knows about all chemicals used in the plant

LNG and gas leaks are not the only hazards (chemicals etc. see Figure 43) associated with plant operations. Debris, electrical, or chemical (paints, oils, or solvent) fires can be just as serious as an LNG fire.

Figure 43: LNG and boil-off gas are only two of the many hazardous substances used at and LNG plant.
Source: Self-made

6.49.11. The LNG technician studies his/her plant and takes precautions

- The LNG technician knows that the procedures were developed after years of study and scientific analysis of the LNG industry. The technician keeps current by learning from code changes and events at other plants.
- The LNG technician knows that protective gear does little good if it is not worn. Like a seat belt in a car, using it after the accident is a moment too late.

6.49.12. The technician drills and trains

- Although he/she hopes never to need all any of the emergency response skills, the LNG technician stands ready to put his/her training into action to protect himself/herself and their fellow workers.
- More importantly, the LNG technician studies and follows all the operations and safety procedures to help avoid ever needing to use the emergency response equipment.
- Yes, the training, skill and ability of the LNG technician is, in my informed experience, the most important asset to assure a safe, secure, and reliable plant.

6.50. Scenario 5

- 3 am, 0 deg F
- Sendout in progress and is needed
- An ESD occurs
  - Your outside operator confirms that you have 10% gas in air in your water ethylene glycol (WEG) expansion tank.

6.50.1. Scenario 5 – what might be happening?

The WEG expansion tank is part of the hot WEG loop that provides hot WEG for vaporization. Getting gas into the expansion tank is likely to have been caused by a leak in the WEG/LNG vaporization heat exchanger. Hot WEG may also be used for other gas heating processes in the plant. All such heat exchangers would be suspect.

Of immediate concern is that the WEG expansion tank is a confined space that now contains an air-gas mixture. Thus, the immediate concern would be to purge out that tank with nitrogen to eliminate the explosive mixture. Another option would be to flood the WEG expansion tank with WEG or even water if necessary to push out the air-gas mixture. In either case immediate action would be needed.

6.51. Culture development

The culture developed in a plant is directly correlated with the level of safety that plant experiences. If the culture is one of rewarding keeping the plant on-line as the highest priority and thinking that safety measures are too expensive to implement, then often shortcuts and work-arounds may result in accidents and injuries.

An LNG plant's most critical asset is leadership that lives up to, develops, and rewards a culture of safety and reliability. Everyone from the plant director down to the newest employee must prioritize safety. When it comes to avoiding an unsafe condition, the employee must speak up and his/her concern should be addressed.

Just think, the Challenger disaster could have been avoided by responding to and rewarding the caution about the temperature of the O-Ring seals.

A culture that strictly adheres to developing and updating well-written procedures and following those procedures along with a robust MOC process is a foundation for the proper culture. If it is not the culture you are working in, it may be wise to speak up. You may consider working elsewhere if your intervention does not help create safety and reliability culture.

A paraphrase of how the Chemical Safety Board states it, in the video "Anatomy of a Disaster," is "if you think safety is expensive, look at the expense of an accident"! Accidents, not only cause the loss of plant operational on-line time, but they also ruin the reputation the company, damage plant infrastructure, open the company up to regulatory fines and litigation expenses, and emotionally and physically injures employees. Some events like the one described early in this study, result in death.

7. Closure

In this training, LNG safety measures and technologies have been covered at a very high level and is not intended to be all inclusive training needed to design, operate or maintain an LNG facility. This training is intended to present some introductory technical materials to help develop a culture of safety and reliability in your thought processes. It is intended to give the learner the basic technical knowledge needed as a starting point, to encourage further study, to make informed design, planning, maintenance and operating decisions to ensure plant safety and reliability.

In the follow-on lessons, more detail will be given on the operation of an LNG plant, refrigeration systems for liquefying, and the thermodynamics involved in producing, storing, transporting and re-vaporizing LNG.

Please remember that, the most important intention of this document is to give you the basic technical knowledge, at an introductory level, that you need to start your study, on how to continue to make the Liquid Natural Gas Industry "Safe and Reliable."