Insights from the Risk Analysis of a Nearby Propane Tank Farm

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Abstract: Due to the flammability and explosion characteristics of the propane vapor cloud, a nearby propane tank farm could possibly present a significant risk to the operation of nuclear power plants. Accidental releases of propane may occur in the propane supply pipeline, at the propane storage tanks, or on the propane transportation routes due to propane transport trailer truck accidents. Loss of containment could result in toxic vapor cloud affecting the nearby nuclear plant control room habitability, Vapor Cloud Explosion (VCE) overpressure due to both deflagration and detonation, Boiling Liquid Expanding Vapor Explosion (BLEVE) missile impacts, and thermal radiation from BLEVE fireballs, flash fires, pool fires, and jet fires. The thermal radiation impact ranges of a pool fire, jet fire, flash fire, and BLEVE fireball is typically less than the shortest distance between the propane tank farm and the nearby nuclear plant. The explosion overpressure and missiles are the most critical hazards to the nearby nuclear plants. Only VCE overpressure greater than 1 psi and BLEVE missiles can potentially impact the PRA related structures and equipment at the nearby nuclear plant. The total frequency of unacceptable damage at the nearby nuclear plant resulting from accidents at the propane tank farm and from propane transport truck accidents is estimated to be less than 10^{-7} per year. This paper discusses the insights gained from the analysis of the risk impact on a nearby nuclear plant due to accidental release of propane from the propane terminal related operations, including the propane storage/distribution facility and the propane transport trucks. The important considerations used in the analysis of the risk scenarios resulting from a propane transport truck accident, large and small releases at the propane distribution facility, and exploding missile hazards are presented.

Keywords: Propane Storage and Distribution Terminal, Nuclear Power Plant, Vapor Cloud Explosion, BLEVE, PRA.

1. INTRODUCTION

Nuclear power plants are typically sited in areas separated from the most densely populated regions. However, to minimize the cost of power transmission, large capacity nuclear plants cannot be situated too far away from the industrial areas and/or population centers to which these plants supply power. In today's world, propane has become one of the important energy sources. To facilitate the delivery of propane to industrial and other facilities, propane storage and distribution terminal may be installed at selected, strategic areas. Therefore, as a result of the industrial development, such facilities as a propane storage and distribution terminal may occasionally be built nearby a nuclear power plant after it has been in commercial operation for a number of years. Due to the flammability and explosion characteristics of the propane vapor cloud, a nearby propane tank farm could possibly present a significant risk to the operation of nuclear power plants.

Unlike natural gas which, due to its lighter-than-air vapor density, dissipates in the atmosphere very quickly, propane vapor is heavier than air and would remain close to the ground, if released, and drift with the wind until either dispersed to concentrations below its lower flammability limit or encountered by an ignition source. Ignition of a propane vapor cloud could cause a fireball/flash fire and/or a VCE in a congested or confined space. Vapor cloud explosion of the released propane gas most commonly involves deflagration. However, in very rare conditions, it may result from a detonation of the propane vapor cloud, as evidenced in the 1970 Port Hudson explosion. In addition, a BLEVE event may also occur if the propane storage tank or container is exposed to such heating condition as a pool fire or a jet fire.

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As such, the potential hazards to the nuclear plants in the vicinity that may result from an accidental release of propane from a nearby propane tank farm include toxic gas cloud, pool fires, jet fires, flash fires, VCE overpressure, VCE missiles, BLEVE overpressure, BLEVE fireball, BLEVE missiles, etc. Toxic gas cloud is considered as a potential hazard mainly because propane can displace oxygen and acts as an asphyxiant. BLEVE and VCE (whether it is deflagration or detonation) can generate not only blast overpressure in excess of 1 psi which can possibly cause failures of the accident mitigation Systems, Structures, and Components (SSCs), but also explosion fragments (i.e., missiles) with an impact range as far as thousands of feet. Any risk-significant SSCs located within the impact range of explosion missiles can also be damaged. The thermal radiation impact ranges of a pool fire, jet fire, flash fire, and BLEVE fireball is typically less than the shortest distance between the propane storage and distribution facility and the adjacent nuclear plants. As such, the explosion overpressure and missiles are the most critical hazards to the nuclear plants in the vicinity of a propane storage and distribution facility.

Considering the business nature of a propane storage and distribution facility, accidental release of propane may result from the propane supply pipeline, propane storage tanks and the interconnecting piping system at the propane tank farm, and the propane transport trucks on the segments of the transport routes within the VCE overpressure and explosion missile impact ranges from the nuclear plants. For BLEVE, the explosion occurs at the location of the propane container; e.g., propane storage tanks in the propane terminal or the propane transport trailer truck involved in an accident. For VCE, the explosion may take place at the location of the propane leaks due to immediate ignition. However, as a result of delayed ignition, VCE can also occur at a distant location downwind from the propane leakage or rupture area. Nevertheless, this typically requires a congested or wooded area with potential ignition sources to lead to a VCE.

2. TYPICAL U.S. PROPANE STORAGE AND DISTRIBUTION TERMINAL

A typical propane storage and distribution terminal in the U.S. may contain a significant number of pressurized, above-ground propane storage tanks (each with, for example, 90,000 gallons of water capacity) mounted on cement piers. The facility is usually constructed to the Liquefied Petroleum Gas (LPG) Code of the National Fire Protection Association. To reduce the likelihood of tank rupture due to heat-induced overpressure, the propane tanks are allowed to be filled with liquid propane to only about 85% to 90%. Overpressure protection is also provided by pressure relief valves.

A fire suppression system consisting of an inter-connected loop of fire hydrants surrounding the propane tanks is usually installed. The system can quickly target water via installed nozzles to cool the tanks in case of fire. This would prevent the spread of a fire to other tanks by keeping the tanks cooled with water spray to prevent the tanks from rupturing by the combination of overpressure due to heating of the propane and weakening of the tank metal because of the increased temperature.

The supply of propane to the storage tanks at the terminal is typically through a pipeline equipped with remotely-controlled isolation valves. The propane pressure and temperature in the supply pipeline can vary depending on the ambient temperature and the weather conditions.

The distribution of propane from the storage facility is via transport trailer trucks. In the U.S., propane is shipped on highway in LPG rated cargo tanks. Typically, none of the trailers used to carry propane are insulated. The maximum sizes/weights of transport trucks are specified by the state department of transportation (DOT) code. This is to limit the amount of flammables that can be carried in each trailer and thus bound the potential consequences of possible fires and explosions that may result from accidental releases. The large-capacity highway cargo tank trailers usually are not designed with double trailers. These LPG cargo tanks are specifically designed to carry pressurized liquefied gases (e.g., LPG, liquefied carbon dioxide, or anhydrous ammonia), have a much sturdier, thicker shell compared to gasoline tankers, and can often withstand impacts such as rollovers. In addition, the LPG cargo tanks are designed with the following important safety features:

- Containers are never completely filled, in order to provide vapor space for product expansion (normally filled up to about 85%)
- A rear bumper
- Pressure relief vents
- Overturn protection for fittings, manway covers, and vents
- Discharge piping that is designed to break away from emergency valves or be protected by guards

The number of transport trucks that can be filled by the propane distribution facility each day must also remain within the limits specified by the Environmental Protection Agency (EPA) permit.

3. POTENTIAL HAZARDS ASSOCIATED WITH THE OPERATIONS OF THE PROPANE STORAGE AND DISTRIBUTION TERMINAL

During normal operation, accidental releases of propane may occur in the propane supply pipeline, at the propane storage tanks, or on the propane transportation routes due to propane transport trailer truck accidents. After an accidental propane release, a number of potential safety hazards may result.

3.1. Toxic Gas Cloud

Given that a release of propane forms a vapor cloud that does not ignite, it may be possible for it to spread and diffuse into the nearby nuclear plant control room via its ventilation intake and incapacitate the operators inside the control room. Propane is not toxic by nature; however, it does pose a potential for asphyxiation due to displacement of the available oxygen. Based on the results of the conservative dispersion model analysis, it was demonstrated that the nearby nuclear plant control room should remain habitable in regard to toxicity (i.e., the propane concentration in the control room area would be below the asphyxiation limit) in the event of an accidental release of propane from a propane storage and distribution terminal in the vicinity.

3.2. Pool Fires

Upon release, the propane that does not flash to vapor is flammable and, therefore, can be ignited and poses the hazard of thermal radiation. Pool fires can occur when a significant quantity of liquid propane is released and ignited. These can be confined (e.g., in case of releases into containment dikes) or unconfined (e.g., in case of releases from LPG road tankers). Some of the propane terminals are designed with a dike around the storage tanks such that any liquid propane released from these tanks will not be spread far. Thermal radiation levels are generally moderate for pool fires (e.g., for a propane pool fire, the thermal radiation at the surface of the flame is about 100 kW/m^2), although the duration of the fire can be long. As such, there is usually no thermal impact to the adjacent nuclear plants from a propane pool fire at the storage facility. However, due to the moderate heat flux and long duration it is possible for pool fires to cause BLEVEs of nearby propane storage tanks if they are not properly cooled by water sprays.

3.3. Jet Fires

A high-pressure release of propane vapor into the atmosphere, if ignited, will burn as a flame jet. Any equipment on which that flame jet impinged would be subjected to very high thermal loads, often exceeding the capacity of fixed water sprays. Outside the flame jet itself, thermal radiation hazards are very small. There is generally no thermal impact to nearby nuclear plants from a jet fire at the propane storage facility. Nevertheless, the main concern from a jet fire is its potential to impinge on nearby propane storage tanks causing a BLEVE.

3.4. Vapor Cloud Fires (Flash Fires)

Upon release, propane can form a vapor cloud that spreads horizontally. The maximum dispersion distance of flammable vapor cloud is defined by the lower flammability limit of the vapor material. If little or no wind is present and atmospheric conditions are very stable, the spreading cloud mixes slowly with oxygen. It can burst into flames if ignited and flash back to the source of the release. As such, when a flammable vapor cloud encounters an ignition source in a non-congested and unconfined space, the cloud can catch fire and burn rapidly in a flash fire (which is the non-explosive combustion of a vapor cloud resulting from the release of flammable material into the air) because that portion of the cloud where the concentration is in the flammable range (i.e., between the Lower and Upper Explosive Limits, LEL and UEL) is already pre-mixed to the right mixture of fuel and air for burning to occur. Following the rapid burning, the part of the cloud where the fuel-air concentration is above the UEL may continue to slowly burn as air mixes with the cloud. Possible hazards associated with a flash fire include thermal radiation, smoke, and toxic byproducts from the fire. The most critical hazards from flash fires are thermal radiation and direct flame contact. However, the flash combustion of a vapor cloud normally lasts no more than a few tenths of a second. Thus, the total intercepted thermal radiation by an object near a flash fire is substantially lower than in the case of a pool fire. Therefore, the release and dispersion of propane/LPG, if ignited, could lead to a flash fire burning that part of vapor cloud within the flammability limits. Within the burning cloud, there may be ignition of equipment, but due to the short duration of the phenomenon, the risk for domino effects is small.

3.5. VCEs and Blast Overpressure

As described previously for vapor cloud fires, when a flammable chemical is released into the atmosphere, it forms a vapor cloud that will disperse as it travels downwind. If the cloud encounters an ignition source, the parts of the cloud where the concentration is within the flammable range will burn. In some situations, the cloud will burn so fast that it creates an explosive force (blast wave). Due to its chemical/combustion properties, the release and dispersion of propane/LPG, if ignited, may also result in an explosion if there is sufficient mass within the cloud (e.g., >1 ton). The effects of an explosion, defined by blast overpressure, can be significant. Overpressure 0.7 bar is considered as the limit of domino effects. However, explosions are unlikely, unless the cloud is confined in a building, or semi-confined in a heavily congested area (e.g., in a densely populated process equipment or wooded area). As such, if the vapor cloud is ignited in a confined or congested space, an explosion could occur. The speed at which the flame front moves through the cloud determines whether the explosion is a deflagration or a detonation. In a deflagration, the blast wave is subsonic, while a detonation is characterized by a supersonic pressure wave with significantly higher flame speed and blast pressure. The severity of a vapor cloud explosion depends on the chemical, the cloud size at the time of ignition, the type of ignition, and the congestion level inside the cloud. Therefore, propane vapor clouds are potentially explosive both in unconfined (either with an explosive charge or in a congested space) and confined arrangements. The hazard of such an explosion generally results in building damage or breaking of windows.

3.6. VCE Missiles

Debris and fragments resulting from the vapor cloud explosions may also be projected and become damaging missiles to the nearby nuclear plant SSCs.

3.7. BLEVE and Blast Overpressure

A BLEVE is an explosion involving violent flash evaporation of pressure liquefied gases upon sudden loss of containment resulting in a release of a large mass of pressurized, superheated liquid to the atmosphere. The primary cause is usually an external flame impinging on the shell side of a filled vessel above the liquid level (with insufficient cooling from the liquid), weakening the container and leading to a sudden shell rupture. Thus, propane tanks, when exposed to an external source of fire, are vulnerable to explosion. The external fire weakens the tank shell while also heating the liquid inside well above its boiling point. This may lead to a rupture of the tank containing the pressurized liquid propane and result in an almost instantaneous release of the contents of the tank. Instantaneous evaporation of the released propane after rupture of the tank causes a strong pressure wave. In addition to blast overpressure, the outcomes of a BLEVE may include BLEVE fireball and missiles.

3.8. BLEVE Fireball

Following the rupture of a propane storage tank due to a BLEVE, the large, pressurized release of superheated liquid propane vapor cloud, if immediately ignited, may burn as a large fireball with significant thermal radiation hazard. The fireball grows larger and moves upward continuously because of buoyancy. The duration of the BLEVE fireball is small (typically < 40 sec), but the thermal radiation levels are intense (e.g., the thermal radiation at the fireball surface can be up to 200 kW/m^2). Due to this intense heat, there will be severe damage to process equipment and buildings within the radius of the fireball. However, beyond this distance, the danger is mainly for the people that may be affected by the thermal radiation. Based on previous analyses, there could be no significant thermal effects to nearby nuclear plant SSCs from a BLEVE fireball, since the maximum thermal radiation at the closest nuclear plant critical structure due to a BLEVE at the propane storage and distribution terminal is less than 10 kW/m^2, and the fireball diameter is about 332 yards (996 feet) with a burn duration of 18 seconds.

3.9. BLEVE Missiles

Following a BLEVE rupture of a propane storage tank or a propane container after a propane transport truck accident, there is a possibility for large fragments from the exploding vessel to be projected for great distances. For accidents involving such materials as propane, it is possible that these fragments develop a "rocketing" effect; i.e., may be scattered into the environment like "rocketing" missiles. If the tank fragment retains a portion of the vessel's liquid contents (e.g., the horizontal cylindrical storage tanks splits circumferentially in half), the liquid can vaporize during the initial stage of flight, thereby accelerating the fragment as vapor escapes through the opening. Based on past evaluations, it is possible for these BLEVE "rocketing" missiles, originating from the propane tank farm or a transport truck involved in an accident, to reach the nearby nuclear plant site.

3.10. Primary Damaging Hazards

In terms of the possible damaging impacts to nuclear plants located in the vicinity, the principal types of hazards associated with the accidental releases of propane from a propane tank storage and distribution facility include:

1. Toxic propane vapor or gases and their potential for incapacitating nuclear plant control room operators
2. Overpressure on plant structures due to shock or blast waves generated by the detonation or explosion of vapor clouds resulting from the atmospheric release of propane with a potential for ignition
3. Missile effects attributable to explosion debris resulting from VCEs or BLEVE
4. Thermal effects attributable to fires.

For propane released from either the propane storage tanks or the largest propane transport truck trailer, typically, the thermal heat flux resulting from a pool fire, jet fire, or flash fire is bounded by the heat flux from a BLEVE event.

4. ACCIDENTAL RELEASE SCENARIOS AND OUTCOMES

Based on the potential damaging hazards discussed previously, the critical accident scenarios include the following:

- Accidental release at the propane storage and distribution facility
  - Release due to breach of propane supply pipeline
  - Release of the complete inventory from a propane storage tank at the propane facility
  - Continuous leak from a propane storage tank at the propane facility
- Accidental release due to a propane transport truck accident

4.1. Propane Pipeline Break

Emergency Shutdown (ESD) isolation valves are usually equipped in the propane supply pipeline inside the propane storage and distribution terminal to cut off the additional supply of propane to any break that may develop in the storage tank area. These isolation valves are designed to automatically close very quickly upon receipt of the ESD signal. In addition, alternate shutdown (ASD) isolation valves are also provided at the control center of the propane supplier. Closure of these ASD isolation valves are initiated manually by the propane supplier personnel within a very short period after receipt of the ESD signal.

The maximum amount of propane that can be released from the broken pipeline before completion of the ASD isolation includes the amount of liquid propane contained in thousands of feet of the supply pipeline plus the maximum amount of propane that can possibly be delivered during the period prior to the completion of the ASD valve isolation, which includes the time to initiate the isolation action and the time to complete the isolation action.

Typically, the maximum amount of propane that can be released through the pipeline break is significantly less than the full capacity of a single propane storage tank. As such, the risk impact results of the analyses performed for the scenario involving the loss of containment from a single propane storage tank are bounding for the effects of VCE and BLEVE.

4.2. Release of Complete Propane Tank Inventory due to Catastrophic Tank Rupture

This may include (1) a catastrophic rupture of the propane tank resulting in the instantaneous release of the entire propane content within a couple of minutes, or (2) a serious leak or failure of the propane storage tank in which the tank remains pressurized, such that there is a continuous release of the complete propane inventory in a longer period at a constant rate of release. Since both of these two cases cannot be isolated, the entire contents of the tank will eventually be released into the environment.

An event tree can be used to determine the frequencies of the different incident outcomes. For this type of accidental release events, the event tree will model the frequency of the catastrophic release from the storage tanks, as well as the probabilities of immediate ignition, wind blowing toward to the nearby nuclear plant and the congested area, delayed ignition, unconfined VCE, detonation, flash fire flashing back to storage tank, pool/jet fire, fire suppression cooling nearby tanks, BLEVE of nearby tanks, BLEVE resulting in projected missiles, BLEVE missile launch direction toward nearby nuclear plant, BLEVE missiles reaching nearby nuclear plant, BLEVE missiles striking a critical nuclear plant area, BLEVE missiles exceeding design basis missile energy, etc.

Immediate ignition of the released propane by such ignition sources as sparks at the release source location may occur within a short period from a catastrophic propane storage tank failure. However, based on the results of past VCE overpressure evaluations, accidental VCEs occurring within a few minutes following a catastrophic propane tank failure may not result in a peak overpressure in excess of 1.0 psi at the closest critical structure of a nearby nuclear plant. Furthermore, due to the general openness in the area of the propane storage tanks at a propane distribution terminal, immediate ignition of the vapor cloud resulting from the release of the liquid propane from the failed storage tank would not cause a VCE. The main concern associated with an immediate ignition of the released propane is thus jet fire or pool fire which may cause overheating and possibly BLEVE of the adjacent propane storage tanks. However, since this event involves a catastrophic failure and release of the entire contents of the propane storage tank in a short period of time, the break is of such a significant size and as such an immediate ignition would not lead to a jet fire

Since the propane vapor is heavier than air, it would remain close to the ground and drift with the wind if the propane released from the catastrophically failed storage tank does not ignite immediately. Subsequently, a delayed ignition of the propane vapor cloud formed via flashing and vaporizing from the liquid propane released may still occur after drifting along with the wind for a period of time until encountering an ignition source. To cause an overpressure effect at a nearby nuclear plant, a VCE must occur. Without a strong, energetic ignition source (e.g., an explosive charge), an unconfined VCE in the form of deflagration would only occur in a congested space. As such, to permit a possible VCE that may cause damage to the nearby nuclear plant, the wind must blow in the direction toward the nearby nuclear plant and an ignition source (e.g., hot surfaces, mechanical friction, or sparks generated from a railroad track) must be present in the vicinity of a congested space (e.g., a wooded area) located in the same direction and within the VCE overpressure impact range of the nuclear plant. Once the propane vapor cloud enters and encompasses the congested area, ignition of the propane vapor cloud and VCE could occur. Following ignition of the unconfined vapor cloud in a congested space, the incident would proceed with characteristics of both a flash fire and an explosion.

If the wind does not blow in the direction of the nearby nuclear plant, the propane vapor cloud would be drifting toward other areas. A VCE could still occur in other congested areas which are, however, further away from the nuclear plant. Thus, only detonation could produce an overpressure greater than 1 psi at the adjacent nuclear plant. Deflagration in these other areas would not cause a pressure wave greater than 1 psi at the critical structures of the nearby nuclear plant. Occurrence of a detonation in an unconfined vapor cloud is highly improbable. Direct initiation of a detonation can occur in open air with no confinement or obstructions if a strong, energetic ignition source is present, which is extremely rare. Without a strong, energetic ignition source, an unconfined VCE in the form of a deflagration can only occur in a congested space. Nevertheless, a transition from deflagration to detonation could still occur if additional energetic ignition source is present or a significant length of congestion/obstructions provides sufficient flame acceleration to a speed characteristic of detonation.

Given a delayed ignition of the propane-air mixture with no vapor cloud explosion, a flash fire would occur and could flash back to the liquid propane pool collected underneath the ruptured propane storage tank. This would then cause ignition of the pool of liquid propane leading to a pool fire. Further, the liquid propane pool collected underneath the catastrophically failed propane storage tank is also assumed to spread to the area underneath the nearby storage tanks to fuel a pool fire below the nearby tanks and possibly cause a BLEVE due to heating up of the non-wetted portion of the tank metal shell.

Due to the moderate heat flux, a pool fire at the propane storage tank area would not cause a significant thermal impact on the structures and outdoor equipment of the nearby nuclear plant. However, because of the duration of the fire, a pool fire can threaten the adjacent propane storage tanks to possibly cause a BLEVE if they are not adequately cooled by the fire suppression water. As such, the operating crew must activate the propane storage facility fire suppression system following a pool fire at the propane storage tank area to effectively cool nearby storage tanks and prevent a BLEVE from occurring. The time available to complete this action is on the order of approximately 30 minutes before occurrence of a BLEVE on a large diameter, full storage tank. In most cases, a BLEVE event, if occurs, will result in projected fragments which could fly in the direction toward the nearby nuclear plant and damage its critical SSCs.

In general, the fragments thrown by the explosion in a BLEVE event have a restricted and directional action, but with a larger radius of destructive effects than the BLEVE pressure wave and the thermal effects of the BLEVE fireball. Large fragments from the exploding propane storage tank can possibly be projected/rocketed for great distances reaching the nearby nuclear plant and damaging critical structures/equipment following a rupture due to BLEVE. For a rocketing missile generated from the rupture of a propane storage tank due to BLEVE to penetrate a vital structure or damage critical equipment, the missile must be projected in a direction toward the nearby nuclear plant, the missile must travel far enough to reach the nuclear plant (note that roughly 80% of BLEVE fragments fall within 1,000 feet), the missile must strike a vulnerable critical area of the plant, and the missile must have sufficient energy required to penetrate to vital areas through the wall thickness (i.e., exceeding the design basis missile energy) or producing secondary missiles that could damage vital equipment.

There are generally two kinds of projectiles from BLEVE events: (1) primary projectiles, which are the major fragments of the propane storage tank in this analysis, and (2) secondary projectiles, which are generated by the acceleration of nearby objects (e.g., pipes). The number of primary projectiles will depend on the type of failure, the shape of the vessel, and the severity of the explosion. Typically, a BLEVE will involve a ductile failure; the cracks will propagate at lower velocity and without branching. The number of fragments will be less than if it were a fragile failure. The number of projectiles will be in the range of 2 to 15. Normally, there will be less than five projectiles. For cylindrical tanks, the initial crack for the rupture of the tank due to BLEVE explosion usually follows an axial direction and then changes and follows a circumference (e.g., following a welding seam); thus, the vessel is usually broken into two pieces. The two fragments are typically assumed to travel in opposite directions of the cylinder axis. Therefore, if one of the rocketing fragments is pointing in the direction toward the nearby nuclear plant site, the other fragment will be pointing in the direction away from the plant. As such, the number of primary fragments traveling in the direction toward to the nearby nuclear plant is one. However, the pool/jet fire resulting from a ruptured propane tank can spread to additional adjacent tanks, each of these adjacent tanks could experience a BLEVE (due to domino effect) producing two missiles with one pointing toward the nuclear plant and one pointing away from the plant. Therefore, the total number of missiles directed at the nearby nuclear plant per loss of containment or leakage event can be taken to be the number of adjacent tanks that the leaking liquid propane can spread to. This is considered as conservative since a jet fire resulting from a small tank leak may only affect one tank resulting in a BLEVE. For the launch direction, the BLEVE missiles will probably follow the direction of the cylinder axis.

If a delayed ignition also does not occur, the only adverse effect of the un-ignited propane vapor cloud is the possible asphyxiation that may result in the main control room. However, based on previous evaluations, the concentration of propane vapor that may diffuse into the main control room due to catastrophic propane release at the nearby propane tank farm is below the threshold to cause asphyxiation in the main control room.

4.3. Continuous Leak from a Small Hole in Propane Storage Tank

This event involves a continuous release of propane from a small hole in one of the propane storage tanks. The event progression is largely similar to that following the catastrophic release of the entire contents of the propane in the failed storage tank, except the following:

- The rate of release for this initiating event is much slower than that in the event where the entire contents were released in a short period of time.
- Due to the much slower rate of release, isolation of the leak can be credited.
- Also, due to the much smaller rate of release, the probability of immediate ignition is also much lower.
- Due to the much smaller break size, a direct, immediate ignition of a pressurized leak can be assumed to cause a jet fire. A delayed ignition without causing a VCE would cause a flash fire which would also flash back to the leaking tank, leading to a jet fire.
- A jet fire could be impinging on the adjacent propane storage tank heating up the non-wetted area (i.e., vapor space) of the tank shell, which would requires cooling by the fire suppression spray to prevent a BLEVE event.

The event tree used to determine the frequencies of the different incident outcomes models the frequency of continuous leaks from the storage tanks, as well as the probabilities of leak isolation by

ASD, immediate ignition, wind blowing toward to the nearby nuclear plant and the congested area, delayed ignition, unconfined VCE, detonation, flash fire flashing back to storage tank, jet fire from leaking tank, jet fire impinging on vapor space, fire suppression cooling nearby tanks, BLEVE of nearby tanks, BLEVE resulting in projected missiles, BLEVE missile launch direction toward nearby nuclear plant, BLEVE missiles reaching nearby nuclear plant, BLEVE missiles striking a critical nuclear plant area, BLEVE missiles exceeding design basis missile energy, etc.

For this event, since the leak is from an attached pipe upstream of the automatic isolation valves, the tank will be isolated from the leak once the automatic isolation valves are closed. Note that the pipe length from the tank to the automatic isolation valve is quite short compared to the pipe length from the supply pipeline. Leak detection in the storage tank and process pumps area is usually provided by hydrocarbon detectors. Upon detecting a leak, the ESD system is automatically actuated, closing air-operated valves to isolate each individual tank and the incoming site supply line. The ESD system is also designed to be capable of being actuated manually at multiple pull stations located around the site. In addition to the ESD system, the supply line and each tank can be isolated individually. Additionally, there usually exist several normally open mainline valves on the supply pipeline system. None of these valves are automatically closed by the ESD actuation signal. Time to close these valves include the time to initiate the offsite isolation following the receipt of the ESD signal and the time to complete the ASD action. Failure of the ASD system isolation could result from failure to manually initiate isolation or failure of the pneumatic isolation valve to operate on demand. If leak isolation is unsuccessful, the released propane could be ignited to cause a jet fire, flash fire, pool fire, VCE, and even detonation.

Since this event involves a very small leak size, immediate ignition of the pressurized release from the break would lead to a jet fire. For a delayed ignition, the flash fire resulted will also flash back to the leaking storage tank causing a jet fire. Due to the moderate heat flux, a jet fire at the propane storage tank area would not cause a significant thermal impact on the structures and outdoor equipment at the nearby nuclear plant. However, any equipment on which the jet flame impinged could fail due to the high thermal loads. In particular, it has the potential of causing a BLEVE of the affected propane storage tank if not adequately cooled by the fire suppression water. Below the level of the filled propane liquid (i.e., the portion of the tank shell with wetted inside surface), the thermal load on the tank shell from a jet flame is partially transferred to the propane liquid inside the tank thus limiting the elevation in the tank shell temperature. Spray of the fire suppression water on the tank could possibly avoid a BLEVE failure of the tank. If the jet fire is impinging on the part of the tank shell above the level of the filled propane liquid (i.e., the part with non-wetted inside surface), a sudden shell rupture could occur due to heatup and weakening of the tank shell, even with successful spray from fire suppression water. This is because, with insufficient heat transfer from the impinging jet flame to the vapor space inside the tank, the very high thermal loads may exceed the cooling capacity of the fire suppression water. Note that fire suppression water is typically provided by fire hydrants equipped with nozzles aiming at the propane tanks.

In general, jet fires from a burning propane storage tank would not impinge directly on any nearby propane storage tanks due to the tank separation and the location of the piping connections (which are the most probable leak sources) being on the top and bottom of the tanks, as opposed to on the sides. However, even if the jet flame does not directly impinge on the adjacent propane storage tank, the heat radiation from the jet flame could cause a BLEVE of the nearby propane storage tanks, if the fire suppression water cannot effectively cool the storage tank. Fortunately, the tank area that would be affected by a jet fire is small in relation to the overall outer surface area of a propane storage tank.

4.4. Release due to Propane Transport Truck Accident

An accidental release of LPG/propane, while in transport, may result in the following hazards: pool fires, vapor cloud fires (flash fires), VCEs, BLEVE blast overpressure, BLEVE fireball, and BLEVE missile. The release incidents without ignition would not generate blast pressure or missiles, or induce thermal radiation. The ignited vapor cloud without explosions would not generate blast pressure or missiles.

For the hypothetical propane transport trailer truck accident, previous unconfined vapor cloud explosion analyses showed that the distance to the 1 psi overpressure from an immediate ignition of a propane cloud at the nearest truck transport route does not reach any critical structure at the nearby nuclear plant. Also, as discussed before, thermal radiation resulting from a pool fire, flash fire, or jet fire is bounded by that from a BLEVE fireball. However, based on past analyses, it is possible for BLEVE generated missiles resulting from a propane truck accident on the truck transport route to reach the nearby nuclear plant site and potentially damage its structures or outdoor equipment.

The evaluation of the propane transport truck missile hazard is based on an accident which occurs within the possible impact range of a propane transport truck generated missile from the nearby nuclear plant. The propane transport truck missile exposure rate is expressed as the product of three main factors: frequency of shipment of propane transport trucks per year, missile exposure distance in miles, and missile generation rate for the substance and the transportation mode per mile.

In the U.S., the EPA permit specifies the number of propane transport trucks that can be filled per day at a propane distribution facility which basically determines the maximum frequency of shipment of propane trucks. The missile exposure distance is determined based on the maximum impact range of missiles generated by the propane transport trucks transiting in the vicinity of the nearby nuclear plant and the propane distribution facility. Due to differences in the direction, degree of winding, and extent of obstructions (e.g., by hills), the maximum missile exposure distance may vary depending on the transport routes leaving the propane distribution facility. As such, the maximum distance traveled per truck transport on the road segments within the missile impact range from the nuclear plant consists of the unobstructed road segments of interest (i.e., within the missile impact range from the nuclear plant) weighted by the percentage of transport trucks on each route.

The missile generation rate for the propane transport trucks is estimated as the product of the propane transport truck accident rate per mile, the conditional probability of an explosion given a propane transport truck accident, and the conditional probability of missile generation given a propane transport truck explosion in an accident. In terms of using the accident rate for Hazardous Material (HM) Class 2.1 (Flammable Gas) cargo tanks to approximate the in-transit propane transport truck accident rate per mile, it should be noted that not all HM Class 2.1 cargo tank accidents involve LPG/propane, nor do all HAZMAT accidents involve a release of a hazardous material. Therefore, only those accidents that involved the specific type of propane cargo tankers used should be considered in the analysis of propane transport truck trailer accidents. However, if only the specific type of propane cargo tankers are considered, both the total number of accidents and the total miles traveled will also be reduced. Assuming that the rates of accidents are roughly the same for the specific type of propane cargo tankers and the overall fleet of vehicles carrying the Category 2.1 HM, the rate of accidents of the vehicles carrying the Category 2.1 HM can be used as a surrogate for the rate of accidents for the specific type of propane cargo tankers.

The likelihood of an explosion per accident can be estimated from the highway in-transit incident data associated with propane cargo tank motor vehicles. The probability of missile generation per explosion accident can also be estimated using the same incident data events based on the number of explosion events that actually involved projectiles or fragments resulting from the LPG/propane explosion and the distance that the projectiles/fragments traveled.

For the determination of the frequency of missile striking the critical nuclear plant area, the propane transport truck missile generation frequency needs to be multiplied by the number of missiles generated by the propane transport truck explosion accident (can be estimated to be 1.0 for those that fly in the direction toward the nuclear plant), the probability of missiles reaching the nuclear plant site, the probability of missile striking a critical area of the nuclear plant, and the probability of missiles exceeding the energies required to penetrate to vital areas or producing secondary missiles that could damage vital equipment.

Because the exposure distances traveled by the propane transport trucks are estimated using the exposure miles within the maximum missile impact range, any missile generated by the propane transport truck accident could potentially reach the nearby nuclear plant. However, based on the actual explosion events recorded in the past incident reports, none of the fragments/projectiles travel farther than the shortest distance between the transport truck routes and the nearby nuclear plant site. As such, the probability of missiles reaching the nuclear plant site should be significantly less than 1.0. In fact, past study had shown that roughly 80% of LPG explosion fragments fall within a 735-foot range.

The probability of missiles that can reach the nearby nuclear plant (e.g., traveling farther than 735 feet) striking a critical nuclear plant area can be estimated by the ratio of the critical nuclear plant area to the area within the annulus missile impact range between a distance of, for example, 735 feet and the maximum impact range from the nuclear plant site. The critical nuclear plant site area may include all of the buildings that contain PRA equipment (e.g., turbine building, service building, auxiliary building, containment, intake structure, diesel generator building, etc.), outdoor transformer areas, switchyard, cooling towers, etc. The missile impact area is the area of a circle with a radius of the longest missile range.

However, for explosion fragments/projectiles generated from a distance as far away as the maximum missile impact range, the missiles have practically lost almost all of its kinetic energy by the time they reach the nuclear plant site. Therefore, most of the missiles may not have sufficient energy to penetrate the building walls to cause damage to the PRA equipment.

Since each missile is likely to only hit one piece of equipment or one structure following a long-distance flight, the Conditional Core Damage Probability (CCDP) for a missile damage scenario should at most represent failures of equipment located in one building. From the conditional core damage risk standpoint, the most critical component to be damaged is perhaps the reactor vessel which is located inside the containment. If the reactor vessel is assumed to be damaged by a propane transport truck accident generated missile, the probability of missile striking a critical area should be much smaller because the containment footprint is much smaller than the total area estimated for the critical nuclear plant site area (perhaps less than 1/10). Similarly, severe plant damage may also result from damage to the auxiliary building which also has a much smaller footprint than the total critical nuclear plant site area. As such, a CCDP value of 0.1 can be justified considering the ratio of the containment building footprint to the total critical site area.

4.5. Possible and Critical Release Event Outcomes

The various scenarios discussed in the preceding can lead to the following possible outcomes:

- Controlled incident
- Pool fire
- Jet fire
- Flash fire in congested areas
- BLEVE with a fireball
- BLEVE with projected missiles
  - No damage to nearby nuclear plant
  - Non-critical SSC damage
  - Minor critical SSC damage
  - Critical SSC damage
- VCE involving deflagration with an overpressure of < 1psi on nearby nuclear plant
- VCE involving deflagration with an overpressure of > 1 psi on nearby nuclear plant
- VCE involving detonation with an overpressure of > 3.5 psi on nearby nuclear plant
- Toxic cloud away from nearby nuclear plant
- Toxic cloud toward nearby nuclear plant

Of the different possible outcomes listed above, only the following consequences would lead to damages to the structures and/or outdoor equipment of the nearby nuclear plant:

- BLEVE with projected missiles
    - Non-critical SSC damage
    - Minor critical SSC damage
    - Critical SSC damage
- VCE involving deflagration with an overpressure of > 1 psi on nearby nuclear plant
- VCE involving detonation with an overpressure of > 3.5 psi on nearby nuclear plant

5. CONCLUSION

Loss of containment and small leaks from the propane storage tanks at the propane storage and distribution terminal, in principle, could result in toxic vapor cloud affecting the nearby nuclear plant control room habitability, VCE explosion overpressure due to both deflagration and detonation, BLEVE missile impacts, and thermal radiation from BLEVE fireballs, flash fires, pool fires, and jet fires. Among these, only VCE overpressure greater than 1 psi and BLEVE missiles can potentially impact the PRA related structures and equipment at the nearby nuclear plant.

However, for the loss of containment event or leak of a single propane storage vessel at the propane distribution facility, the total core damage frequency (CDF) contributions from VCE overpressure due to deflagration in excess of 1 psi, VCE overpressure due to detonation, and BLEVE missile impact is less than 10-7 per year for the nearby nuclear plant.

Because the exposure rate for propane transport truck missile generation is estimated using conservative assumptions and is significantly less than the NUREG-800 acceptance criteria of 10-7 per year, the risk of explosion (e.g., by BLEVE) and missile damage to the nearby nuclear plant due to fragments/projectiles generated from the propane transport truck accidents is considered sufficiently low. The associated CDF is less than 10-8 per year for the nearby nuclear plant.

The total combined frequency of unacceptable damage at the nearby nuclear plant resulting from accidents at the propane storage and distribution terminal and from propane transport trailer truck accidents is also less than 10^{-7} per year. Therefore, the aggregate annual frequency of all credible offsite propane hazards associated with the propane storage and distribution facility having the potential to cause onsite accidents (i.e., core damage) leading to the release of significant quantities of radioactive fission products is less than the NUREG-0800 acceptance criteria of 10^{-7} per year, and thus have a sufficiently low frequency of occurrence. As such, the risk of public exposure is low.

References

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