MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

19th Annual International Symposium
October 25-27, 2016 • College Station, Texas

Improving Prevention and Mitigation Efforts Related to Accidental Releases of LNG

Jesse Brumbaugh, P.E.†, John Burgess, P.E., Keith Farrell
Smith & Burgess Process Safety Consulting
7600 W Tidwell Rd, Suite 600
Houston, Texas 77040
† Presenter E-mail: jesse.brumbaugh@smithburgess.com

Abstract

Liquefied Natural Gas (LNG) is a rapidly growing industry, both in terms of the increase in export terminals, as well as the growing number of regasification plants required to put natural gas back into pipelines. In the selection of a location or design of new facilities, the potential impact of an accidental release must be evaluated. Some of the protective and mitigative measures required by onshore storage and handling facilities for reducing impacts due to accidental releases are dictated by 49 CFR 193, with design requirements based on accidental leakage calculations following NFPA 59A. In the United States, these measures are reviewed by the US Pipeline and Hazardous Materials Safety Administration (PHMSA). Siting and construction of onshore and nearshore LNG facilities are authorized by the Federal Energy Regulatory Commission (FERC). While various specific regulations and codes require some measures, a detailed evaluation of the potential consequences may indicate that additional mitigative actions are needed.

PHMSA requires both pool fire and dispersion models from scenarios of accidental releases of accumulated LNG in containment basins as per the 49 CFR 193 regulation in order to meet the NFPA 59A standards. Containment basins include LNG tank impoundments, trenches, and sumps, which are often modeled with LNG accumulating due to a guillotine break of the largest pipe.

While accidental releases of LNG can be mitigated by trenches, sumps, and other forms of impoundment, the effectiveness of the mitigation is impacted by the nature of the trenches and containment basins. Any positive or negative impact is difficult to predict without complex evaluation. For example, if the tank itself is designed in such a way that a rip or rupture of the inner tank wall followed by thermal cracking of the external wall is a credible scenario, the elevation of a resulting hole as well as the size of it could render the basin walls inadequate depending on the location and extent of tank damage and impoundment geometry. Also, in terms of trenching used to direct LNG to containment basins, the geometry of the trench itself combined with the wind direction can have a significant impact on the generated plume size with LNG

accumulation. In particular, a long linear span of trenching that is parallel with the wind direction may result in enough accumulation to generate a large plume well in excess of 1 kilometer.

CFD models predict that the magnitude and location of an LNG release, the weather conditions, the regional terrain, release impingement, and the duration of the release can all greatly influence how far a combustible gas cloud will travel. Proximity of pipelines to vehicular or railway traffic can lead to an increased frequency of pipe breaks, and sometimes older facilities may be lacking in protective measures such as vapor fences that could better protect the public. Potential causes of releases will be explored and a range of possible improvements with prevention and mitigation measures will be discussed.

Introduction

Changes in the market due to enhanced recovery methods have led to cheap abundant natural gas (NG) in countries such as the United States. This has led investors to build LNG export terminals, and by 2020 the United States is forecasted to account for 15% of global liquefaction capacity, becoming the third largest exporter in the world (1). All onshore LNG storage and handling facilities in the United States are regulated by the US Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), and a lot of focus has been placed on ensuring the safety of the public in the transportation of LNG and operation of LNG facilities.

Some of the first imports of LNG occurred in the 1960's in Europe, and four marine terminals were built in the United States from 1971-1980 (2). During the years when LNG import terminals were built in the United States and Europe, there was a growing interest in better understanding the behavior of LNG released into the environment, after which several computer models were developed in the 1970's and several LNG spill experiments were done in the 1980's. Today, DEGADIS (Dense Gas Dispersion Model), PHAST (Process Hazard Analysis Software Tool), and GexCon's FLACS (Flame Acceleration Simulator) are the primary modeling tools used in the evaluation of consequences related to accidental releases of LNG.

This paper will discuss the evolution of LNG dispersion research, as well as an evaluation of the applicability, strengths, and weaknesses of some of the more commonly used tools. Additionally, further details will be provided on flashing and jetting releases of LNG.

After providing an overview of the models, two case studies will be presented, one for a PHMSA facility siting project that explores arrangements of sumps and trenches, and another for an existing LNG facility in a location with complex terrain. Both facilities were studied with computational fluid dynamics (CFD) models, with the first case study using FLACS and the second one using Star-CCM+ (computational continuum mechanics) by CD-adapco (Computational Dynamics-Analysis & Design Application Company). Further detail will be provided on the methodology and rationale used for the Star-CCM+ model for the second case study.

Finally, an overview of several preventative and mitigative measures will be presented that can help with efforts related to reducing or eliminating consequences related to accidental releases of LNG.

History of LNG Dispersion Research

In the 1970's there were a number of models regarding LNG vapor cloud dispersion, but with great variations in results. In a study by Dr. J. A. Havens in 1977, seven of these models were evaluated and predicted dispersion distances anywhere between 1.2 - 81 km (0.75 - 50 miles) for the same catastrophic 25,000 m^3 (6.6 million gallon) LNG spill (3). Due to the wide variation in modeling results, experimental testing was desired to better understand the behavior of cryogenic liquid spills and resulting vapor cloud dispersion. Maplin Sands, Burro, and Coyote LNG spill experiments were performed in 1980 and 1981 leading to the development of the earliest models including the SLAB and FEM3 computer codes (4). The Dense Gas Dispersion model DEGADIS was later developed for Gas Research Institute (GRI) in 1985 for ground level dispersion, and went through several iterations throughout the years improving the predictions of the model. Additional testing was later done with the Falcon LNG spill experiments in 1987.

Figure 1: 1987 Falcon LNG spill experiment (5)

As a result of the full scale experiment, several unique physical phenomena are observed with LNG vapors such as reductions in turbulent mixing with air, density stratification, and gravity flow of the cloud (4). As the cloud is heated, the turbulent mixing activity increases until the vaporized NG eventually disperses into the surrounding air. However, as long as the cloud remains cool, the NG dispersion will be limited. The driving force for dispersion of an LNG vapor cloud is predominantly the wind, any obstacles the cloud may encounter, as well as the terrain. The layered nature of the atmosphere and the large amount of force applied to it by the atmosphere also tends to stratify or "pancake" horizontal releases of material. All of these factors combined lead to vertical dispersion being very low while horizontal dispersion is very high with releases of cryogenic materials.

As computing power has advanced over the years along with our scientific understanding, the sophistication of our modeling capabilities has improved to the point of modeling the underlying physics in 3-dimensional geometries through CFD modeling. Today, CFD modeling is commonly used for LNG spill dispersion modeling. GexCon's FLACS is perhaps one of the most well-known CFD models for LNG spill dispersion modeling and has had extensive validation, being the only CFD software with official approval by the US Department of Transportation (DOT), PHMSA for LNG vapor gas dispersion modeling as of 2016 (6). Other consequence modeling software, such as DNV-GL's PHAST, has also been approved by PHMSA for LNG vapor gas dispersion modeling (7). Other CFD modeling tools are actively going through the PHMSA approval process, such as CD-adapco's Star-CCM+ (5).

Evaluation of Available Models

The models used for LNG releases can be divided into two types: empirical, which try to match experimental observations with characterizing equations and often rely on Gaussian plume correlations for gas dispersion, and CFD models, which attempt to simulate the underlying physics in a discretized 3D computational domain. 49 CFR 193.2059 explicitly approves DEGADIS and FEM3A. Other models approved by PHMSA are the empirical model PHAST and the CFD model FLACS. DEGADIS allows the modeler to define the LNG vapor source term, such as a predefined LNG containment sump with the vapor generation rate defined by the user. PHAST can directly simulate a release from a pressurized vessel through a pipe break or leak, an orifice release over a set period of time, or through a user defined source term such as a vaporizing pool. In comparison to the mentioned empirical models, FLACS is more sophisticated and in a sense more exact by simulating the actual LNG spill in real time as it grows and boils off due to heat transfer from the ground and also the sun, not requiring a separate source term for vapor generation. This allows the model to be applicable to trenches and other complex geometric features which are more challenging to model or sometimes not possible with depending on the empirical model. Additionally, FLACS has a FLASH utility that allows the user to separately calculate a resulting vapor release from a liquid jet release flashing into a gas at high pressures and velocities.

Formal interpretations by PHMSA place additional requirements on LNG vapor dispersion modeling that restrict the types of models that may be used under different circumstances. Empirical models are restricted to flat terrain, and with the exception of PHAST allowing a single structure's wake influence, obstructions in the dispersion pathway are not incorporated into these models. PHMSA has stated that DEGADIS can no longer use the SOURCE5 source term model to calculate vapor gas dispersion zones for LNG facilities, and further states that DEGADIS does not account for jetting and flashing releases from pressurized piping and equipment (8). It has been found that jet release scenarios are typically the bounding case for facility siting studies, and in order to model a jet release, methods other than DEGADIS must be used, which commonly leads to PHAST being an initial screening tool and FLACS being a more detailed tool to evaluate mitigations such as vapor fences, trenches, and troughs (9).

PHMSA has specified a list of experimental results that models must be compared to become approved for LNG vapor dispersion modeling, known as the Model Evaluation Protocol (MEP). Currently, the only LNG tests specified in the MEP database are the Maplin, Burro, Coyote, and Falcon tests in the 1980's (10). A brief summary of the scale of these LNG tests is illustrated in the table below.

Table 1: Comparison of LNG Experiments

Experiment Set	**Year**	**Release Rate (m^3/min)**	**Release Amount (m^3)**
Maplin	1980	1-instant	5-31
Burro	1980	12-18	24-39
Coyote	1981	6-19	3-28
Falcon	1987	9-30	20-66

Based on these parameters, the total duration of the releases except for the Maplin tests (which consisted of direct spills into the sea) is estimated between 0.5 - 2.2 minutes. In addition, these are relatively small volumetric releases of LNG; by comparison, a tanker truck can hold 40 m^3 of LNG whereas a marine tanker may hold 25,000 m^3 of LNG (11). As such, there is currently no officially listed experimental data for jetting and flashing releases of large quantities of LNG from high pressure sources, catastrophic failures of large LNG storage tanks, or long time duration releases of LNG (such as the 10-minute duration specified by NFPA 59A (12)). LNG spill tests of 300 m^3 and 3,000 m^3 have already been suggested to address variations found in model predictions at increased volumes (11). Regarding jets, it is well documented that a large fraction of the liquids present in flashing LNG jets can vaporize before raining out into a pool, as shown in testing undertaken by Shell in 1974 and Advantica in 2007 (13). The lack of experimental data on flashing jet releases is especially problematic because all of the aforementioned tests dealt with LNG spills into pools of water. In fact, even leaks from the base of a large LNG tank can result in a jet release (13). If the jet release is mechanically fragmented, as is typically the case with pressurized or highly turbulent LNG releases, heat transfer with the air due to mixing of spray may be sufficient to vaporize the entire jet even before it hits the ground (13). In order to better validate models that deal with large jet releases over a long time duration, there would be great value in further experimental testing of LNG releases covering large volumetric release rates and large flashing jet releases and adding these to the MEP database.

While both PHAST and FLACS are able to model flashing jet releases, PHMSA has noted certain limitations to be mindful of when choosing these models. For PHAST, these limitations are regarding dispersion from high aspect ratio sources such as trenches (though this can be accomplished with some non-default parameters), crosswind releases, dispersion over varying or sloped terrain, and dispersion with obstacles causing wind channeling (7). FLACS is more robust in that it can handle obstacles and channeling effects, but its main limitation is inaccuracies with dispersion over terrain with at least a 10% grade due to the stair-stepping method of representation of the Cartesian grid (6).

In summary, as long as the terrain throughout the LNG facility and surrounding area has no greater than a 10% grade, FLACS is well suited for LNG facility siting requirements. For flat terrain with minimal obstacles other software packages – with great care in defining non-default parameters – such as PHAST may be used. Fortunately, most LNG facilities being constructed in the United States are LNG export and import terminals located on rivers and coastlines where marine tankers can be filled with LNG or offload LNG and the terrain is relatively flat. However, there are LNG facilities that have been constructed in hilly or mountainous regions, and under these conditions, there is currently no officially approved model for dispersion in these areas. As such, persons doing LNG dispersion models in these regions are using unapproved general purpose CFD modeling software packages capable of incorporating complex angled terrain, until FLACS is upgraded to allow for proper handling of sloped terrain.

1st Case Study –Greenfield LNG Facility with River Levee and Trenching

The first case study involved a greenfield LNG facility along a river at a preliminary front end engineering design (FEED) stage. The facility was on flat terrain with the exception of a levee found along the river for flood control.

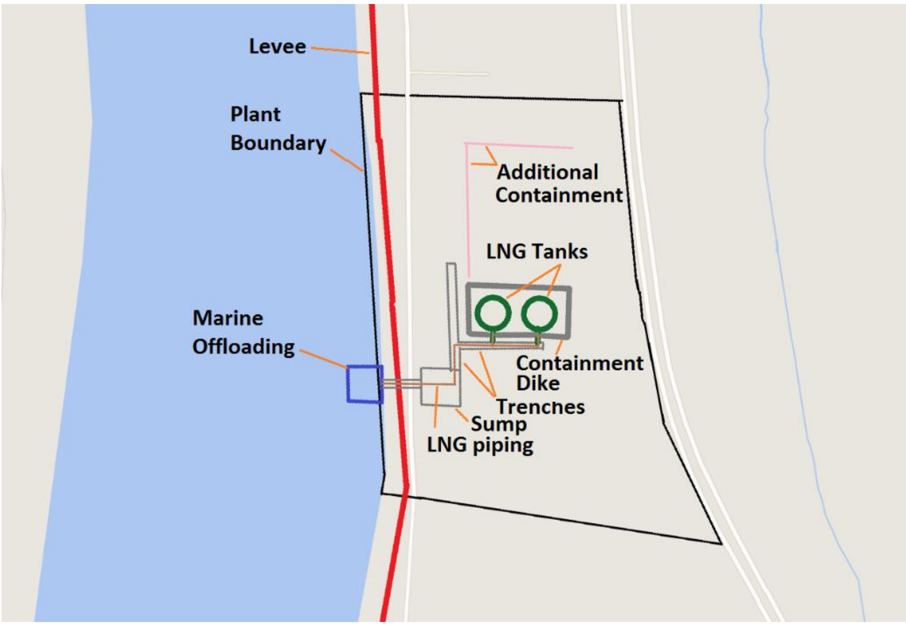

Figure 2: Greenfield LNG facility – Initial FEED concept

Spills from the LNG tanks are designed to be held by the containment dike. In addition, LNG is pumped from the tanks to the marine offloading arms via large diameter overhead LNG piping. Additional containment is found throughout the facility for truck transportation or other facility equipment leaks. Trenches and sumps underneath large diameter loading/unloading piping are designed to contain leaked material allowing for safe evaporation and dispersion out of the containment system.

Preliminary modelling of the facility was done using PHAST, followed by more detailed modeling of LNG pooling and vaporization out of the containment dike, sump, and trenches found throughout the facility using FLACS. While using FLACS for LNG spill vaporization dispersion modeling due to leaks from the large diameter LNG piping, one interesting observations was that if the wind direction was parallel to the trench that contained LNG, the dispersion distance of the ½ lower flammability limit (LFL) contours out of the long trench would be substantially further compared to the same ½ LFL dispersion contours from vaporizing LNG in the sump or containment dike alone under otherwise similar conditions. The levee itself was roughly 13 feet tall and had a maximum grade of 30°. Containment dikes also had a relatively steep grade. During modeling it was discovered that the orientation of the trench being parallel with the additional containment diking found above the LNG storage tank containment dike and the levee combined to create a strong channeling effect, even though the distance from the trench to the levee was approximately 100 meters. This channeling effect combined with the trench caused the LNG to become more concentrated due to it restricting expansion in lateral directions. This restriction to expansion resulted in much higher concentrations further downwind compared to those seen with other wind directions or different spill locations.

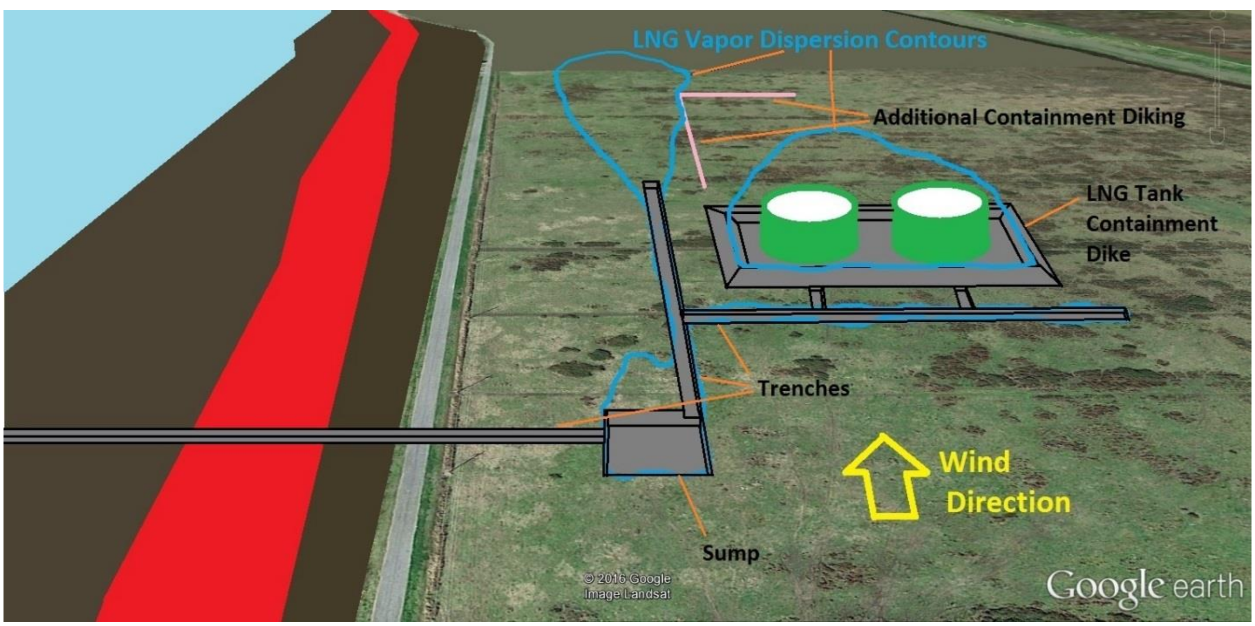

Figure 3: Illustration of relative travel distances of FLACS LNG vapor dispersion contours from containment basins

2nd Case Study – Worst Case Scenario Modeling for an LNG Facility with Hilly Terrain

The second case study considers an existing LNG facility with hilly terrain and large variations in elevation. The goal was a series of worst case scenario (WCS) models of the facility. While the Environmental Protection Agency (EPA) requires WCS models for facility risk management plans (RMPs) under their jurisdiction as part of the Clean Air Act Section 112(r), LNG facilities fall under the jurisdiction of DOT and do not require a WCS model for siting evaluation. In fact, PHMSA's siting requirements are that all failure scenarios with a minimum failure frequency of 3×10^{-5} occurrences per year be evaluated. This frequency corresponds to the rupture frequency of the largest diameter LNG withdrawal line connected to an LNG storage tank (14). Going back to the desire to generate WCS models for this facility, they were not based on any regulatory driver, but instead were used for emergency response planning (ERP) purposes.

Model Setup

The LNG storage area is located close to the top of a large hill, with many parts of the surrounding area having over a 10% grade. These characteristics meant that the terrain would play a large role in how LNG vapors would disperse throughout the region. The complexity of the terrain and the large slopes meant that FLACS would fall outside of PHMSA's criteria for using the software for an LNG facility. Although no other software is approved by PHMSA for such circumstances, these WCS models are not a requirement by PHMSA in either case so the usage of another software was not an issue. As such, it was decided that Star-CCM+ by CD-adapco would be used to conduct CFD modeling for this facility since it can import and use complex terrain. It should be noted that this decision does not constitute an endorsement of this product but is strictly shown to highlight the findings and provide a methodology that can be followed for facilities under similar circumstances. The topography of the region is illustrated below.

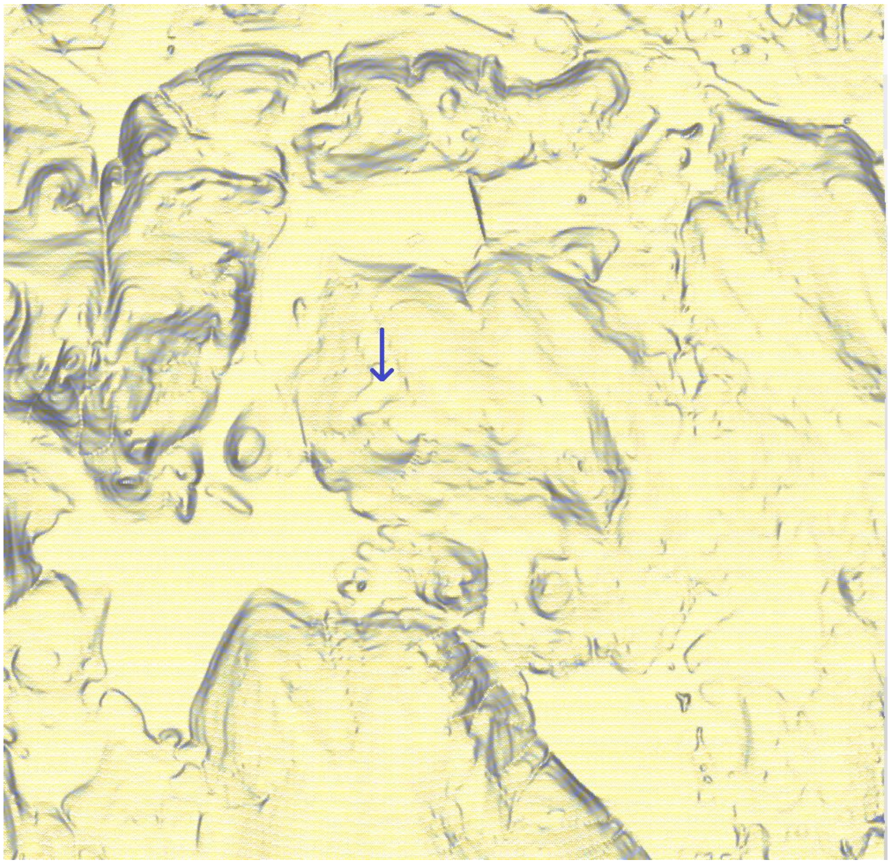

Figure 4: LNG containment location (blue arrow) and surrounding topography

The terrain was generated from a digital elevation model (DEM) downloaded from the United States Geological Service (USGS) National Elevation Dataset (NED) in a grid float format. This data has a resolution of 1/3 arc-second, which corresponds to an elevation data point roughly every 10 meters. One of the challenges that is often experienced with atmospheric dispersion models over complex terrain is the issue of turbulence eddy clipping, which occurs when jagged terrain is found along an inlet or outlet plane of the model. When a geometric feature creates a recirculation zone that reaches the edge of the computational domain, it can lead to instabilities in the model or even solution divergence and a crash. To resolve this issue, an additional smoothed border was added around the terrain shown in Figure 4. This smoothed border is illustrated in Figure 5 below.

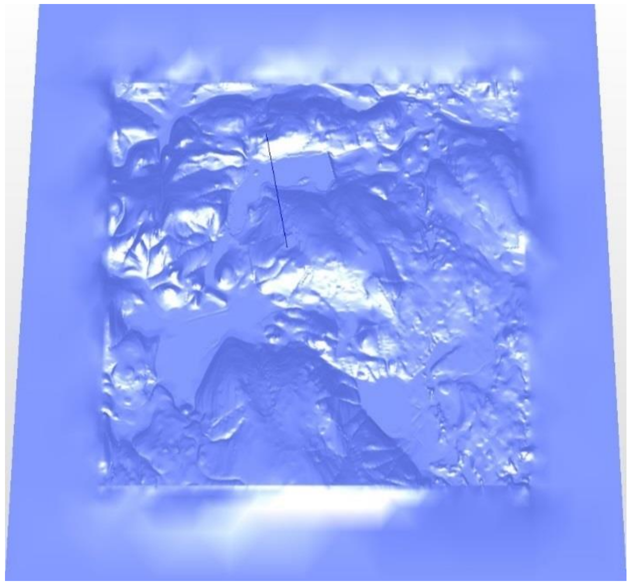

Figure 5: Border smoothing technique applied around topography

Another challenge for the model was the nature of the LNG release itself. Most LNG vaporization models involve the filling of a containment basin with LNG and subsequent vaporization as heat is transferred, mostly from ground conduction, wind convection, and solar radiation, and are relatively straightforward in that a separate vapor generating source term can be defined as the input into the model. As mentioned earlier, LNG releases that are jetting and flashing can easily pose the greatest consequences, so these were the focus of the chosen WCS models. This can be evidently seen by simulating a high pressure horizontal release of a flashing liquid in PHAST, where consequence distances can easily extend over a mile depending on the nature of the release, as illustrated in Figure 6.

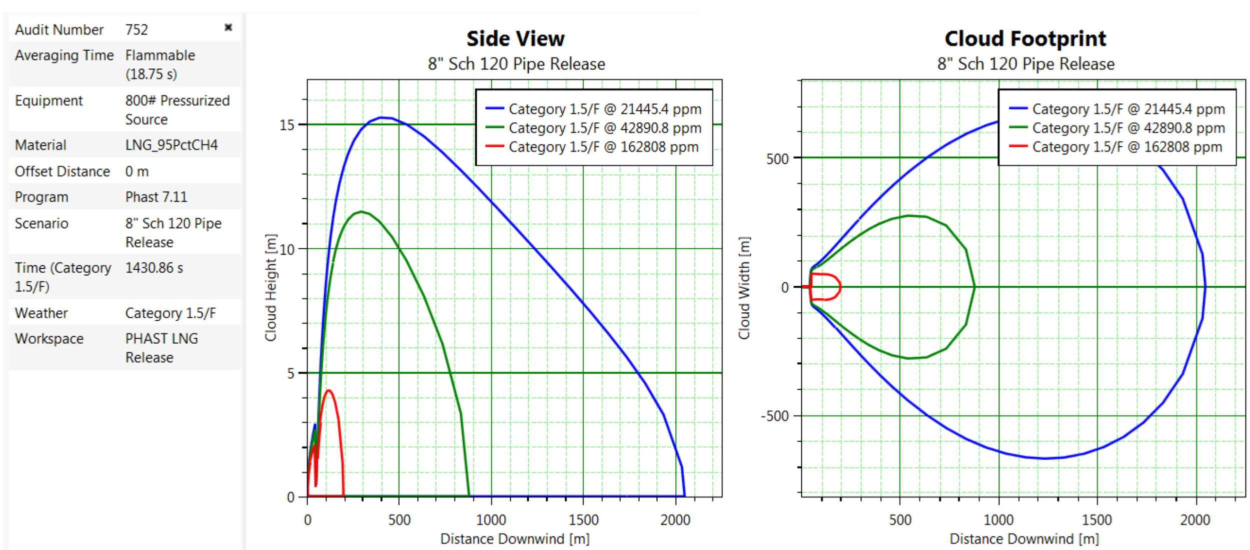

Figure 6: Horizontal release of high pressure LNG in PHAST

These sorts of releases are much more complicated to simulate in CFD, and the simpler technique of a fixed vaporizing pool with a spill cannot be done. Without having access to the FLACS FLASH utility, this jetting and flashing mechanism was instead directly simulated in the Star-CCM+ CFD software.

Two different wind speeds were used, the standard speed of 2 m/s and the lowest wind speed of 0.46 m/s excluding the 10^{th} percentile both at class F stability and a relative humidity of 50% in accordance with NFPA 59A (12). Additionally, the average annual temperature of 50°F and barometric pressure of 101720 kPa was used.

The wind in the simulation was first converged under steady state conditions, then the simulation was changed to unsteady state to better capture varying turbulence eddies and converged. The LNG release was then introduced into the model under unsteady conditions. The release was slowly introduced at very low flow rates at short time steps, then steadily increased until reaching its maximum release rate to maintain stability during the simulation.

Failure Scenario 1 – Worst Case Pipeline Guillotine

The first scenario involved a worst case pipeline guillotine in the facility. The hypothetical mechanism was a vehicular collision causing a complete shearing of the pipe resulting in a release of LNG. Since this was a worst case analysis, the piping with the highest pressure in the facility was used, which was 800 psig. Not much information was known about the location of the piping, so it was assumed to be found close to a road. ASPEN HYSYS was used to calculate the flow rate out of an 8” schedule 120 pipe at the given pressure and came up with 509 kg/s, or 1.2 m^3/s. The pipe release was assumed to have a TI (turbulence intensity) of 5% (medium-high turbulence) and a TLS (turbulent length scale) of 0.0128 m.

From the simulation, the very high pressures resulted in a mechanically fragmented jet that quickly absorbed heat from the ambient air and flashed into NG, which appeared correct based on the literature cited in Evaluation of Available Models. Pink vertical slice planes of these releases at the two wind speeds are shown in Figure 7 below.

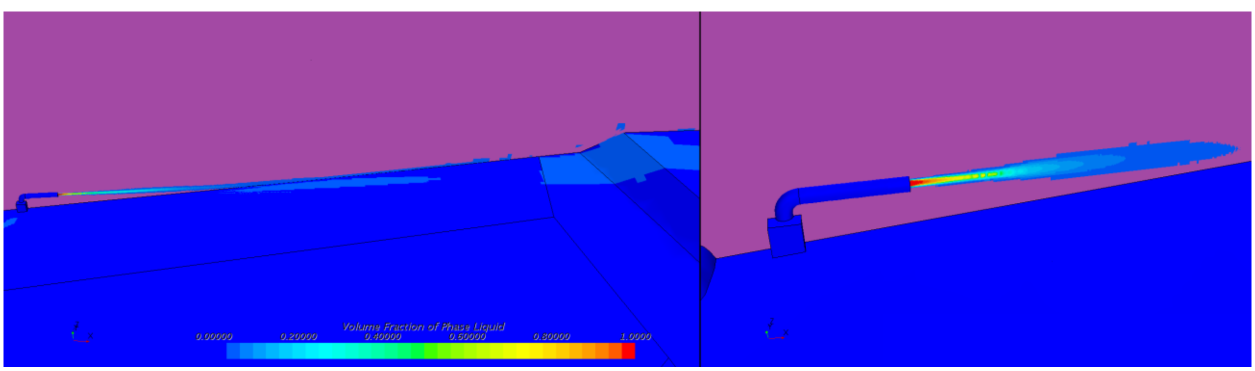

Figure 7: Flashing LNG jet release with 0.46 m/s wind shown on the left and 2 m/s wind shown on the right

Greater wind speeds increase the volatilization rate due to increased convection, as would be expected. The change into NG vapor from this release can be seen in the next picture.

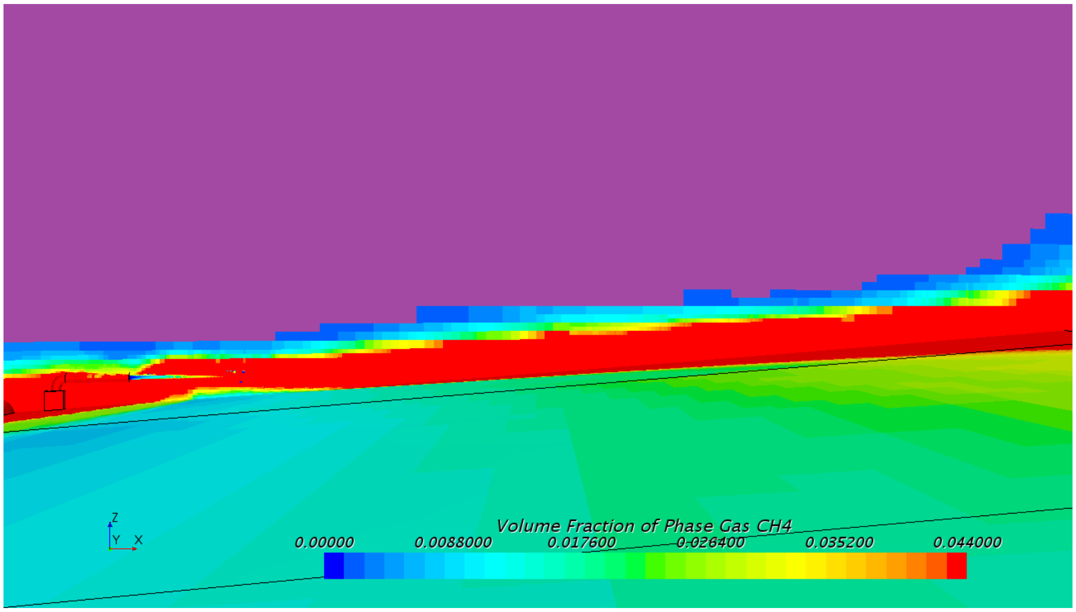

Figure 8: NG vapors formed from flashing release with 2 m/s wind (red = LFL)

One interesting observation from the images shown in Figure 7 and Figure 8 is that because the ground is slightly sloping upwards while the pipe release eventually impinges on it, the LNG plume is even closer along the ground starting out. Different wind directions were run, and in each simulation the plume tended to follow wherever the wind took it. The wind travel itself was also strongly influenced by the terrain. One example is shown in the following simulation that had a wind from north-northwest at 2 m/s.

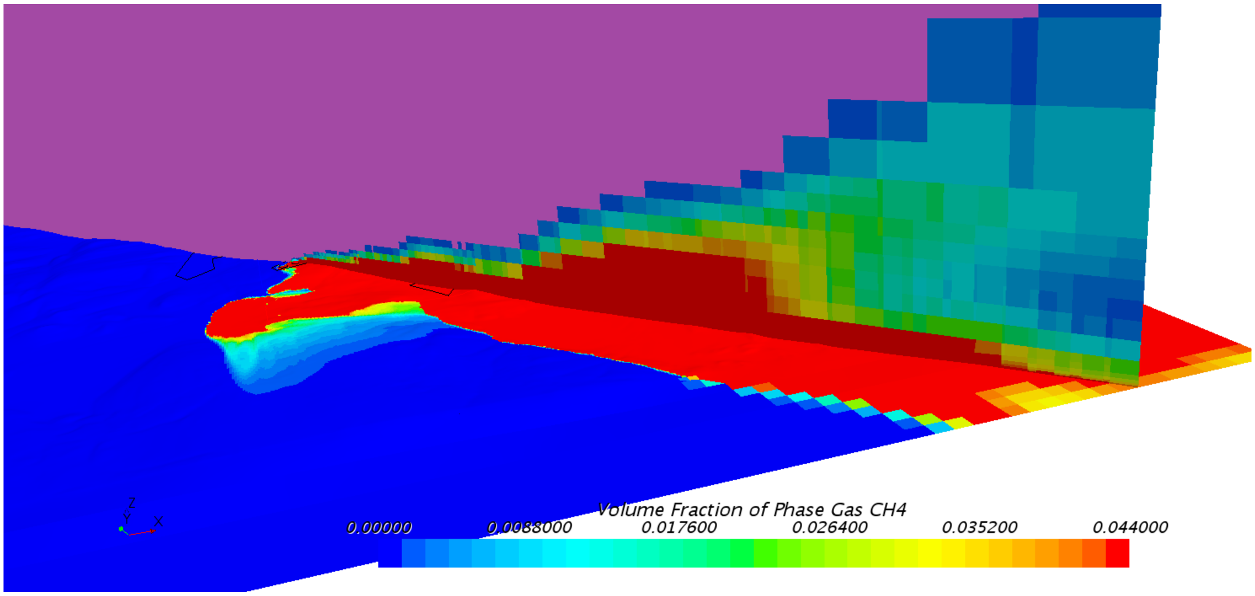

Figure 9: NG vapors from high pressure flashing release, 2 m/s wind from north-northwest (red = LFL)

In this example, the furthest extent of the plume is 6 km to the southeast corner of the domain. Note the PHAST example shown in Figure 6 had the LFL contours only rising up 11.5

meters, and extending 880 meters downwind. PHAST also predicts much greater horizontal dispersion in proportion to the plume length in the absence of terrain obstacles, with a total width of 580 meters. In the case of the CFD model, there is a great deal of channeling from the terrain, especially given the fact that cryogenic gases tend to pancake and stay low to the ground. This case had one hill to the south and another to the east (see Figure 4) essentially choke the LNG plume and channel it out to the southeast corner of the domain, illustrating the critical importance of factoring in topography in this particular model.

Failure Scenario 2 – Catastrophic LNG Tank Rupture

The second scenario involved a rupture of a single LNG storage tank. The tank consists of a typical inner tank within an external tank. The hypothetical mechanism was an unspecified heater malfunction that causes ice formation from the moisture in the air between the tanks, eventually causing the internal tank to shift and possibly fail, spilling LNG into the cavity. The cold LNG along the wall may ultimately cause the external tank wall to crack due to the high temperature differential with the outside environment, creating a triangular shaped hole for LNG to jet out of the tank. Since this was a worst case analysis, the hole size was a 1.27 m x 2.6 m triangular hole, which has a cross-sectional area of 1.65 m^2. Note that this is roughly twice the 1 m diameter hole size in PHMSA's table that is considered an 8 x 10^{-5} per year event for a single containment atmospheric storage tank and a 1 x 10^{-5} per year event for a double containment atmospheric storage tank, and then a 5 x 10^{-6} and 5 x 10^{-7} per year event for respective catastrophic failures (14). The Bernoulli equation was used to determine the maximum flow out of the hole (15). For this hole size and a liquid level of 19.4 meters, the maximum flow came out to 33 m^3/s or 13,500 kg/s. Different flow rates out of the tank can be achieved with different hole sizes or spill amounts from the internal tank, depending on the breach. The tank release was assumed to have a TI of 10% (high turbulence) and TLS of 0.0684 m.

As mentioned in the literature, again, a rupture at the base of an LNG tank can cause jetting and flashing to occur (13). The flow was also highly turbulent, and due to mixing with the air and a swirling eddy generated off the side of the tank, the release from the tank rapidly aerosolized and a large portion flashed into a vapor in the simulation. A vertical slice plane of the release is shown in Figure 10.

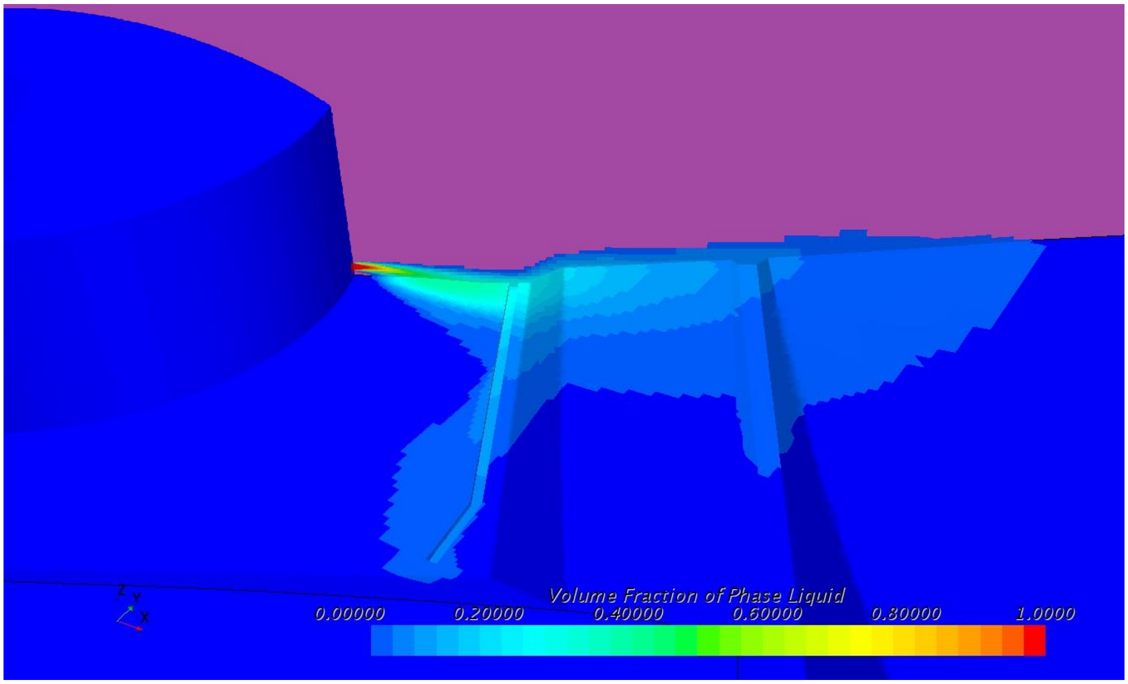

Figure 10: LNG Tank Rupture through 1.65 m^2 hole

The results from these simulations were similar to the ones of the pipe guillotine, though much more concentrated and wider reaching. An example is shown in the following tank rupture simulation, that had the same wind from north-northwest at 2 m/s as the pipe guillotine simulation.

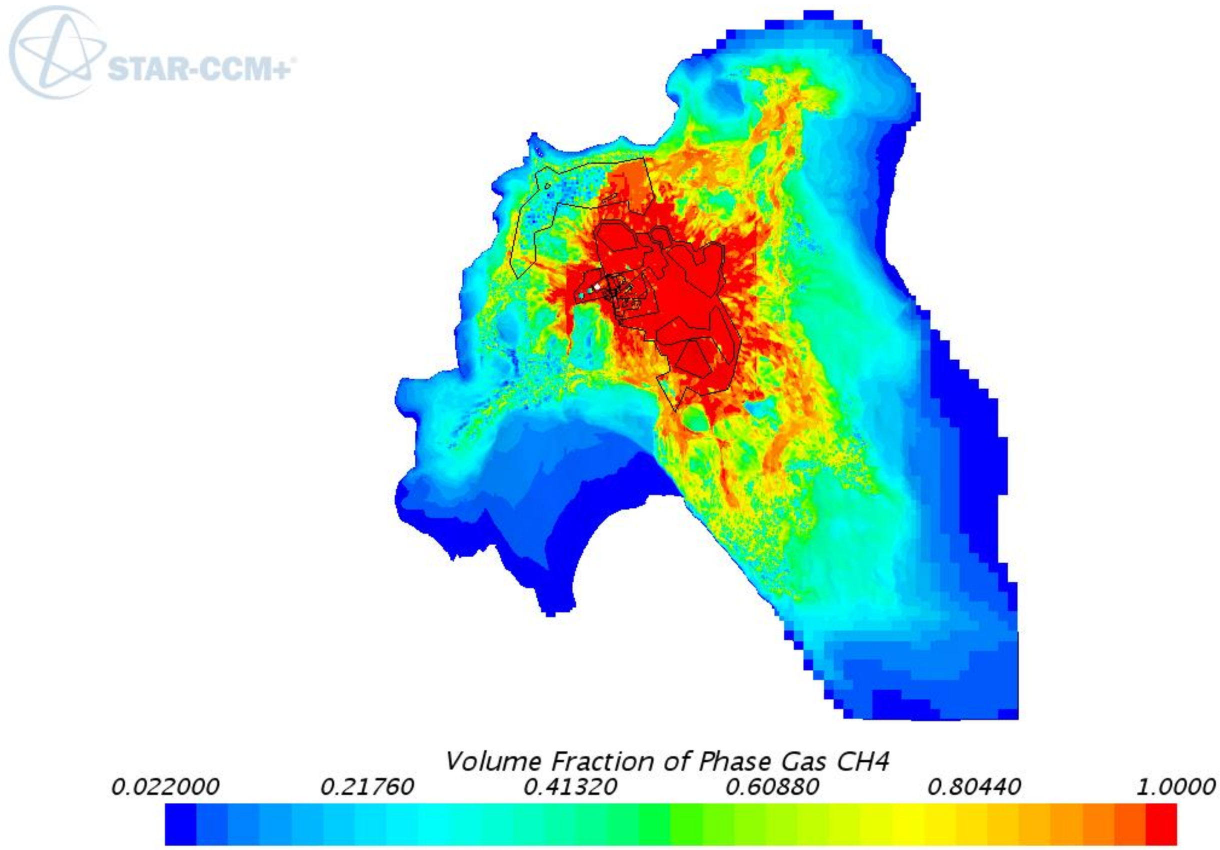

Figure 11: NG vapors after catastrophic tank rupture, 2 m/s wind from north-northwest (blue = ½ LFL)

Again, as can be seen from the topography images, the cryogenic NG vapors closely follow the terrain and the wind direction. Another observation is that while the ½ LFL contours for both scenarios reached the southeast corner of the domain, the LFL contours for the high pressure pipe guillotine scenario (Figure 9) extended further than those for the tank rupture scenario (Figure 11). Both simulations went for roughly 17 minutes. Even though the tank had a much larger release rate (by a factor of roughly 20), this decreased dispersion distance could be attributed to a slower volatilization rate, the physical location of the release being in the containment basin, or perhaps both factors. However, the cloud is also notably wider in several areas as well, likely due to more area overall where volatilization is occurring.

Further Remarks on Model

It needs to be emphasized that these are WCS models, and that not only would an ignition source be found well before the NG cloud travels several kilometers and mitigative systems would likely detect the leak and isolate it, but the actual models required by PHMSA for LNG facility siting should have a frequency threshold of 3×10^{-5} occurrences per year. Also, regarding pressurized leaks from pumps instead of vessels, if the maximum pump flow rate is known from pump curves then that should be used for a PHMSA LNG facility siting study, depending on the maximum number of pumps that could be in service (16). As such, neither of these models would apply for PHMSA facility siting and an actual consequence would be considerably smaller. Regarding selection of single accidental leakage sources (SALS) for calculating exclusion zones, it should be emphasized that because the terrain played a large role in these model outputs, other LNG facilities in locations with complex terrain may need to consider multiple wind directions to find the largest exclusion zone, and it is strongly encouraged to use a CFD model due to the channeling effect which leads to further dispersion distances than the empirical models.

Another remark is that there is currently no way to check this model against the PHMSA validation protocol using the MEP database, since there are no cases with flashing jet releases. It would be beneficial for the LNG community if new experiments are carried out that focus on flashing jet releases so that such a model can be validated, and not just having data for spill pool models. Nevertheless, some basic qualitative comparisons can be made to see if the results are reasonable. The comparison to the PHAST LNG plume height versus length appears to be satisfactory based on the figures, as well as to pictures and videos of actual cryogenic gas plumes flowing across a surface. In addition, a basic test of a sealed container filled with a layer of 100% NG vapor at the bottom and another layer of 100% air at the top was simulated to see how well the model accounted for air and NG vapor mixing, particularly to make sure that the model treated the air and NG vapor as completely miscible and that the NG would end up slightly more concentrated at the top due to density differences. The test was run for 1 minute and revealed that this indeed was the case.

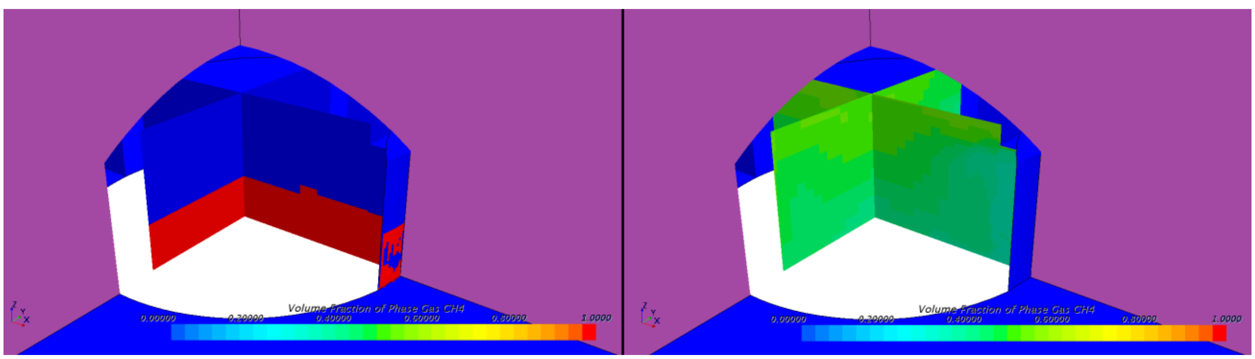

Figure 12: Tank with air layer at top and NG layer at bottom at 0 seconds (left), then diffused after 62 seconds (right)

Accident Prevention and Mitigation

There are many factors to consider in design of the facility to prevent or mitigate accidental releases of LNG. For the sake of brevity, they are bulleted in the following list, and some will be further discussed in the conclusion.

- Geometry of trenches that avoids long linear stretches without bends or angles;
- Relocating site obstructions or additional containment that could potentially lead to channeling;
- Geometry of dikes to better contain worst case jet releases from base of tanks through adequate height, slope, and proximity;
- Reducing volumes of LNG by choosing smaller vessel sizes or using less inventory;

- Creating more isolation points between LNG vessels and pumps by installing fail close (FC) valves that can trigger upon detection of a leak or trigger upon emergency shutdown (ESD) to reduce leak duration;
- Safety instrumented systems (SIS) that monitor for gas, temperature, pressure, vacuum, and flow anomalies;
- Using mechanical interlocks and other passive preventive measures on LNG pumps;
- Reducing congestion of piping and equipment to decrease overpressures from flame acceleration or chain reaction events (17);
- Using gas fueled turbines and compressors instead of boilers (18);
- Eliminating hazards of road collisions with piping through checkpoints, covering exposed piping, rerouting roads, or putting in barriers capable of stopping a runaway truck;
- Considering train derailment as a possible scenario and locating major LNG piping and equipment far enough away from train tracks to prevent significant releases;
- Increasing numbers of gas detectors in the facility, particularly at high hazard areas or areas prone to leakage, and consider mapping detectors through dispersion modeling to improve response time and reduce leak duration;
- Placing emphasis on automatic systems that detect the hazard and trigger an ESD and not relying solely on operator intervention or emergency response (ER);
- Reducing tank rupture frequency by using a double containment LNG tank instead of a single containment LNG tank, or even further reducing the frequency by using a full containment LNG tank (19);
- Monitoring integrity of large LNG tanks, internal heaters, ventilation systems;
- Relief devices and systems for cryogenic equipment to prevent catastrophic failure of vessels and piping due to overpressure events;
- Placement of vapor barriers around the site to redirect NG vapors or reduce their potential to impact the public;
- Usage of gas lamps or other ignition sources around the site perimeter as a last line of defense to safeguard the public;
- Usage of water spray curtains (20);
- A robust process safety management (PSM) program that is regularly audited and continually improved;
- A robust ERP that has considered all potential scenarios, trained ER personnel appropriately, and coordinates public communication effectively;
- Risk based inspections (RBI);
- Double walled piping to serve as secondary containment, especially for large diameter high pressure pipes, and shrouded piping;
- Vacuum jacketed pipe (VJP) or vacuum insulated pipe (VIP);

In general, the best way to stop problems from occurring is by putting into place robust prevention measures. How can we best prevent a release of LNG from occurring in the first place? It is important to have a robust mechanical integrity (MI) program. Is there the potential for water to contact the piping and act as a surfactant to transfer acids or bases that lead to corrosion of the pipe? Is there a possibility of impact by ground transportation? Safety systems should also be in good working order. Is there an automated dump or blowdown to manage excessive inventory and holdup in tanks? Running equipment at or near capacity can make it difficult to control a process if there is a unit upset or other incident. Do we always need a tank? Can the substance be left in the pipe? Is there the potential to flood the system or dump heat into it? Flare sizing is also very important. Is there a water seal at the bottom of the flare that could be blown off from rapid boiling? Cryogenic gases are highly compressed and expand very rapidly as they are heated. As such, flares at LNG facilities may need to be quite large, and the flashing of liquids into gases should be taken into account for the sizing calculations.

If an accidental release does occur, mitigative options will also be important and should involve careful consideration from detailed consequence modeling. How closely are equipment placed in the plant? Equipment congestion can cause a loss of control at one piece of equipment to quickly involve another piece of equipment. Examples can include a spreading pool fire being fed by additional equipment or the increased flame acceleration from a congested vapor cloud explosion. The effects of channeling and the design of trenches, sumps, and vapor fences are very important should likewise be very closely evaluated to optimize dispersion of cryogenic vapors.

Conclusion

Through the help of complex analysis, especially CFD modeling, critical areas of an LNG facility that pose a considerable hazard and have large exclusion zones can be better identified and mitigated. Whether it be geometry of the trenches, containment dikes, contributions to channeling, or certain piping or process equipment too close to a road, hazards are more likely to be found to help direct mitigation efforts. Depending on the severity of a consequence, piping could be made safer by adding secondary containment and finding ways to reduce the release duration. LNG tanks can be made safer by choosing double or full containment tanks instead if the option is available, or by installing appropriate safeguards such as alarms for moisture content and temperature within the cavity of a double-walled tank. Also, mitigative barriers such as vapor fences and water curtains can reduce the dispersion distance of vaporized NG. Finally, while WCS may not be applicable to the PHMSA approval process, it can be of help for development of a robust ERP that considers all possible scenarios and knows how to respond in every situation.

In addition, evaluation of SIS than can help prevent incidents from occurring or respond to them more quickly can be evaluated through a layer of protection analysis (LOPA) or other process hazards analysis (PHA) technique. Such credits for independent protective layers (IPLs) can then be applied to reduce the frequency of potential incidents to lower risk to an acceptable level. Any FC valves connected with the SIS can be placed in a manner that reduces release duration from LNG release events by isolating inventories and decreasing potential leakage sources downstream of a pump. Finally, gas detectors tied into the SIS can be placed throughout the site and mapped appropriately through placement by items of concern and those prone to leakage, as well as with dispersion modeling.

Included with a focus on instrumentation should be a focus on mechanical aspects of the system. A robust MI program can likewise help in reducing the frequency of piping and equipment leakage.

As a final remark, facilities with considerable topography variation need to consider the channeling effects from the terrain due to the considerable under prediction of dispersion distances without it. There are also holes in the MEP database used by PHMSA where jetting and flashing releases of LNG, especially at high pressures and flow rates, have not been accounted for. It would be desirable to have a way to validate these releases, since they appeared to be the most hazardous based on the discussions made by others, some of the models run, and also PHMSA's own recognition of their importance from their request that these releases be included as SALS.

References

1. **Pedersen, Chris.** S&P Global Platts - The Barrel. *The US enters a brave new world as it begins LNG exports.* [Online] February 10, 2016. [Cited: August 16, 2016.] http://blogs.platts.com/2016/02/10/us-brave-new-world-lng-exports/.

2. **Dominion.** History of LNG. *Dominion.* [Online] 2016. [Cited: August 16, 2016.] https://www.dom.com/corporate/what-we-do/natural-gas/dominion-cove-point/history-of-lng.

3. **Havens, J. A.** *Predictability of LNG Vapor Dispersion from Catastrophic Spills Onto Water: An Assessment.* Washington DC : US Coast Guard, 1977.

4. **Morgan, D.L. Jr. et al.** *Phenomenology and modeling of liquefied natural gas vapor dispersion.* California : Lawrence Livermore National Lab, 1984.

5. **Graham, Alex.** *Validating STAR-CCM+ for LNG Dispersion Simulations.* Prague : CD-adapco, 2016.

6. **Quarterman, Cynthia L.** *PHMSA Docket No. 2011-0101 FINAL DECISION.* Washington DC : US Department of Transportation Pipeline and Hazardous Materials Safety Administration, 2011.

7. —. *PHMSA Docket No. 2011-0075 FINAL DECISION.* Washington DC : US Department of Transportation Pipeline and Hazardous Materials Safety Administration, 2011.

8. **Gale, John A.** PHMSA Interpretation #PI-10-0017. *US DOT Pipeline and Hazardous Materials Safety Administration.* [Online] December 22, 2010. [Cited: August 13, 2016.] http://phmsa.dot.gov/portal/site/PHMSA/menuitem.6f23687cf7b00b0f22e4c6962d9c8789/?vgne

xtoid=749a7428d17ae210VgnVCM1000001ecb7898RCRD&vgnextchannel=2b9b34d513f95410VgnVCM100000d2c97898RCRD&vgnextfmt=print.

9. **Phil Suter, Jenna Wilson.** Design, Siting Considerations for LNG Facilities. *Pipeline & Gas Journal.* April, 2015, Vol. 242, 4.

10. **S. Coldrick, C. J. Lea, M. J Ivings.** *Validation Database for Evaluating Vapor Dispersion Models for Safety Analysis of LNG Facilities: Guide to the LNG Model Validation Database.* Quincy : The Fire Protection Research Foundation, 2010.

11. **John L. Woodward, Robin Pitbaldo.** *LNG Risk Based Safety: Modeling and Consequence Analysis.* s.l. : Wiley.

12. **Hoffmann, Richard A. et. al.** *NPFA 59A: Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG).* Quincy : National Fire Protection Association, 2006.

13. **Dr DM Webber, Dr SE Gant, Dr MJ Ivings & SF Jagger.** *LNG source term models for hazard analysis.* Buxton, United Kingdom : Health and Safety Executive, 2010.

14. **US Department of Transportation, PHMSA.** Table 1 - Nominal Failure Rates. *Pipeline Technical Resources.* [Online] February 11, 2015. [Cited: August 13, 2016.] http://primis.phmsa.dot.gov/lng/docs/Failure%20Rate%20Table%201%20-%20Rev%2002112015.pdf.

15. **Lindeburg, Michael R.** *Chemical Engineering Reference Manual for the PE Exam.* Belmont : Professional Publications Inc, 2012. 9781591264101.

16. **PHMSA.** LNG Plant Requirements: Frequently Asked Questions - DS12. *US Department of Transportation Pipeline and Hazardous Materials Safety Administration.* [Online] December 7, 2015. [Cited: August 16, 2016.] https://primis.phmsa.dot.gov/lng/faqs.htm#DS12.

17. **Washington Times.** Report sheds new light on LNG blast in Algeria. *Alexander's Gas & Oil Connections.* [Online] April 14, 2004. [Cited: August 16, 2016.] http://www.gasandoil.com/news/2004/05/nta41868.

18. **hydrocarbons-technology.** Sonatrach Skikda LNG Project, Algeria. *hydrocarbons-technology.com.* [Online] June 15, 2011. [Cited: August 16, 2016.] http://www.hydrocarbons-technology.com/projects/sonatrach/.

19. *Comparative Risk Assessment for Different LNG-Storage Tank Concepts.* **Stefan Rath, Marian Krol.** s.l. : The Italian Association of Chemical Engineering, 2013, Vol. 31.

20. *Use of water spray curtain to disperse LNG vapor clouds.* **Morshed A. Rana, Yuyan Guo, M. Sam Mannan.** 1, Netherlands : Journal of Loss Prevention in the Process Industries, 2010, Vol. 23. 0950-4230.